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Welcome to ECF23, the 23rd European Conference on Fracture.
The European Conference on Fracture has been a reference forum for the discussion of relevant scientific and technical developments in a multitude of topics concerning both behaviour and performance of Engineering materials and structures.
The conference scientific program is structured in thematic sessions for the different research fields and topics on a total of 69 sessions, plus an additional Poster session. The program further includes a set of 14 plenary lectures from internationally known researchers.
ECF23 should have been organized back in 2020, but was postponed two years on account of the difficult period the world is now coming out of due to the pandemic. As Chairmen, we share our enthusiastic expectation ECF23 will make up for this absence period and expect the presented research and fruitful discussions will be a reference for future research directions, developments and innovation, and that they will foster the collaboration between researchers, engineers, designers, experts and students from around the World. We wish you a very productive and pleasant conference as well as an enjoyable stay in Madeira, Portugal.

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# #PLI Prediction of fracture of polymer composite materials across different length scales

**Pedro Camanho**
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**ABSTRACT**

The accurate prediction of the onset and grow of damage mechanisms in laminated polymer composite materials, as well as the final collapse of composite structures, has been challenging the scientific community over the last decades. In this work, several analysis models that span different time and length scales will be described. Computational micromechanical models enable the detailed representation of the damage mechanisms at the scale of the reinforcing fibres, however this level of detail is associated with high computational costs, especially when using direct numerical simulation. This calls for the development of mesomechanical models that, ideally, use information obtained at smaller scales. Mesomechanical models typically combine continuum damage mechanics, which represent ply damage, with cohesive zone models, which represent delamination. While being a methodology that properly balances accuracy with reasonable computing times, mesomechanical models alone are not well-suited to perform uncertainty quantification and management analysis as the computational cost would be too high. This calls for micromechanical models, developed at the length scale of the laminate, and their combination with machine learning techniques. This work will show how to use theory-guided machine learning to generate B-basis allowables used in the certification of aircraft structural details.

# #PLII Fatigue and Fracture of Additively Manufactured Metallic Materials and Components

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European Conference on Fracture 2022 (ECF23)

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**ABSTRACT**

Additive manufacturing (AM) has recently gained much interest from researchers and industry practitioners due to the many advantages it offers, as compared to the traditional subtractive manufacturing methods. However, porosity and lack of fusion defects, residual stresses due to the thermal history of the part during the fabrication process, and anisotropy of the properties are some of the distinguishing features of AM metals. These features play important roles in controlling fatigue performance of AM in general, and in their multiaxial fatigue behavior in particular because of their multi-directionality. This talk will present an overview of these issues using recent data generated from Ti-6Al-4V and 17-4 PH stainless steel specimens made by laser-based powder bed fusion (LB-PBF) and subjected to axial, torsion, and combined axial-torsion loadings and under a variety of conditions including thermo-mechanical treatment and different surface roughness.  Issues important to fatigue performance at the component level, such as stress concentrations and variable amplitude loading typical of service load histories will also be included.  Model frameworks for fatigue analysis and life predictions using both critical plane and crack growth approaches will be illustrated by correlating and predicting fatigue data and life under the variety of materials, geometries, post-process treatments, and loading conditions considered.Ali Fatemi

# #PLIII Probing nanoscale mechanical properties of additively manufactured metallic alloys

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Trondheim, Norway

Additive manufacturing (AM), also termed as 3D printing, is currently one of the most emerging and disruptive engineering technology that changes the way of designing and manufacturing products. AM is an innovative technology that builds three-dimensional (3D) parts layer-by-layer guided by a computer-aided-design (CAD) model. Compared with the conventional manufacturing methods, the superiority of AM lies in the fast fabrication speed and the great shape-design freedom. Therefore, AM has been widely applied in producing high-performance components for aerospace, medical, energy, construction, and automotive areas. AM-ed metallic materials commonly experience a complex thermal history involving repeated melting and rapid solidification as well as subsequent heating-cooling cycles after solidification, which lead to the inhomogeneous microstructure associated with high residual stress and locally different mechanical properties, impacting the overall performance of the AM-ed component. The highly inhomogeneous microstructures lead the conventional testing methods like tension or compression to be inapplicable for the exploration of the mechanical properties in a constrained size or irregular shapes. Hereby nanoindentation is employed to investigate the local mechanical properties in AM-ed metallic alloys. The effect of heat input during AM process and the deformation mechanism, i.e. dislocation activities, indentation size effect, creep mechanism, etc, are explored, serving as a reference for improving the performance and further engineering applications of AM-ed metallic materials.

# #PLIV Fracture in Structural Adhesives Joints- Achievements and Challenges

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UK

**ABSTRACT**

Advances in structural adhesives technology and the development of a wide range of advanced lightweight materials such as fibre reinforced composites, light metal alloys and polymers has led to the rapid adoption of structural adhesive bonding. Such adhesively bonded structures allow modern transport vehicles to be designed with lower structural weight together with other advantages such as improved fatigue resistance and enhanced impact resistance. However, as adhesives have become more fracture resistant, so the fracture test methods used to assess them have had to develop in parallel. The lecture will describe how fracture mechanics has been used to assess the integrity of adhesively bonded joints over a range of anticipated operating conditions, and will consider some of the current challenges faced by researcher in this field.

# #PLV Mechanical behaviour of biomedical materials

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Analysis of mechanical problems related to biomedical applications has gained significant momentum in recent years, in part to meet demands related to technical advancements in personalized medicine. However, our understanding of mechanics of biological tissues, their properties and performance as well as their interaction with biomedical devices remains limited. Even traditional engineering materials, used for medical applications, when exposed to physiological conditions, demonstrate specific features of deformation, damage and fracture processes. Their supposed long-term performance is significantly affected by such exposure, resulting in deterioration of their properties and performance. Besides, in some applications, a special emphasis is on controlled deterioration of medical implants, e.g., biodegradation of stents (that could be metallic and plastic) and scaffolds, contrasting with traditional ideas of structural integrity.

This paper focusses on the effect of environmental conditions on mechanical properties and performance of, on the one hand, collagen that can be found in many biological tissues, and, on the other hand, biopolymers used in personalised medical devices, manufactured with 3D printing. It demonstrates that physiological conditions cause significant changes in mechanical behaviour of different biomaterials.

# #PLVI Finite Fracture Mechanics to predict the initiation of new cracks in brittle materials

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Crack nucleation modeling often requires a detailed knowledge of the microstructure and involves complex micro-mechanisms. The question is: following the example of Griffith's criterion for the study of the growth of a pre-existing crack, can we have a macroscopic criterion, based on few material parameters, to predict the nucleation of new cracks in a brittle material?
Among other more numerical methods like cohesive zone models or phase field method, Finite Fracture Mechanics tries to provide an answer. This approach has many variations, an overview is proposed of one of the most successful one: the coupled criterion (CC). The common feature of all criterions predicting crack nucleation is the need of two failure parameters. Material toughness and tensile strength are the two ingredients of the CC which states that crack initiation can occur if two conditions are fulfilled simultaneously: the released energy by a potential crack with length $l$ is large enough and the tension acting all along the presupposed crack path is larger than the material strength. In this sense, it is a non-local criterion. A consequence of these two conditions is that initiation is an unstable process, the crack jumps a given length that can be determined, and then goes on growing or stops. The CC enjoys an interesting property: it coincides with Griffith's criterion in case of a pre-existing crack and with the maximum tensile stress condition if no stress concentration.
The CC is available in 2D and 3D in two versions: a full Finite Element computation and an asymptotic approach, the latter allowing quasi-analytical expressions of the criterion provided the asymptotic framework holds true. Examples from various origins illustrate the presentation.

# #PLVII Structural Integrity of prestressed bridges

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**ABSTRACT**

In the last years, Italy experienced the collapse of five road bridge: Petrulla viaduct (2014), Annone (2016) and Ancona (2017) overpasses, Fossano viaduct (2017) and Polcevera (2018) bridge. Around the world several collapses also have been occurred.

Although for deeply different reasons, the collapses occurred can all been gathered into the same common cause: the (lack of) knowledge of the effective structural condition, a serious problem that affects existing constructions.

Different problems such as missing of the as-built designs, an appropriate construction and movement precautions, a heavy vehicle checking, and a material decay monitoring can nevertheless be addressed as an inadequate knowledge of what is happening to/in the structure.

In the first part of the lecture, it will report a short description of the failures for some bridges, while in the second part a main set of problems involved in bridge safety and maintenance will be discussed.

Finally, in the third part, a review on innovative and peculiar investigation and monitoring techniques will be illustrated. The collected results can shed new light on future perspectives for the Civil Engineering sector, sector that has to be ready for facing the challenges of preservation, restoration and/or replacement of the existing infrastructural constructions, worldwide.

# #PLVIII Dependence of fatigue life on the sequence of individual load cycles of different amplitudes and mean values explained by fracture mechanics


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**Abstract**


The sequence of variable amplitude loads, which are characterized by different amplitudes, mean values and temperatures, can strongly influence the service life. The frequently used Palmgren-Miner rule does not consider the sequence of the individual load cycles, any deviation from this rule can be classified as a sequence effect. The resulting fatigue life of a component under variable amplitude loading is the result of several sequence effects that can amplify or cancel each other out. Another finding is dependent on crack lengths: Overloads reduce fatigue life for short cracks, while fatigue life for long cracks is mainly increased. Fracture mechanics concepts are essential to consider these effects.

As part of a completed research project, an extensive experimental database was created in collaboration with the Fraunhofer IWM in Freiburg to quantify sequence effects and validate the models developed. The test program included unnotched and notched specimens as well as welded joints made of austenitic stainless steel 1.4550 (X6CrNiNiNb18-10 / AISI 347). Several types of load sequences (constant amplitudes as base, two-stage, eight-stage and service load sequences) were applied.

The developed concept for the calculation of the short and long crack propagation life uses the effective cyclic J-integral as crack driving force. It can be seen as an improvement and extension of the established $P_J$ concept. The improvements are achieved by substituting the crack growth law and performing a crack growth calculation instead of a damage accumulation calculation. Further improvements in accuracy can be achieved by capturing the transition from the short crack to the long crack threshold and by taking transient crack closure into account.

In summary, it can be said that the scatter of the ratio of experimentally determined lifetimes under variable amplitude loading to those calculated with the new concept is only in the order of magnitude of the scatter of the lifetimes in constant amplitude tests.

# #PLIX Revisiting Cleavage Fracture Modeling in Steels: From the Griffith Assumption to the Beremin Model, and Beyond

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There has been a long history of concern with the brittle fracturing of materials in connection with the need to understand and control the often sudden catastrophic failure with low energy absorption associated with this failure mode. In view of the great technological importance of brittle fracture behavior of engineering structures ever since the late nineteenth century, much earlier attention focused on a qualitative analysis of the fracture process until A. A. Griffith bridged the gap between stress analysis and crack size in his seminal contribution published in 1921, thereby providing a major impetus for developing the field of fracture mechanics. After Griffith's fundamental concept of energy conservation applied to stress analyses of cracks, there followed a long hiatus until further development was achieved in advancing fracture mechanics based approaches for quantitative analysis of unstable fracture by cleavage, as of interest in assessments of crack-like flaws formed during in-service operation for many structural applications made of carbon and low-alloy steels. However, while these approaches clearly simplify structural integrity assessments, they often have limited ability to predict the potential strong influence of constraint on fracture behavior and, perhaps more importantly, do not address the strong sensitivity of cleavage fracture to material characteristics at the microlevel. The early recognition of these limitations prompted a surge of interest in analyzing, predicting and unifying toughness measures across different crack configurations and loading modes based on a micromechanics interpretation of the cleavage fracture process. Among these earlier research efforts, the seminal work of the French group Beremin provided the impetus for development of a framework establishing a relationship between the microregime of fracture and macroscopic crack driving forces (such as the $J$-integral) by introducing the Weibull stress as a probabilistic fracture parameter directly connected to the statistics of microcracks (weakest link philosophy).

The presentation will focus on key aspects of cleavage fracture spanning from fundamental assumptions, experimental characterization and temperature dependence of cleavage fracture stress to the development and application of conventional and novel procedures for cleavage fracture assessments, including computational and probabilistic modeling at the micro and mesoscale levels. Despite powerful computational resources now available, there are still restrictions imposed by our current understanding of the methodology and its fundamental concepts to obtain meaningful predictions which are reasonably invariant to model details, including crack and loading configuration, Clearly, the need to incorporate all the relevant mechanical and metallurgical microfeatures into the model to obtain a more accurate description of the physical mechanism (thereby placing emphasis on developing a more fundamental, scientific model) should be tempered by the need to develop a relatively simpler, but yet highly effective, engineering model capable of dealing with complex situations with only modest effort.

# #PLX Void-based predictive framework for hydrogen embrittlement

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**Abstract**

The attention to hydrogen embrittlement (HE) has been recently intensified in light of hydrogen as a carbon-free energy carrier. The drastic consequence of HE is the transgranular to quasi-cleavage and intergranular fracture transition. Despite the worldwide research, the intrinsic mechanism causing the fracture transition even for quasistatic loading condition remains a matter of debate, and there is a lack of mechanism-based predictive tool which can capture the whole transition process. This talk starts from an atomistic study of HE mechanism and highlights the importance of the nanoscale voiding process prior to decohesion. Enlightened by the nanoscale findings and supported by the experimental evidence that the dimples are still visible on hydrogen-induced fracture surfaces but their sizes become significantly smaller, a void-based predictive framework is developed to model the hydrogen-induced ductile to brittle transition. The complete Gurson model, designed to predict ductile failure by void nucleation, growth and coalescence, is extended to include failure by decohesion. In the absence of hydrogen, void coalescence controlled ductile failure prevails. However, with the increase of hydrogen concentration, the likelihood of void coalescence failure is gradually replaced by the decohesion failure driven by a hydrogen-informed decohesion failure criterion. Coupled with hydrogen diffusion, the proposed model can predict a realistic level of embrittlement as well as the suppression of dimples in a hydrogen induced fracture surface. The model may serve as a basis for interpretation of laboratory experiments and enable the transferability of the laboratory results to the integrity assessment of engineering components in hydrogen environment.

# #PLXI Creating a new generation of functional multi-material fatigue resistant solid-state joints

Filippo Berto

**Abstract**

Future innovations lie in parts that derive their multifunctionality from material complexity at all scale levels. This is made possible by combining properties in thin multilayers by packaging (combining electrical, mechanical, fluidic and optical devices) and exploiting nanoscale effects (quantum confinement, surface states). To fulfil these needs, for example, micro- and nanojoining have become an integral part of microelectronic, medical, aerospace and defence industries. Still, the development of the field faces challenges because of the ever-advancing of the devices. One of the most important property is the capacity of bearing properly fatigue loadings by means of highly resistant bonding interfaces. Another fundamental aspect is the capacity of joining together different materials with a flexible and quick process able to assure high mechanical properties. In this work an overview of different solid-state welding techniques will be carried out introducing some recent and interesting developments in field. With the ambition of creating highly fatigue resistant joints it will be shown how it is possible to take full advantage of recent advances in macroscale low temperature metal joining to create a unique, controlled process for microjoining with the ambition to scale it down to nanojoining.

# #PLXII Revisiting characteristic region description for crack initiation in very-high-cycle fatigue

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**Abstract**

With regard to very-high-cycle fatigue of metallic materials, we proposed the concept of characteristic region of crack initiation with the characteristic parameter of related $\Delta K$ (IJFatigue 2014;58:144–51), and proposed the Numerous Cyclic Pressing (NCP) model to reveal the formation mechanism of this characteristic region (IJFatigue 2016; 89:108–18). This characteristic region is so-called fine granular area (FGA) for high-strength steels or rough area (RA) for titanium alloys. The proposed NCP model suggests that the formation of FGA or RA nanograin layer requires two basic conditions: (1) the existence of compressive stress between originated crack surfaces to result in the contacting and pressing between the crack surfaces, and (2) sufficient number of loading cycles to provide enough cycles of repeated contacting and pressing. Between 2016 and 2018, we presented plenary talks in ECF21 (2016), VHCF7 (2017), 12th Int Fatigue Congress (Fatigue 2018), ECF22 (2018) and other international events to share our findings. Since then, further investigations and revelations regarding this topic have arisen. This plenary presentation will revisit the concept of characteristic region and the NCP model by introducing the newly results of ours and others in the literature. After the brief description of basic propensities for characteristic region and NCP model, the following issues will be addressed. Does the microstructure refinement as well as nanograin formation in characteristic region happen before or after crack initiation? What is the correlation between applied stress ratio and the formation of characteristic region? What are the details of refined microstructure in characteristic region including the thickness and the distribution of nanograins? Does vacuum environment is the necessary condition for the formation of characteristic region? What are the features of characteristic region in different materials and different loading modes? Such issues of revisiting will be an addition to the descriptions of this topic in our previous review article (TAFM 2017;92:331-50).

# #PLXIII Modeling the Contribution of Fiber Bridging in Unidirectional Composites

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*Fiber bridging* *Fracture resistance curve* *Fatigue*

**Abstract** Composite materials are widely used in aerospace applications in order to increase strength-to-weight ratios as compared to metals, thus decreasing the weight of structures and consuming less fuel. A common type of composite is a polymer matrix reinforced with fibers arranged in one direction. Beam-type specimens are commonly used to determine the fracture toughness of this type of material, and in mode I double cantilever beam (DCB) specimens are usually tested. DCB specimens of unidirectional laminates exhibit 'fiber bridging', a phenomenon that occurs when a delamination, the most common failure mode in laminate composites, propagates as a result of an external load. While propagating, reinforcement fibers from one face of the delamination cross over to the other face, such that fibers are simultaneously pulled from both faces, increasing the apparent resistance of the material to delamination propagation. However, in most applications fiber bridging is not observed in components containing a delamination, and in such cases fiber bridging may be considered an artifact of fracture toughness laboratory testing performed on DCB specimens.

The aim of this investigation is to determine the fiber bridging contribution to the energy release rate of the material. To this end, analytical and numerical models are developed that describe the material behavior during interlaminar delamination propagation. These models are based on mode I laboratory tests conducted in quasi-static and fatigue loading on coupons of a carbon/epoxy composite, and may be used to predict failure of composite laminate structures. The experimental work for quasi-static delamination propagation consists of standard testing, adjusted to enable the determination of fiber bridging parameters. The results of these tests allow determination of the fracture toughness of the material, as well as the fiber bridging parameters required to model the material response. For determination of fatigue delamination propagation parameters, two test protocols are used. The first protocol consists of testing a specimen containing a delamination in fatigue for about three million cycles with no intervention during the testing procedure. The second protocol consists of a series of fatigue test sequences applied consecutively to a single specimen. The results of the quasi-static and fatigue tests are used in the calibration of the respective numerical models.

In order to construct a numerical tool to predict delamination propagation, the cohesive zone approach is used to model the behavior of the material. A cohesive zone model is used in both quasi-static and fatigue loading. Each of the two cohesive zone models is implemented in finite element analyses via a user element (UEL) subroutine coded for that purpose. The results of the laboratory tests are used to calibrate the models. Good correlations are obtained for both the quasi-static and fatigue tests. The cohesive zone models enable determination of the contribution of fiber bridging to the energy release rate of the material in both quasi-static and fatigue loading. Thus, the actual energy release rate of the material is obtained.

# #PLXIV Simulation of anisotropic thermomechanical fatigue crack growth in nickel base alloys

Author: Prof. Meinhard Kuna

Co-authors: Dr. Ludwig, Dr. Rabold (TU Freiberg), Dr. Schurig, Dr. Schlums (Rolls-Royce Germany)

**Abstract:**
ALLVAC R718Plus is a nickel base superalloy possessing outstanding abilities to withstand both mechanical and thermal loads, which make this material ideal for turbine disks and blades in aero engines. The thermomechanical fatigue (TMF) crack growth behavior depends on temperature, in-service load cycles and material orientation. In particular, the crack growth at high temperature dwell time shows significant influence of material anisotropy due to platelet-like precipitations, which leads to crack deflection from the maximum principal stress direction. These specific properties must be taken into account properly to ensure a safe design and the desired lifetime of components. The focus of this presentation is to develop an appropriate fracture criterion to describe crack deflection for such kind of anisotropic material resistance. This criterion and the associated crack growth laws for thermomechanical fatigue are implemented in the FEM software PROCRACK for fully automated three-dimensional crack propagation simulation. The numerical simulation of experiments on CT-specimens with various material orientations provided evidence that the software can capture the actual fracture behavior. Moreover, a suitable set of material parameters could be identified. The performance of the presented approach to predict realistic three-dimensional TMF crack propagation is demonstrated by an application to a typical turbine component made from ALLVAC R 718Plus.

# #001 Understanding the effects of hydrogen on the transition reference temperature of a reactor pressure vessel steel using sub-sized pre-cracked Charpy specimens

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*Impact test* *Ductile-brittle transition* *Master curve*

**Abstract** The reactor pressure vessel (RPV)—thick steel container that houses the nuclear reactor core for fission power generation—is considered irreplaceable and that is why maintaining its structural integrity during the whole lifetime of reactor is indispensable. Irradiation embrittlement which lowers the ductile-to-brittle transition temperature of RPV steels poses serious concerns to its integrity given lifetime extension of reactors worldwide—as it will cause more accumulation of defects and microstructural changes. Embrittlement of RPV should be monitored periodically with evaluation of fracture toughness, usually carried out with surveillance Charpy specimens. Given the limited number specimens in surveillance capsules, the possibility of using sub-sized specimens to monitor the integrity of RPV has been receiving a lot of attention. In the present research, quasi-static and dynamic fracture toughness of the reference steel JRQ for reactor pressure vessels was investigated using sub-sized pre-cracked Charpy specimens. Fracture behaviour in the ductile-to-brittle transition region was evaluated in accordance with the master curve method, which is an alternative to assess the irradiation embrittlement effects of RPV. Effects of hydrogen, which can be picked up from the high-temperature water environment, and of loading rates on the reference transition temperature are discussed. In addition, fractography analyses were performed to identify change in the failure mode in samples tested with absorbed hydrogen and at different loading rates.

# #002 Innovative crystallizing materials for waterproofing concrete

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*Concrete* *Waterproofing* *Crystalline formations*

**Abstract** Nowadays, in the construction sector, the ability of a structural system to perform the functions for which it was designed, under certain conditions of use and for a fixed operating time, is increasingly associated with the concept of durability.

Durability, in turn, is linked to very different variables (correct design and construction of the structural elements, quality of the materials and their exact prescription, environmental conditions) and it is often too expensive to achieve, both in economic and designing terms. Furthermore, in case of materials such as concrete, neglecting even one of the variables, the possibility of guaranteeing the durability of a structure is compromised provided that neither major nor expensive restoration works are carried out.

This work is part of the research line concerning the study of innovative materials to increase the durability of concrete constructions. In particular, it wants to demonstrate the effectiveness of a multifunctional, ready-to-use, ecological and water-based crystallizing liquid treatment to waterproof and protect concrete and all cement-based materials. This additive is characterized by a "green" connotation, ease of use (it can be sprayed directly on the surface of the elements), and cost-effectiveness, therefore its application is particularly interesting in the field of concrete technology, since it can be a smart and a sustainable solution to ensure the durability of concrete in structures.

The experimental campaign considered the preparation of standard concrete specimens and concrete specimens treated superficially with the innovative and ecological waterproofing additive. Based on the indications provided by UNI 7699:2018, the absorption of water at atmospheric pressure was determined for all samples, varying their nature, the age and the state of degradation. The primary purpose was to evaluate the phenomena connected to the durability of the concrete, which can be largely attributed to the transport of liquids in their porous structure due to both the capillary rise and the pressure gradients.

The results of this research work have shown that the liquid crystallization treatment allows a decrease in water penetration on the treated samples. Furthermore, this innovative smart additive is extremely capable of making the concrete hydrophobic by forming a water repellency on the surface and showing a good resistance against hydrostatic water pressure.

# #004 Fracture mechanics performance of 3D printed amorphous thermoplastic polymers at impact and quasi-static loading

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*Thermoplastic polymers* *3D printing* *Crack growth behaviour*

**Abstract** Rapid manufacturing of individualized products made from plastics using 3D printing technologies will now become a highly growing market. However, the influence of morphology and processing parameters (such as speed of printing and screen angle) on the fracture mechanics performance of such additively produced materials is still inadequately investigated. Therefore, the effect of processing parameters, loading rate (impact and quasi-static loading) on the crack-growth behaviour (unstable and stable crack growth) of thermoplastic polymers (acrylonitrile–butadiene–styrene copolymer (ABS) and polycarbonate (PC)) has been analysed using instrumented Charpy impact test, essential-work-of-fracture approach and crack-resistance-curve concept combined with non-destructive methods.

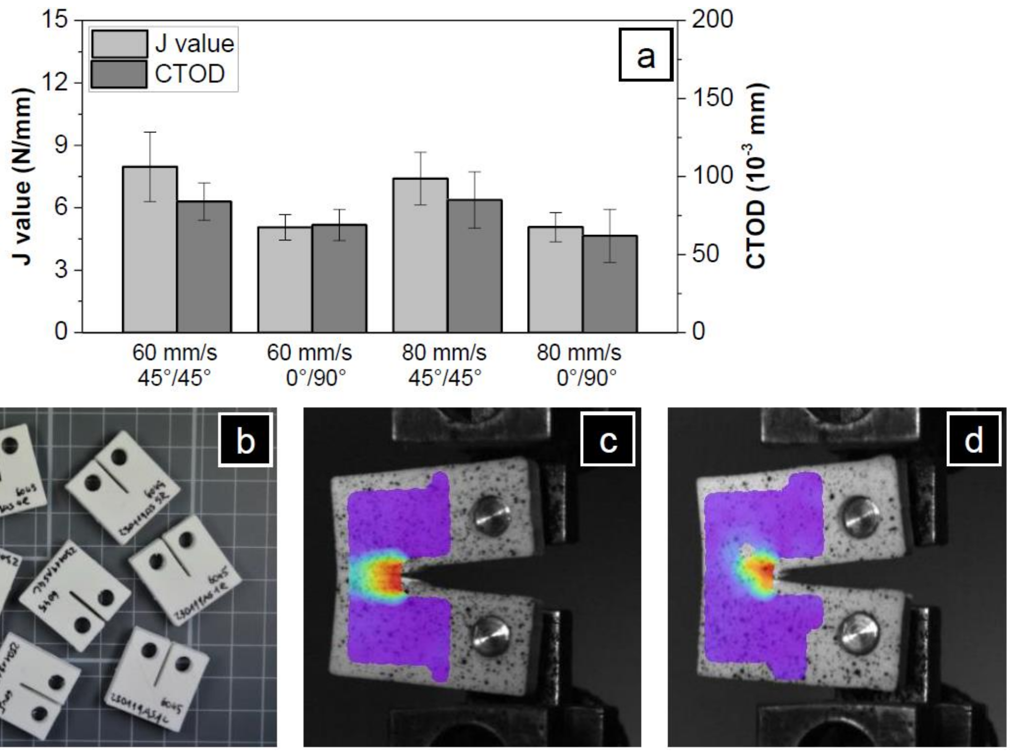


***Figure 1** – Fracture mechanics parameters for ABS at impact loading as a function of the processing parameters (a); fracture mechanics tests (0°/90° (c) and 45°/45° (d)) on small CT specimens (b) of ABS at quasi-static loading combined with strain field analysis*

**Acknowledgement.** The authors acknowledge Investitionsbank Sachsen-Anhalt for financial support regarding the project dealing with „Prognose des Einsatzverhaltens 3D-gedruckter Bauteile mittels bruchmechanischer Ansätze" (acronym: FFD-Crack).

# #005 Microstructure and fracture behaviour of the TRIP/TWIP laminate produced by accumulative roll bonding

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*TRIP steel* *Accumulative roll bonding* *Laminated metal composite*

**Abstract** The 4-layered bi-metal laminate made of X5CrMnNi-16-6-6 (TRIP steel) and X5CrMnNi16-6-9 (TWIP steel) was manufactured by accumulative roll bonding (ARB). The intermediate annealing between rolling passes allowed to achieve good bonding between the laminate layers. The microstructure of the laminate at each step of production was analysed with a main focus on the bonding interface and deformation lenses by means of electron microscopy, including chemical and orientation mapping techniques, and microhardness measurements. The tensile specimens were cut out from the laminate and tested under quasi-static loading with subsequent microstructural and fracture surface analysis. Subsequent rolling and annealing of the steel layers resulted in the alteration of the grain size and microhardness. The microstructure of a deformation lens was found to fully change from severely deformed brittle steel matrix with excessive oxygen content after rolling (Fig. 1b) to a ductile mixture of sub-micron globular oxides and austenite grains after annealing (Fig. 1c). These ductile deformation lenses ensure excellent bonding of layers (Fig. 1d) and microcracks blunting. This allowed to achieve a remarkable combination of mechanical properties of the 4-layered TRIP-TWIP laminate with the yield strength up to 800 MPa and elongation to failure up to 45%, which resulted in the work of deformation up to 41 GPa·%.

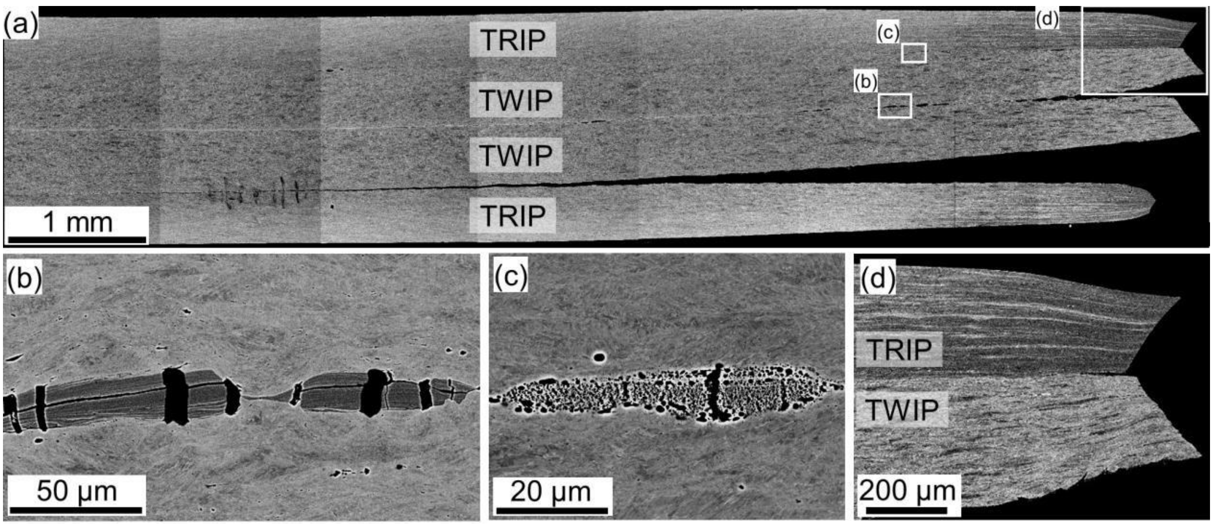


***Figure 1*** *- Back scattered electron (BSE) images of a tensile specimen cross-sectioned parallel to the loading axis after failure. (a) Overall view with the indication of layers. Magnified views of the (b) annealed deformation lens, (c) non-annealed deformation lenses, (d) fully bonded TRIP/TWIP interface.*

# #006 In situ damage monitoring during ultrasonic fatigue testing by the advanced acoustic emission technique

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*Ultrasonic fatigue testing*    *Acoustic emission*    *Digital signal processing*

**Abstract** Ultrasonic fatigue testing (USFT) is an effective method for rapid determination of the fatigue properties of structural materials under high cycle ($\geq 10^6$ cycles) loading. However, the occurrence and accumulation of fatigue damage in this test method remains uncertain due to the limitations of existing measurement methods. Currently used monitoring methods allow to detect fatigue cracks, but only on the late stages of failure. Despite the superior sensitivity to localized processes in materials, the use of the acoustic emission (AE) method in ultrasonic testing is extremely difficult due to the presence of resonant noise. The aim of this work was to suppress resonant noise and extract the signal for the early detection of fatigue damage. Samples of the aluminum alloy AlSi9Cu3 were tested under asymmetric cyclic loading (R = 0.1) at a resonant frequency of 19.5 kHz with a thresholdless continuous AE streaming. The fracture surfaces were analyzed by electron and optical microscopy. The AE were processed by the digital filtering method consisted in detecting resonant noise and removing it from the spectrum. The processed spectrograms were integrated by frequency with further extraction of the AE events by the threshold method. Digital filtering method revealed correlation between AE signals and fatigue damage, whereas the undamaged control sample showed no signals.

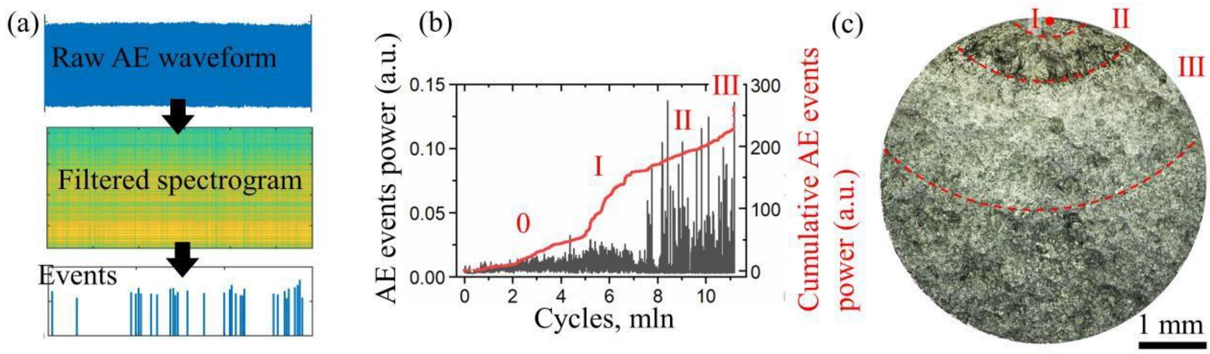


***Figure 1** – Graphical abstract of the work, showing (a) digital processing of the acoustic emission (AE) data during ultrasonic fatigue testing, (b) resulting AE activity, and (c) fracture surface a specimen after fatigue failure with fracture stages*

# #007 Patterns of Structural Formation of Tricalcium Phosphate Nano-coating by Density Functional Method

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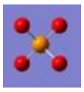
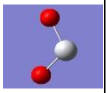
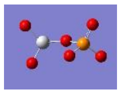
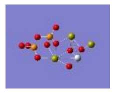
*Tricalcium Phosphate Coatings* *Ab initio Calculations* *Adhesive Strength*

**Abstract** The focus of this research is to propose a method of calculating the adhesive strength of a nano-crystalline structure of Tricalcium Phosphate—a material used in dentistry to cover a titanium tooth implant to increase osseointegration, which is the conduciveness of its mating to bone—by using Density Functional Theory (DFT). The nano-crystalline structure of Tricalcium Phosphate has shown to increase osseointegration between the coating and the bone. While fast osseointegration is most attractive, it is important to have a strong adhesive bond between the coating and the titanium implant. A measure of the coating-to-substrate (titanium implant) binding energy is the energy of this bond. We suggest a theoretical method how to calculate the adhesion strength of Tricalcium Phosphate coating on titanium substrate, using *ab initio* calculations. We slowly “built up” Tricalcium Phosphate by way of calculating the binding energy between its constituent parts and titanium. We used the Gaussian09 DFT B3LYP with a basis set of 6-31G to structurally analyze the bond lengths, bond angles, dihedral angles, and point charges to understand the interactions of these substances and how they contribute to the strength. ***Table 1** - Binding Energy Calculations*

| **Molecule** | $PO_4$ | Ca | $TiO_2$ | $TiO_2PO_4$ | $TiO_2(PO_4)_2$ | $TiO_2Ca_3(PO_4)_2$ |
|---|---|---|---|---|---|---|
| **Picture** |  |  |  |  |  |  |
| **Ti-O Bond Lengths** (Å) | N/A | N/A | 1.63 | 1.76 & 1.63 | 1.85&1.60 | 1.70 & 1.71 |
| **Ti-O Bond Angles** (degrees) | N/A | N/A | 107.61 | 103.95 | 106.89 | 114.57 |
| **Ground Energy** (a.u.) | -638.2 | -674.2 | -995.0 | -1633.8 | 2272.6 | -4295.9 |
| **Charge of Titanium** | N/A | N/A | 0.961 | 1.156 | 1.188 | 1.127 |
| **Binding Energy** (a.u.) | N/A | N/A | N/A | 0.59 | 0.54 | 0.62 |

# #008 Extension of Finite Fracture Mechanics to dynamic crack initiation

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*Crack initiation* *Coupled criterion* *Dynamic*

**Abstract** The dynamic extension of the coupled criterion [1] appears as one of the remaining challenges within the framework of Finite Fracture Mechanics [2]. It includes several topics to be assessed such as, for instance, dynamic crack initiation under static or dynamic loadings.

The energy condition of the coupled criterion relies on the following balance of external force work ($W_{ext}$), potential ($W_p$), kinetic ($W_k$) and crack surface creation ($\Gamma$) energies between two states prior to and just after crack initiation:

$$\Delta W_p+\Delta W_k+\Gamma=\Delta W_{ext} \tag{1}$$

The quasi-static form of the coupled criterion consists in considering a quasi-static initial state leading to an increase in kinetic energy during initiation: $\Delta W_k \geq 0$, which allows deriving the energy condition of the coupled criterion as the following inequality:

$$\Delta W_{ext} -\Delta W_p \geq \Gamma = G_c\, S \tag{1}$$

where S is the newly created crack surface and $G_c$ the material fracture toughness. The energy condition in the quasi-static form of the coupled criterion thus writes as an inequality from which an optimization problem can be written in order to determine the initiation crack surface and imposed loading. It turns out that most of the time, the solution of this problem corresponds to replacing the inequality (2) by an equality, thus neglecting the kinetic energy creation during the new crack formation.

The objective of this work is to take into account the dynamic crack propagation and the resulting inertial effects in the coupled criterion. It yields to writing the energy condition in a new fashion nevertheless consistent with the quasi-static formulation. Several crack initiation configurations are studied, such as the influence of dynamic crack initiation under tensile or compressive loading of circular hole specimens or transverse crack initiation in 0/90/0 laminates. The dynamic extension of the CC enables assessing crack initiation under quasi-static or dynamic loading. The crack velocity profile during initiation appears to have a strong influence on the initiation loading.

[1] Leguillon, D. Strength or toughness? A criterion for crack onset at a notch. Eur. J. of Mech. - A/Sol. 2002;21:61-72.

[2] Weissgraeber, P., Leguillon, D., Becker, W. A review of Finite Fracture Mechanics: crack initiation at singular and non-singular stress raisers. Arch. Appl. Mech 2016:357-401.

# #009 Analysis of additively manufactured PLA containing notches using Failure Assessment Diagrams

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*Additively Manufactured PLA* *Notch* *Failure Assessment Diagram*

**Abstract** This paper provides a methodology for the estimation of the load bearing capacity of additively manufactured (AM) PLA specimens that may be applied to both cracked and notched conditions. The methodology is based on the use of Failure Assessment Diagrams (FADs), which are, in practice, the main fracture-plastic collapse assessment tool provided by structural integrity assessment procedures. When dealing with notch-type defects, the methodology requires, additionally, the application of a notch correction that it is based on the Theory of Critical Distances (TCD) and the Creager-Paris stress distribution ahead of the crack-tip. The results show that the FAD methodology (alone, in cracked conditions, or in combination with the TCD in notched conditions) can be successfully applied in this AM polymer.

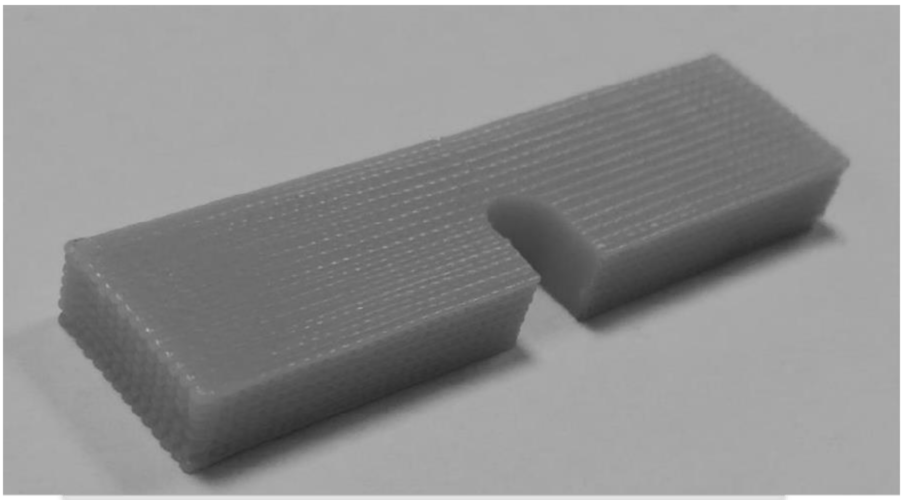

***Figure 1** – PLA SENB specimen containing a U-notch (radius = 2.0 mm)*

# #010 Environmentally Fatigue Analysis of nuclear components within the framework of INCEFA-SCALE project

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*environmentally assisted fatigue* *pressurized water reactor* *long-term operation*

**Abstract** This paper provides the current status of the H2020 INCEFA-SCALE project. INCENFA-SCALE is a five-year project, which began in October 2020, and its main objective is to improve the ability of predicting the lifetime of Nuclear Power Plants components subjected to environmental assisted fatigue.

EPRI, in the USA, is leading a series of component-scale environmental fatigue tests which are expected to advance data availability significantly; however, the ability to address transferability of laboratory-scale tests to real component geometries and loadings will still be constrained by limited test data. This is the knowledge gap addressed by INCEFA-SCALE; it is recognized worldwide as significant. The project strategy will be: (1) the development of comprehensive mechanistic understanding; and (2) testing focussed on particular aspects of component-scale cyclic loading. So far, the data mining of different finished projects (INCEFA-PLUS, USNRC, EPRI, MHI and AdFaM) has been carried out, and test conditions for filling the knowledge gaps have been established. Nowadays, testing campaign is focused on producing reference data, analysing complex waveforms (variable amplitude) and the effect of the surface finishing. Next testing phases will focus on particular conditions: multi-axial tests, notches, stress/strain gradient effect and size effect. Furthermore, the microstructural analysis of common material and a guideline for fatigue striations measurement on the fracture surface have been developed. This article provides an update to the project status and the advances made in data analysis, mechanical understanding and testing conditions.

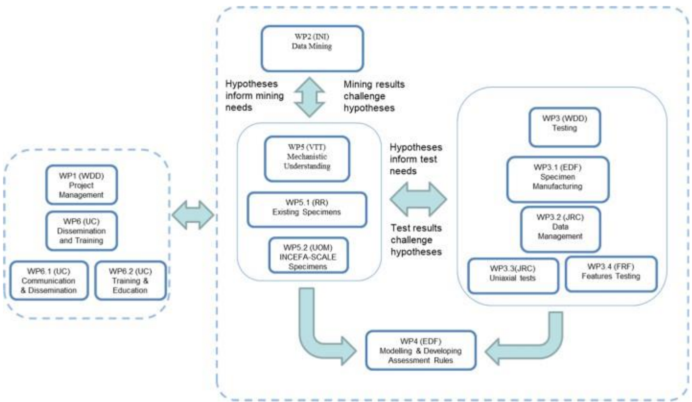


***Figure 1** – INCEFA-SCALE Work Packages interdependencies*

# #011 FRACture mechanics TEsting of irradiated RPV steels by means of SUb-sized Specimens

Marcos Sánchez[1], Sergio Cicero[1], Borja Arroyo[1], Sergio Arrieta[1]

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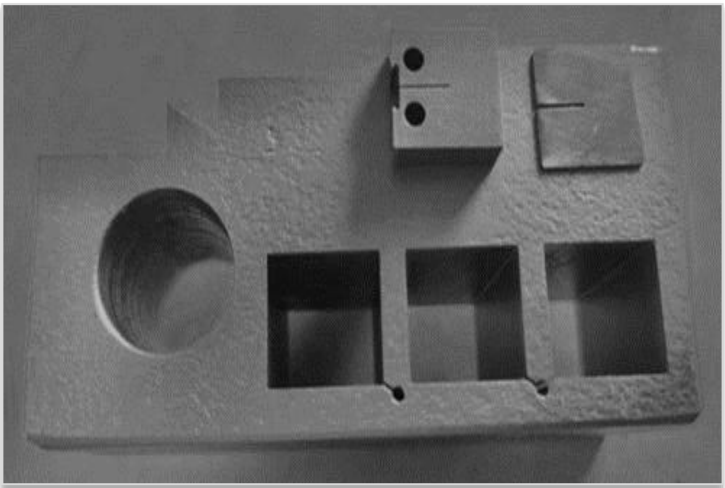
*FRACTESUS* *Miniature Compact Tension* *Reactor Pressure Vessel Steel*

## Abstract

**Abstract** This work presents the overall structure of the FRACTESUS project and the progress carried out so far, showing the first experimental results. The project is part of the EURATOM work programme 2019-2020, topic NFRP-04: Innovation for Generation II and III reactors. The project developments will contribute to the long-term safe operation of nuclear power plants, addressing the goals of the European Union in terms of sustainable and green energy, where the decarbonisation of the energy system is a priority. FRACTESUS intends to demonstrate the viability of measuring the fracture toughness of reactor pressure vessel steels by means of sub- sized specimens (e.g., 0.16CT or mini-CT specimens). This will allow, among others, to notably increase the number of specimens available in the surveillance programs of the nuclear power plants.



# #013 The effect of cooling transients on tearing resistance of a rolled steel

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*Cooling transient* *Tearing resistance* *Normalization method*

**Abstract** The fracture toughness in the upper shelf area is determined with J-R curves. Presently, there is no data, nor predictions, regarding the J-R curve development during a decreasing thermal transient. In this study, the effect of rapid cooling on J-R curves is investigated.

Fracture toughness specimens of a rolled steel S 460 were cooled from 300 °C to the room temperature at a cooling rate of 2 °C/s determined at the center location of the specimen. The cooling rate is faster close to the surface. The cooling rate was selected to be in the same range as during a loss of coolant accident. The following was concluded:

1. No brittle fracture in the upper shelf region was observed for the investigated material during the cooling transient. The transient can promote splitting observed in the specimens.

2. Based on the results, when doing structural integrity analyzes of thermal transients in the upper shelf region, it is recommendable to use the lowest fracture toughness properties in the investigated temperature range, if no other information is available.

The objective of the investigation is to develop a model for prediction of the J-R curve behavior during a cooling transient.

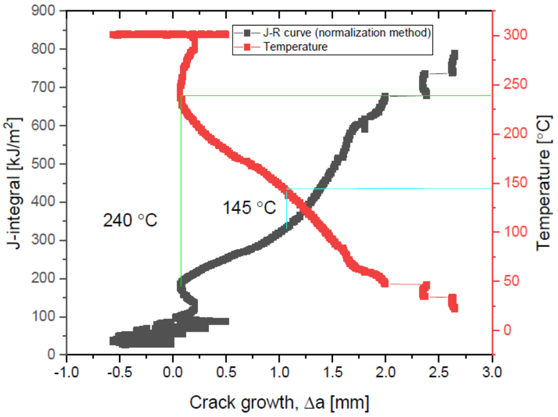


***Figure 1*** *- Comparison of the temperature and the effect on the shape of the J-R curve, for specimen 5.3.*

# #014 Phase field modelling of hydrogen assisted fracture

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[1]*Department of Civil and Environmental Engineering, Imperial College London*

[2]*Department of Mechanical Engineering, Technical University of Denmark*

*Hydrogen embrittlement* *Phase field fracture* *Chemo-mechanics*

**Abstract** Hydrogen is ubiquitous and causes catastrophic failures in metallic components. The sensitivity of metals to hydrogen damage increases with material strength, compromising decades of metallurgical progress and extending the problem beyond aggressive environments (e.g, off-shore structures) to numerous applications across the transport, energy, defence and construction sectors. However, the development of models capable of predicting cracking in hydrogen-sensitive environments remains an elusive challenge.

In this work, we present a phase field framework for predicting hydrogen assisted fracture in elastic-plastic solids. The model builds upon: (i) a coupled mechanical and hydrogen diffusion response, driven by chemical potential gradients, (ii) a strain gradient plasticity description of crack tip deformation, and (iii) a hydrogen-dependent fracture energy degradation law grounded on first-principles calculations. The theoretical model is numerically implemented using a mixed finite element formulation and several 2D and 3D boundary value problems are addressed to gain physical insight and showcase model predictions. The results reveal the critical role of plastic strain gradients in rationalising decohesion-based arguments and capturing the transition to brittle fracture observed in hydrogen-rich environments. Crack growth resistance curves are computed in a wide variety of scenarios, showing that the model can appropriately capture the sensitivity to material strength, loading rate and hydrogen concentration. Model predictions are also quantitatively compared with laboratory experiments, showing a good agreement. Moreover, the model is used to enable *Virtual Testing* by delivering large-scale multi-physics predictions in technologically-relevant applications – see Fig 1.

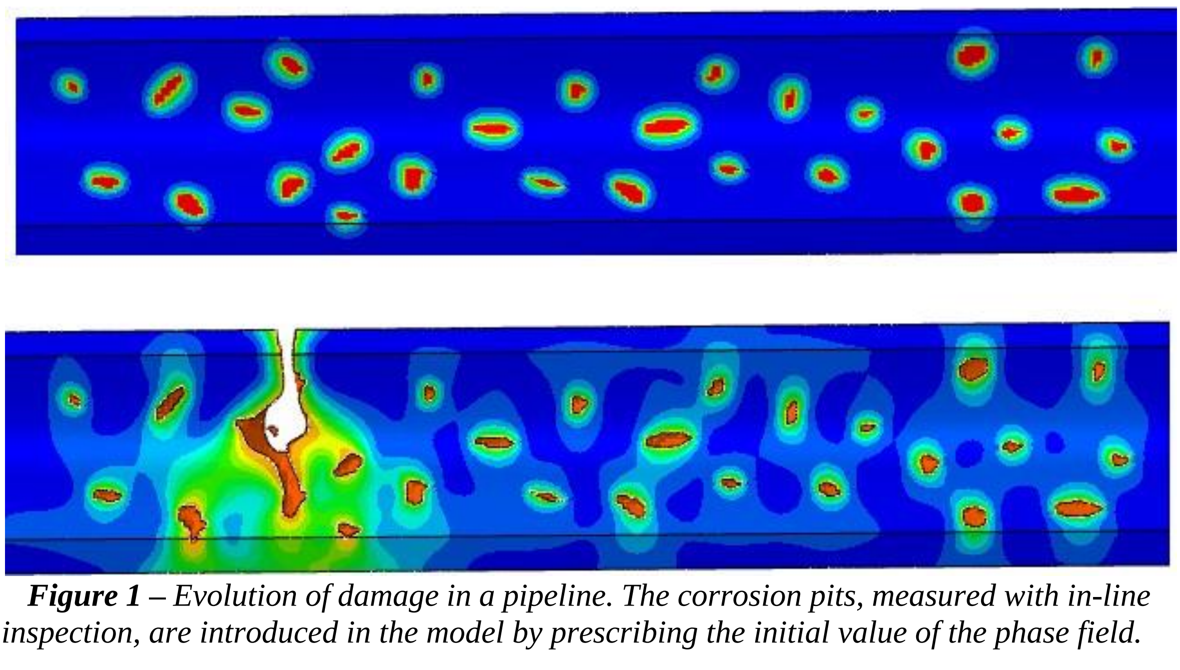

***Figure 1** – Evolution of damage in a pipeline. The corrosion pits, measured with in-line inspection, are introduced in the model by prescribing the initial value of the phase field.*

# #015 The role of plastic strain gradients on metallic fracture

Emilio Martínez-Pañeda[1], Norman A. Fleck[2]

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*[2]Department of Engineering, University of Cambridge*

*Fracture* *Strain gradient plasticity* *Finite element analysis*

**Abstract** Macroscopic fracturing in metallic materials depends sensitively on properties that pertain to the micro and atomic scales. Durability predictions of engineering components require enriching continuum theories to properly characterize behaviour at the small scales involved in crack tip deformation. The deficiencies intrinsic to conventional plasticity motivate the development of mechanistically-based models. Namely, unrealistically low stresses are predicted ahead of the crack tip, with toughness being unbounded for cohesive strengths of approximately 3 times the yield stress in a perfectly plastic material ($\hat{}/\sigma_Y \rightarrow 4$ in a mild hardened solid). Tensile stresses on the order of 3-5 times the initial yield stress fail to explain decohesion at the atomic scale. Brittle fracture in the presence of significant plastic flow has been observed in numerous material systems; well-known examples include ferritic steels at low temperatures, hydrogen-embrittled metals or metal-ceramic interfaces. Since atomic separation requires traction levels on the order of the theoretical lattice strength (10 $\sigma_Y$ or larger), classic continuum theories would appear to rule out a fracture mechanism based on atomic decohesion whenever plasticity develops in the vicinity of the crack.

We investigate the implications of using strain gradient plasticity to provide a richer description of fracture in metallic materials. Strain gradient plasticity can phenomenologically capture the increased dislocation density due to gradients in plastic strain near the crack tip and the associated local strengthening. We aim at: (i) understanding the nature of the associated crack tip stress elevation, and (ii) assessing the influence of strain gradients in crack growth resistance. Thus, we first examine analytically the asymptotic nature of crack tip fields. Our findings, corroborated by finite element analysis, reveal the existence of an inner *elastic* stress state, reminiscent of a dislocation free zone. Crack growth is then predicted for short and long cracks using a cohesive zone model, and a rational basis is provided for brittle fracture in the presence of plasticity

# #016 Correlation found between the tensile strength and the length scale parameter in phase-field fracture based on the coupled criterion

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[2] *MATEIS, Univ Lyon, INSA-Lyon, CNRS UMR5510, 69621 Villeurbanne, Lyon, France*

[3] *SIMaP, Grenoble INP, CNRS UMR5266, Univ. Grenoble Alpes, 38000 Grenoble, France*

*Phase-field* *Length scale* *Tensile strength*

**Abstract** In the last decade, phase-field models [1] have gained significant popularity in fracture simulation. These models regularize the sharp crack by diffusing the damage into the material. Using a continuous gradient, a damage variable establishes the connection between intact and broken solids. The approaches introduce a length scale parameter to achieve their goals, which controls the amount of smearing. Since their first use, it has been a continuous debate whether the length scale bears any physical meaning.

This work [2] presents a macroscopic approach, using the coupled energy and stress-based criterion [3], to investigate the relationship between tensile strength and the internal length scale. We established a unique correlation by comparing the maximum reaction force, the initiation angle, and the crack's arrest length. Furthermore, this correlation can be deduced from the homogeneous solution of the fracture problem. Therefore, we argue that rather than a single curve, the fracture strength can be obtained using a failure surface:

$$\sigma^{c} \doteq \sigma^{\max} = \eta\left(\nu, \frac{\sigma_1}{\sigma_2}\right) \cdot \sqrt{\frac{E g_c}{l_c}}$$

where $\eta$ is a function depending on Poisson's coefficient ( $\nu$ ) and the ratio of the principal stresses. While $E$ is Young's modulus, $g_c$ is the fracture surface energy, and $l_c$ is the length scale parameter.

*[1] C. Miehe, F. Welschinger, M. Hofacker, Thermodynamically consistent phase-field models of fracture: Variational principles and multi-field FE implementations, International Journal for Numerical Methods in Engineering 83(10), 1273–1311, 2010.*

*[2] G. Molnár, A. Doitrand, R. Estevez, A. Gravouil, Toughness or strength? Regularization in phase-field fracture explained by the coupled criterion, Theoretical and Applied Fracture Mechanics, 109, 102736, 2020.*

*[3] D. Leguillon, Strength or toughness? A criterion for crack onset at a notch, European Journal of Mechanics A/Solids 21, 61–72, 2002.*

# #017 Stress justification of aeronautical structure by modeling of four-point bending tests on bonded woven oxide/oxide ceramic matrix composite joints

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*Woven ceramic matrix composites* | *Interface and composite damage mechanisms* | *Modeling prediction and experimental tests*

**Abstract** Safran Ceramics develops ceramic matrix composite (CMC) materials and structures. One of them is an oxide/oxide CMC exhaust cone for aeronautical applications. In order to avoid buckling under pressure and oscillations under vibrations, stiffeners are used. In this study, ceramic bond allows the bonding between oxide/oxide CMC stiffeners and the CMC cone. The industrial design of this part is partially justified by a four-point bending test on bonded woven oxide/oxide CMC joints.

During the experimental tests, fracture of the CMC material occurred. However, an interface damage was also expected. Then, in order to understand the behavior of this assembly, we realized several simulations of the four-point bending test using ONERA Damage Model (ODM) for CMC substrates and bilinear Cohesive Zone Model (CZM) for the interface. ODM describes matrix damages and yarn fractures of the woven oxide/oxide CMC material whereas CZM allows describing both the onset and the propagation of delamination at the interface between the CMC substrate and the ceramic bond. The simulations describe the damage mechanisms observed during experimental tests (Figure 1). Moreover, the correlation between experimental and numerical results allows an identification of interface properties.

This work participates to the industrial justification of the oxide/oxide CMC exhaust cone (Figure 1).

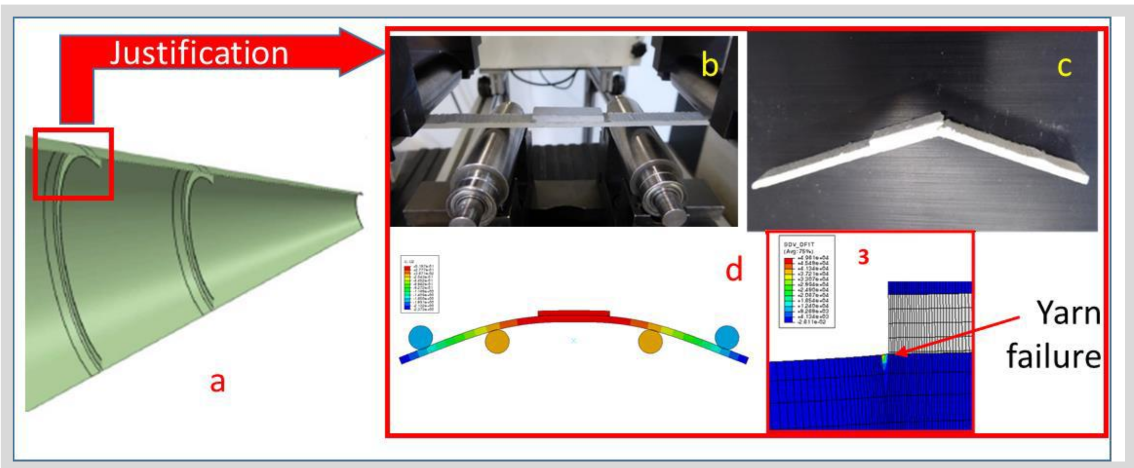


***Figure 1*** *– Illustration of (a) the stiffened CMC exhaust cone, (b) the four-point bending test on bonded CMC joints, (c) the fracture of the specimen and (d) the associated simulation with damage models*

# #018 Intrinsic fracture properties of an epoxy adhesive modified with Core Shell Rubber (CSR) nano-particles

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[1]*University College Dublin, School of Mechanical and Materials Eng., Dublin, Ireland, alojz.ivankovic@ucd.ie*

*Fracture process zone* *CSR nano-particles* *Intrinsic fracture properties*

**Abstract** This combined experimental-numerical study presents recent achievements in understanding the fracture behaviour of CSR modified epoxy adhesive and adhesive joints. The size of the fracture process zone (FPZ) is measured in single edge notched three-point bend (SENB) and tapered double cantilever beam (TDCB) specimens using optical (Figure 1.a) and transmission electron microscopy (Figure 1.b) [1]. Hence, it was possible to calculate the intrinsic fracture energy, $G_0$ associated with FPZ. It is found that the FPZ thickness and failure strain measured from the SENB tests with two different spans and from TDCB tests with different bond gap thicknesses are essentially constant [2]. This indicates that FPZ and $G_0$ are intrinsic, geometry independent fracture properties, which can be used to link the results from tests conducted on different geometries. To achieve this, cohesive zone parameters were extracted from the measured FPZ and $G_0$ and the fracture behaviour of single edge notched three-point bending test (SENB) and tapered double cantilever beam (TDCB) test were successfully predicted. The variation of the total fracture energy in different fracture tests is attributed to the varying far-field plastic deformation energy (dissipated outside of FPZ) with different stress states while the intrinsic fracture energy is considered a material property.

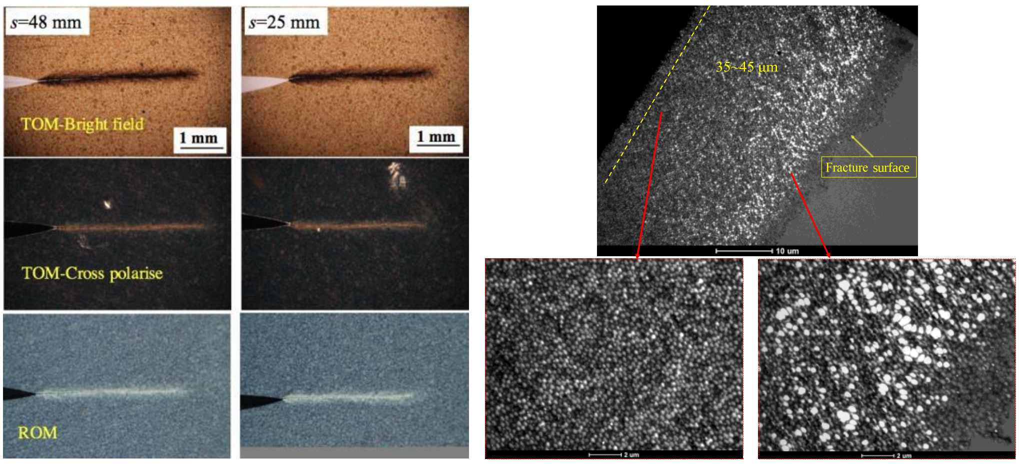


***Figure 1 -*** Microscopy images of fractured 3PB specimens; (a) Optical microscopy images of PDZ, (b) TEM images of FPZ.

[1] D. Quan, N. Murphy, A. Ivankovic, Fracture behaviour of a nano-modified structural epoxy adhesive: bond gap effects and fracture damage zone, Int. J. of Adhesion and Adhesives **77** (2017), 138-150, DOI 10.1016/j.ijadhadh.2017.05.001.

[2] D. Quan, N. Murphy, P. Cardiff, A. Ivankovic, The intrinsic fracture property of a rubber-modified epoxy adhesive: geometrical transferability, Engineering Fracture Mechanics **203** (2018), 240-249, https://doi.org/10.1016/j.engfracmech.2018.04.035

# #019 Hydrogen embrittlement of a 2205 duplex stainless steel under in-situ hydrogen charging

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*Hydrogen embrittlement* *Duplex stainless steel* *In situ hydrogen charging*

**Abstract:** The expected extensive use of hydrogen derived from renewable energy sources is nowadays limited by lack of effective and economical storage and transport solutions. Steels able to be used in contact with high pressure hydrogen gas are needed for the manufacture of safe and reliable storage vessels. On this context, this paper studies the mechanical behaviour of a 2205 duplex stainless steel (54% ferrite and 46% austenite) by means of tensile tests, using plain and notched specimens, submitted to simultaneous electrochemical hydrogen charging. The effect of different charging conditions (applied current density from an acid aqueous medium) representative of different hydrogen pressures was evaluated, and also the influence of the applied displacement rate. Hydrogen embrittlement indexes were determined comparing tensile propertied measured in tests performed in air with hydrogen charged ones. Finally, the failed surfaces of all the tested specimens were thoroughly examined under an scanning electron microscope and the prevalent failure micromechanisms were disclosed.

Embrittlement indexes increase when the applied current density increases (higher hydrogen entrance) and the applied displacement rate decreases (longer time for hydrogen movement in the specimen). Failure mechanisms change from ductile (microvoids coalescence) in tests performed in air to brittle (quasi-cleavage) under hydrogen and, in this latter case, clear morphological differences were observed between the two constitutive steel phases, ferrite and austenite.

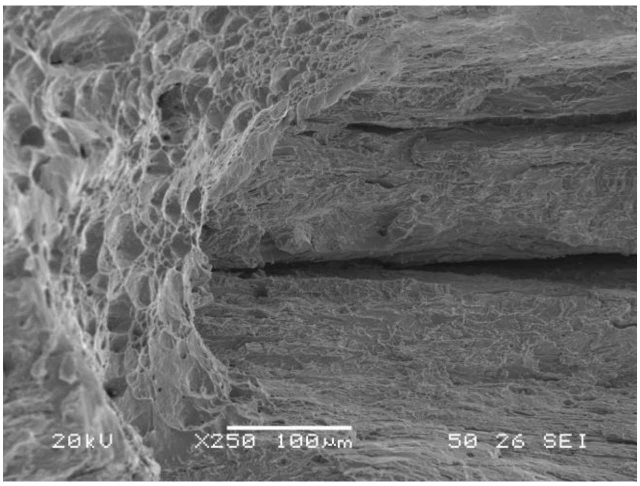


***Figure 1*** *– Failed surface of a plain tensile test with in situ hydrogen charging. Ductile versus brittle micromechanisms*

# #021 Macro to Micro in Fracture - A Modification to Griffith Barrier

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*Fracture Energy* *Bond Breaking Mechanisms* *Dynamic cleavage*

**Abstract** We joined continuum mechanics of fracture and atomistic aspects of fracture. Our approach was to correlate the macro fracture properties and crack front shape to the atomistic bond-breaking events along the crack front. The key variables in our mission is not only the ERR at initiation, $G_0(a_0)$, but also its gradient, $\Theta \equiv dG_0(a_0)/da$. Generally speaking, long cracks are characterized by low $\Theta$, short cracks by high $\Theta$.

Importantly, while the initiation energy is always $\Gamma_0=2\gamma_S$ or $2\gamma_{SCC}$ (free surface energy and surface energy due to stress corrosion cracking, respectively), crack dynamics shows that the energy-speed relationship is govern by a higher cleavage energy at initiation, $\Gamma_0=\Gamma_0(\Theta)$ [1]. From the macroscopic cleavage energy to the microscopic bond-breaking mechanisms,

$\Theta$ governs crack mechanics and physics. Thus, all the important variables are $\Theta$ dependent: the cleavage energy, $\Gamma_0=\Gamma_0(\Theta)$ and also the crack front curvature. Furthermore, crack dynamics is also controlled by $\Theta$, by $\Gamma_0(\Theta)=G_0(1-V/C_R)$ (**Fig. 1**) is replacing $2\gamma_S=G_0(1-V/C_R)$ [2].

The suggested bond breaking mechanisms are based on in-plane step-like kinks, kink advance (migration) and formation (nucleation). While the energy density dissipated by kink advance mechanisms is somewhat higher than $\gamma_S$, kink formation energy can be more than double.

An important result of this investigation is that the strength of a material may increase significantly compares to Griffith [3] prediction. For high $\Theta$, this increase may be tens per-cent higher.

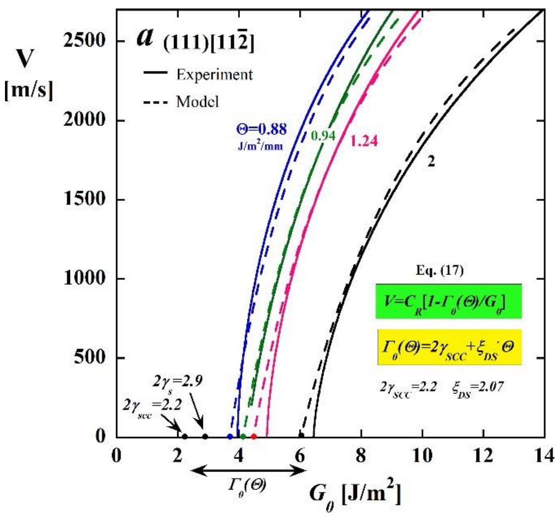


***Figure 1** – The energy speed relationship of a crack propagating on (111)[11 $\bar{2}$ ] low energy cleavage system of silicon crystal. The experimental results (full line) where predicted by a single equation with our new variables, $\Theta$ and $\xi_{DS}$.*

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# #022 PBF-LB/M/316L vs. hot-rolled 316L - comparison of cyclic plastic material behavior

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*Powder-Bed Fusion of 316L using a Laser* *Cyclic Plastic material behavior* *Hot-rolled and annealed 316L*

**Abstract** Powder-Bed Fusion of 316L (1.4404) using a laser (PBF-LB/M) is known for its very high cooling rate of up to 40 K/µs. This high cooling rate results in a fine needle-like microstructure. Compared to that, hot-rolled, annealed 316L consists of coarser grain structures. The quasi-static tensile properties, therefore, differ significantly. PBF-LB/M- manufactured 316L has a yield strength of up to 600 MPa whereas the yield strength of hot- rolled and annealed 316L is at 200 – 220 MPa. This may result in a completely different cyclic plastic material behavior due to the grain boundary strengthening during the PBF-LB/M manufacturing process.

This study compares the cyclic-plastic material behavior of PBF-LB/M-manufactured 316L with hot-rolled, annealed 316L. Strain-controlled fatigue testing of both, PBF-LB/M and hot rolled annealed 316L, was conducted. The strain amplitudes vary from 0.5 % to 3.0 % in steps of 0.5 %. A microstructural investigation of selected specimens was conducted before and after the testing. It consists of surface etching, electron backscatter diffraction (EBSD) as well as energy-dispersive x-ray spectroscopy (EDX). The orientation, phase transformation, twinning formation as well as the general microstructure was compared.

It was found, that the PBF-LB/M-manufactured specimens mainly showed a softening behavior. Only from 2.5 % applied strain amplitude, a secondary hardening phenomenon was observed. The hot-rolled and annealed specimens on the other hand mainly showed a continuous hardening behavior. The maximum engineering stress vs. the number of cycles for both PBF-LB/M and hot-rolled specimens is shown in Fig. 1.

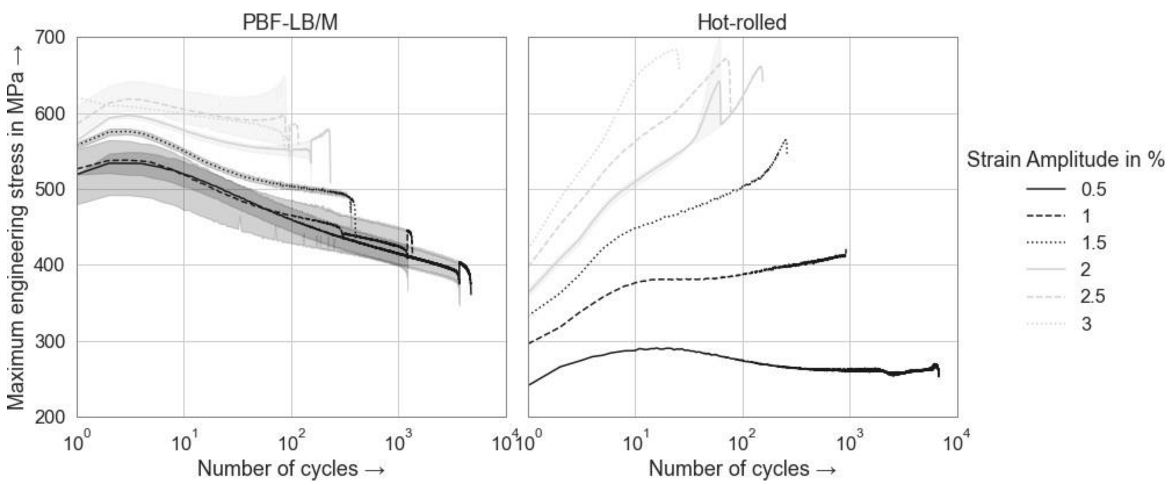


***Figure 1*** *– Maximum engineering stress vs. number of cycles for both the PBF-LB/M-process and the hot-rolling process*

# #023 Investigation of hydrogen embrittlement in a high manganese twinning induced plasticity steel - a multiscale approach

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**Abstract** Hydrogen embrittlement deteriorates the mechanical properties of high-strength metallic materials [1,2]. Twinning induced plasticity (TWIP) steels are promising structural materials but are highly prone to hydrogen embrittlement [3]. Our current work is aimed at examining the hydrogen embrittlement susceptibility of a Fe 28Mn 0.3C (wt.%) TWIP steel alloy. We have studied the effect of hydrogen charging on microstructure evolution during tensile deformation and defect behavior, i.e., the dislocation density and arrangement, the stacking faults and ε-martensite by using electron channeling contrast imaging (ECCI). We also performed the site-specific atom probe tomography (APT) studies after charging the samples with hydrogen/deuterium in order to investigate the role of grain boundaries as hydrogen trapping sites which will be discussed during the talk.

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# #024 Inclusion of Plastic Strain Effects on Cleavage Fracture Toughness Predictions from Subsize Precracked Charpy Specimens

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*Weibull stress* *Cleavage fracture* *Plastic strain*

**Abstract** Accurate assessments of structural integrity and remaining life of reactor pressure vessels (RPVs) play a key role to ensure the continued and safe operation of existing nuclear power plants while, at the same time, to extend its operational life. A case of particular interest and major concern involves strong degradation of the vessel material by neutron irradiation embrittlement in the beltline region which may limit the service life of nuclear RPVs and lead to catastrophic fast fracture of the vessel material. Because of limitations in material availability and, further, to facilitate fracture testing of irradiated RPV materials, current reactor vessel surveillance programs extensively employ fracture testing of precracked Charpy V-notch (PCVN) specimens in three-point bending to assess changes in fracture toughness properties over its operational and service life. However, the specimen measuring capacity prior to constraint loss for small specimen geometries may be insufficient to properly describe cleavage fracture toughness under well contained yielding conditions at the crack tip.

To address these issues, much current research focuses on the development of micromechanics models incorporating key microfeatures of the cleavage fracture process that approach material failure by a probabilistic interpretation of the stress-controlled, transgranular cleavage mechanism. In particular, the early work of Beremin coined the concept of *local approaches to fracture* (LAFs) by employing weakest link statistics and an *ad-hoc* distribution describing the microcrack size to introduce the Weibull stress ( $_w$) as a probabilistic crack driving force. Here, the underlying probabilistic framework assumes that fractured brittle particles (which are associated with Griffith-like microcracks) occur immediately at yielding of the crack-tip region so that the statistical distribution describing the microcrack size remains invariant with changes in loading. However, there are clear evidences of the potential increase of cleavage microcracking in ferritic steels due to increased plastic strain. Because weakest link based models assume that cleavage failure is controlled by a local Griffith instability of the largest of most favorably oriented microcrack, a number of studies provide a compelling reason to consider the potential effects of plastic strain on the density of Griffith-like microcracks which implicitly enter the fundamental form of the Weibull stress.

A probabilistic, micromechanics-based methodology incorporating plastic strain effects on cleavage fracture and its dependence on the microcrack distribution is the focus of this paper. The present work extends current developments of a local approach to fracture (LAF) derived from a plastic-strain based modification of the Weibull stress, phrased in terms of a new parameter denoted as $\tilde{\sigma}_w$, to assess changes in cleavage fracture toughness for a reactor pressure vessel (RPV) steel due to constraint loss effects in subsize precracked Charpy (PCVN) specimens. Cleavage fracture toughness data for an A533 Gr B reactor pressure vessel steel are employed to demonstrate the capability of the modified LAF in predicting specimen geometry effects on experimentally measured values of the $J$-integral, $J_c$. By combining detailed non-linear, 3-D finite element analyses for side-grooved C(T) and subsize PCVN specimens with varying geometries, the new $\tilde{\sigma}_w$ -based methodology is shown to effectively remove the geometry dependence on $J_c$-values thereby generating more accurate predictions of cleavage fracture behavior in larger crack configurations from small specimens.

# #026 Microstructural fracture mechanisms and wear damage of the $Si_3N_4$-Ag-GNP composites prepared by SPS

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*ceramic matrix composites* *SPS* *wear*

**Abstract** Silver particles and graphene nanoplatelets (Ag-GNPs) have been employed as reinforcements to prepare the self-lubricating silicon nitride ($Si_3N_4$) matrix composites via simple ball milling (Turbula mixer) and spark plasma sintering technique. The prepared composites were characterized by scanning electron microscope with energy dispersive spectroscopy, Vickers hardness tester and reciprocating ball tribometer. Microstructural characteristics, namely the various present phase composition, grain sizes, and distributions, were assessed. Microstructural analysis confirmed that silver in combination with GNPs introduced into the ceramic matrix were helpful to prevent porosity or crack defects thanks to improved sinterability. The additives helped to eliminate the structural defects preserving the original hardness and toughness of the ceramic matrix. As a result of good sinterability, there was no interface region and no defects such as pores and micro-cracks in the material. Fracture surface morphology of sintered composites was observed and the results indicated the potential reinforcement mechanism by the ductile silver phase. The mechanical properties testing revealed that Si3N4 composites with Ag and GNPs incorporation exhibited lower hardness and slightly lower toughness compared with monolithic silicon nitride. Friction and wear behaviour was tested by in unlubricated conditions at ambient temperature and humidity, using a reciprocal ball-on-disk tribometer. The wear damage was analysed in terms of microstructural fracture phenomena. The series of tests were performed at the following conditions: a normal load of 1, 2.5, 5 N, sliding speed of 0.1 m/s and total sliding distance of 500 m with alumina ball as the counter body. The development of the coefficient of friction during the test was measurement and recorded. The material losses (volume of the wear tracks) due to wear were measured by a high precision confocal microscope, and then specific wear rates (W) were calculated in terms of the volume loss per distance and applied load. The coefficient of friction and wear in composites exhibited the lower values in 1N friction force testing range. There was a significant improvement from 1.05 to 13 times in the wear resistance. The uniformly distributed GNPs together with the present silver formed the friction film, which provided an effective lubricating effect at the sample surface resulting in improved wear resistance at 1N. The metallographic analysis confirmed that for the monolithic sample without the silver and GNPs additives, the dominant wear mechanism was delamination. The wear mechanism of Si3N4-Ag-GNPs composite samples was abrasion accompanied with creation of an oxidation film. The silver additive acts as friction film reservoir due to its good distribution in ceramic matrix. Exfoliation of the GNPs by shear stresses and their incorporation into the silver lubricating film is probable and potentially leads to strengthening of this film and contribute to high wear resistance. This composite material design with the presented preparation method is usable for low friction loads (up to 1N), where it resulted in the near zero wear

# #027 Use of elastomers as pressure media for fatigue testing of cold forging tools

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*Fatigue* *Elastomer* *Metal Forming*

**Abstract** Cold forging is gaining in importance for the mass production of high-quality technical parts due to its better material efficiency compared to machining and lower energy consumption compared to hot forging. Therefore, there is a demand for increasingly complex cold forged parts. This leads to a challenging stress state in forging tools, since they have to withstand high contact pressures in intricate geometries. The resulting alternating cyclic load makes fatigue the dominating failure mechanism in forging dies for complex part geometries. Since fatigue failure not only causes costs for the production of new tools, but also machine downtime and production stops, an accurate prediction of tool life is necessary in order to better coordinate tool changes.

Current attempts to calculate the service life of cold forging dies face the problem of limited availability of material data concerning fatigue. Additionally, the tests used to generate this data strongly simplify the tool's multiaxial stress state, which is generated by cyclically swelling inner pressures. Additionally, reinforcements are often used to prestress forging dies, so that the tool load alternates between a multiaxial compressive and a multiaxial tensile/compressive stress state. To accurately model this and enable the experimental analysis of different prestressing systems, a new fatigue test is necessary.

For this purpose, a test that incorporates cyclically swelling inner pressures on hollow specimen is analysed within this research. The test setup is based on using an elastomer material as a pressure medium. That way, cyclic testing with high hydrostatic pressures of at least 2000 MPa can be achieved, since the elastomer recovers its original shape after each load cycle. One challenge in the concept is wear on the elastomer specimen. In each cycle, the edge of the specimen is pushed into the gap between the hollow fatigue specimen and the punch used to apply the load causing a continuous decrease in elastomer volume.

To ensure a stable test setup, this wear needs to be minimized. Therefore, the effect of the gap size between punch and fatigue specimen as well as the test load and frequency are analysed experimentally with regard to the occurring elastomer wear. The die load is measured during the test using strain gauges, so that the effect of elastomer wear on the tool's stress state can be taken into account. In addition to the proof of concept of the test setup, this allows the recommendation of test parameters to be used in future fatigue testing using elastomers as pressure media.

# #030 Experimental investigation of ductile tearing within an aged austenitic stainless steel weld – Four point bending test on pipe

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***Keywords**: Ductile tearing Large scale tests Austenitic steel weld*

## Abstract

**Abstract** Degradation, ageing and in-service defects in piping are commonly associated with welds since the inhomogeneous metallurgy and residual stresses facilitate degradation and defect growth. Therefore, the accuracy of structural integrity assessment procedures in weld residual stress fields is very important. In this view, design and execution of innovative, simulation oriented, large-scale experiments on five different mock-ups have been planned within EU funded Atlas+ project. Among them, a four-point bending test on a narrow gap junction for experimental investigation of the ductile tearing of aged austenitic stainless welds is performed at LISN/CEA in collaboration with Framatome.

Two pipes were provided for this study. A junction TOCE (TIG Obital, Narrow Gap junction) was manufactured on pipes with an external diameter of 400 mm and with a thickness of 35 mm, with a chamfer angle of 5 °. The first specimen with 1.2 m length is devoted to the 4 points bending test, while the second one is used for fine characterization of the weld via a specific experimental program. Approximately ¼ is used for characterizing the initial state. The remaining ¾ of the crown has undergone aging in a big capacity oven at the same time as the first specimen, with a thermal treatment of 400°C during 3000 hours.

An experimental campaign on laboratory specimens was run to have a fine characterization of the weld. Tensile specimens were taken across the weld junction, so that the evolution of tensile properties within the different zones of the weld could be investigated. CT specimens were used to investigate the ductile crack propagation within the weld. Then, a large-scale 4-points bending test was performed on the aged pipe, to challenge the issues of transferability of laboratory data to the component scale. A crossing defect has been machined in a quarter of the tube perimeter passing by the middle of the weld. The specimen notch was designed using numerical calculations, so that the most suitable geometry could be found. Two extension tubular arms have been welded to the specimen to increase the lever arm and so decreasing the necessary levels of load to make propagate the defect. A stereo-digital image correlation technique was used for full-field deformation measurements and follow the ductile crack propagation during the pipe-bending test. The results of the large-scale test have been discussed and compared to those obtained on laboratory specimens.

# #031 Application of Uncoupled Damage Models to Predict Ductile Fracture in Metallic Sheet Blanking

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*Sheet Blanking Simulation* *Crack propagation* *Remeshing*

**Abstract** The increasing demand of high-quality products has promoted the development of several models to predict damage accumulation and fracture during their manufacturing process. Due to their simplicity and overall accuracy, the uncoupled damage models (fracture criteria) have been the preferred choice to simulate ductile failure, especially in engineering applications. Nevertheless, the predictive capabilities of these type of models were classically limited by the complexity of the loading paths encountered in several forming processes, making them not suitable for all cases. This drawback is attributed to the use of stress triaxiality as the only variable introducing the influence of the stress state into their formulations, contrasting with several recent studies where it has been demonstrated that the Lode angle also plays a crucial role in damage accumulation [1]. Consequently, some advanced models have been recently formulated in the space of equivalent plastic strain, stress triaxiality and Lode angle, with successful results in a wide range of loading conditions.

In this work, a comparative study of different uncoupled damage models for the numerical prediction of ductile fracture in the blanking process is performed. The selected phenomenological models were recently implemented in a fully implicit homemade Finite Element code [2], which considers large strains, frictional contact, remeshing and crack propagation (i.e. element deletion method). All the models considered here account for damage sensitivity to both the stress triaxiality and the Lode angle. The material characterization is performed thanks to different mechanical tests under different stress states and a full inverse analysis, taking into account the entire loading paths to fracture. Finally, the numerical predictions obtained for different process parameters are compared with experimental results, where especial attention is given to the final shape of the sheared edge.

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# #032 Experimental strength and fracture analysis of additively manufactured continuous carbon fibre reinforced lugs with load-tailored fibre placement

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*Composite* *Additive Manufacturing* *Curvilinear Fibre Steering*

**Abstract** A curvilinear fibre layup for additively manufactured (AM) necked double shear lugs is developed. The fibre trajectories follow the maximum and minimum principal stress directions due to axial tension loading derived from two-dimensional finite element analysis (FEA), see Figure 1. The composite lugs were manufactured with the help of fibre steering slicing (NanoGcode) software and Composer A4. The motivating factor is to understand and elaborate the relation between layer height and fibre volume fraction and its influence on the mechanical properties of AM composite lugs. The result of first mechanical tests on the AM composite lugs is an increase in load-bearing ability by 60% with an increase in fibre volume of 10 % with decreasing layer height.

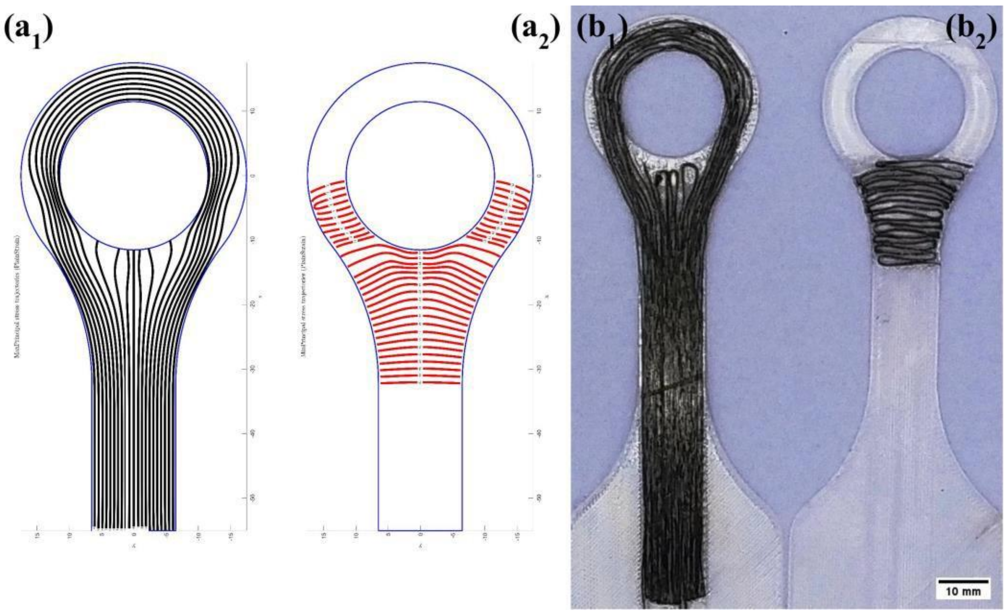


***Figure 1*** *Calculated fibre trajectories and photography of AM composite lugs using research oriented software, ($a_1$ and $a_2$) calculated Max. and Min. principal stress directions for fibre placement, respectively and ($b_1$ and $b_2$) Printed single layer of lug specimen based on calculated principal stress directions.*

# #034 Including effect of bending stress parallel to the crack plane on a developed local limit load model

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*J-integral* *Surface crack* *Bending stress parallel to crack*

**Abstract** In order to estimate required limit load for complex structures in structural integrity assessments, a local limit load model was developed [1] by the author for plate/shell type components containing surface defects. The developed model was a plate of finite width containing a rectangular surface crack. The model should be loaded by the primary stresses of the component at the crack location obtained from elastic uncracked-body stress analysis including the membrane and through-thickness bending stresses normal to the crack plane and the membrane stresses parallel to the crack plane. This model has been validated using the finite element (FE) elastic-plastic J results for defective plates and cylinders under various load types and load combinations. However, recent examinations on more complex structures like defective elbows and pipe branches have shown that there could also be strong bending stress parallel to the crack plane at the crack location and ignoring this bending stress might overestimate limit load values and lead to non-conservative J predictions when such limit load is used in the reference stress J scheme [2]. In this paper, the effect of bending stress parallel to the crack plane on the limit load and elastic-plastic J is investigated and the local limit load model developed in [1] is modified to include such effect.

A plate containing a semi-elliptical surface crack is selected as a typical surface crack case to investigate the effect of the bending stress parallel to the crack plane on the elastic-plastic J and limit load. Elastic and elastic-plastic FE analyses are performed to obtain J values for the surface-cracked plate under combined membrane and through-thickness stresses normal to the crack plane and membrane stress parallel to the crack plane with/without bending stress parallel to the crack plane. The results show that the bending stress parallel to the crack plane, as expected, does not affect the stress intensity factor (SIF) but it does affect elastic-plastic J and the degree of effect depends on the intensity and direction of the parallel bending stress. Then a limit load estimation considering the bending stress parallel to the crack plane is developed and validated by the FE J results via the use of the reference stress J scheme. The results showed that when the limit load evaluated using the newly developed limit load solution is used in the reference stress J scheme, the FE J results can be well predicted. Finally, the local limit load model is modified using the newly developed limit load solution.

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# #035 High-temperature fatigue crack growth from intrinsic material defects in a WC-Co hard metal at 700°C in vacuum

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*High-temperature fatigue* *Defect formation* *Defect coalescence*

**Abstract** WC-Co hard metal are composite materials of choice when it comes to coping with elevated levels of mechanical and thermal loads, such as e.g. present at the cutting edges of cyclically loaded metalworking tools. Currently, the fatigue behavior of hard metals at elevated temperatures is not well-understood, especially in the case of crack propagation in vacuum that is relevant when intrinsic subsurface defects form the origins of fracture. The investigated material was a WC-Co hard metal with a Co binder content of 12 wt. % and an average WC grain size of 500 nm to 800 nm. Eddy current heating was applied to assert a constant temperature of 700°C in the hourglass-shaped specimens tested in a servo-hydraulic machine equipped with a vacuum chamber to avoid oxidation. Strength investigations under monotonously increasing load and cyclic tests until fracture were performed under uniaxial loading. Cyclic tests were performed under a stress ratio $R = \sigma_{min} / \sigma_{max} = -1$ at several constant stress levels above the fatigue limit. Scanning electron microscopy was used to determine the size and density of defects in cross sections of the material volume prior to fracture and on the obtained fracture surfaces. In the case of monotonously increasing load, no material-inherent defects were observed at the origins of fracture such as was the case for cyclic loading. The commonly known inverse proportionality between the size of material-inherent defects such as non-metallic inclusions and pores at the origin of fracture and the observed number of load cycles to specimen failure was violated for the case of cyclic loading. The effectively loaded volume of both load cases was in the same order of magnitude as determined by finite element-based analysis. The results imply that the coalescence of voids and cavities that were observed to form and accumulate in the material during loading are the dominant fracture mechanism for monotonously increasing loading and are very important for $R = -1$ cyclic loading. For a given WC-Co hard metal microstructure, a certain combination of stress amplitude, load cycle number and test temperature exists, at which a transition occurs from failure control by i) the size of material-inherent defects that exist prior to loading, to ii) the kinetics of plasticity- (and creep-) induced initiation of voids and the coalescence of these voids that form in-situ during loading.

# #036 History of ductile-to-brittle transition problem of ferritic steels

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*ductile-to brittle transition* *ferritic steel* *fracture mechanics*

**Abstract** This paper presents a review of different approaches through history concerning DTB transition phenomenon of ferritic steels and their characterization using FM concept, from the earliest studies based on LEFM to the application of the EPFM concept. The large scattering of the experimental fracture toughness data, characteristic of all ferritic steels in the transition temperature region, has imposed the need of including statistical methods for data processing. Such approach that began in the 1970s can be encountered even nowadays as the base of fracture toughness data interpretation in DTB problems. An overview of studies with statistical interpretation of experimental data in the transition temperature region is also given, as well as constraint effects due to fracture of tested specimens. Aforementioned provides a foundation for novel approaches in DTB transition problems, which include size effects and scaling of geometrically similar specimens.

# #037 Master Curve Evaluation at Elevated Loading Rates

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*Master Curve* *Elevated Loading Rate* *Ductile to Brittle Transition*

**Abstract** ASTM E1921 Annex 1 describes the determination of the reference temperature $T_{0,X}$ evaluating tests at elevated loading rates in the ductile to brittle transition region of fracture toughness. X denotes the logarithm of the loading rate rounded to the nearest integer. 1T C(T)-tests were performed according to ASTM E1820 A14 at loading rates from $10^2$ MPa√m/s to $10^4$ MPa√m/s with specimens machined from two steels with different strength: 22NiMoCr3-7 from a reactor pressure vessel (Biblis C) and low temperature high strength quenched and tempered steel S690QL1. Previous investigations testing specimens made from the steel 22NiMoCr3-7 at loading rates above $10^5$ MPa√m/s showed deviations from the standard shape of the Master Curve, causing differences of up to 30 °C between reference temperatures $T_{0,5}$ evaluated for lower and for higher test temperatures. This project analyzes the behavior at intermediate loading rates. An example is given in figure 1, where the evaluation of tests executed at $10^3$ MPa√m/s shows also lower results (-31 °C) for the reference temperature $T_{0,3}$ obtained by single temperature evaluation at a test temperatures above $T_{0,3,}$ than the single temperature evaluation at test temperatures near $T_{0,3}$ (-21 °C) and lower (-21 °C). Impact of crack arrest phenomena and temperature creation during the fracture mechanics tests on the distribution of the dynamic fracture toughness values $K_{Jc,d}$ and suggestions for the modification of the Master Curve evaluation for elevated loading rates are discussed for the loading rates $10^2$ MPa√m/s to $10^4$ MPa√m/s for both materials. Using the large database of results of fracture mechanics tests, executed in this project ("Verification of the Master Curve Concept at Elevated Loading Rates" funded by the German Federal Ministry for Economic Affairs and Energy, 1501563), it is possible for the first time to analyze the distribution of dynamic fracture toughness values $K_{Jc,d}$ with sufficient statistical significance.

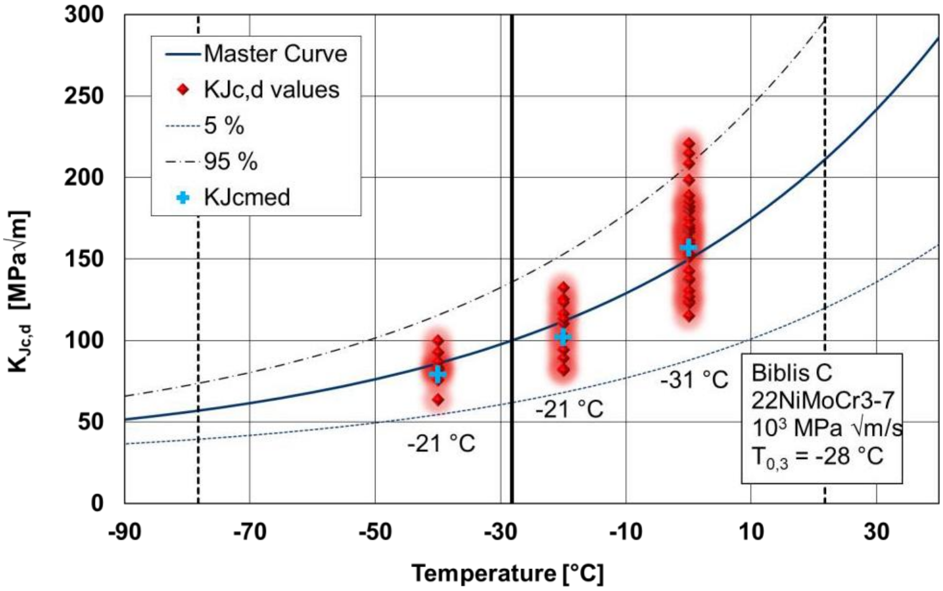


***Figure 1*** *- Comparison between multi-temperature Master Curve evaluation and single-temperature Master Curve evaluation at different test temperatures for $10^3$ MPa√m/s, 22NiMoCr3-7 (Biblis C)*

# #038 Experimental and analytical investigation of Low Cycle Fatigue Damage at notches in a polycrystalline Nickel base superalloy

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*Notches* *Low Cycle Fatigue* *Superalloy*

**Abstract** Turbine blades often contain cylindric holes used to generate an air film that protects the blade alloy from the hot gases. These cooling holes of diameter around one mm are drilled by laser through the thickness of the blades. Unfortunately, the resulting stress concentration and the drilling-induced damage are known to favor crack initiation from the holes. It is thus necessary to assess the impact of these cooling holes on the structural integrity of the blades. Since cracks initiate very readily, the fatigue life of the components is mainly controlled by the propagation of the cracks in the stress gradient induced by the holes.

For this purpose, displacement controlled high-temperature LCF (Low-Cycle-Fatigue) tests were performed with center hole specimens of a coarse-grained Nickel base Superalloy. The tests were stopped after a defined load drop. In addition, crack propagation tests with Double Edge Notch specimens were performed. Moreover, specimens with different hole surface finishes were investigated, which showed a detrimental effect of the hole surface roughness. In parallel, an evaluation of the LCF tests based on a fracture mechanics-based model (Madia et al., *Eng. Fract. Mech.*, 2018) has been applied. Thereby, the specimen life is controlled by the crack propagation time until failure. Crack growth is controlled by a modified NASGRO equation accounting for large-scale yielding and a progressive build-up of crack closure. The initial crack size has been derived from the measurements of defects around the borehole. A reasonable agreement between predicted and measured lifetimes is observed if one keeps in mind the large uncertainty regarding the effective shape of the cracks.

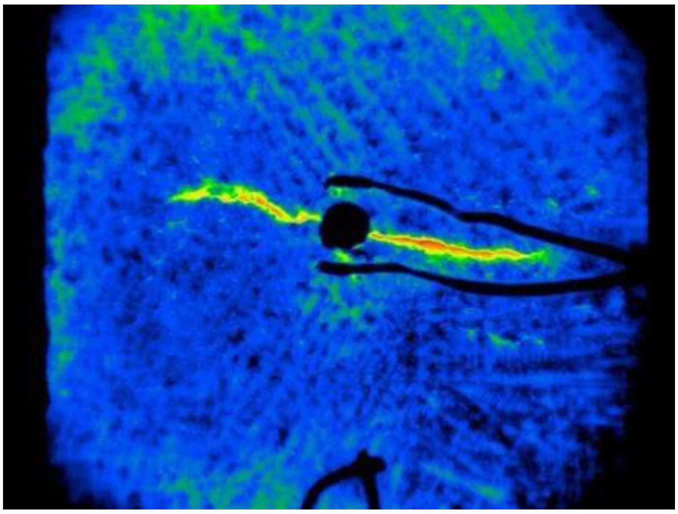

***Figure 1*** *– Cracks emanating from a cylindrical hole in a flat LCF specimen*

# #039 Fatigue of austenitic steel: Micromechanics aspects

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*Fatigue* *Metastable* *Micromechanics*

**Abstract** Microstructural changes accompanying the fatigue of a metastable austenitic steel comprise two main factors: (a) microcracking and (b) nucleation of the martensitic phase. Both factors produce changes in the effective elastic properties that can be monitored by high-precision acoustic techniques. In order to focus on monitoring microcracking, its effect on the elastic properties should be separated from the effect of the martensitic phase that has elastic constant that are somewhat different from the ones of the austenitic phase. To this end, the eddy current technique is used to monitor volume fraction of martensite. The volume fraction parameter is generally insufficient for the prediction of the elastic properties since they depend not only on the volume fraction but, also, on the shapes of the martensitic particles – that are complex and not fully clear. It is shown, however, that, if the elastic contrast between the austenitic and martensitic phases is weak-to-moderate, the effect of shapes can be neglected, so that the volume fraction information is sufficient [3]. This allows one to combine the acoustic and the eddy current data in such a way as to focus on monitoring microcracking [1,2].

References

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2. Kachanov M., Mishakin V., and Pronina Y. (2021) On low cycle fatigue of austenitic steel. Part II: Extraction of information on microcrack density from a combination of the acoustic and eddy current data. *Int. J. Eng. Sci*., **169**, 103569.
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# #042 Physical measuring techniques for VHCF assessment of wheel steel for high speed trains

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*Cyclic deformation* *VHCF* *Electrical resistivity*

**Abstract** Detailed studies of the Very High Cycle Fatigue (VHCF) behavior of the medium carbon steel SAE 1050, used for wheels of high speed trains, were performed with an ultrasonic testing facility (UTF). The design of the UTF allows to control the test parameters and the online monitoring of parameters like generator power, electrical resistivity, displacement amplitude and specimen temperature which can be used to characterize the cyclic deformation behavior at 20 kHz. In preliminary load increase tests (LIT) critical stress amplitudes were identified which lead to a change of the process parameters. The applied measuring techniques allow to detect fatigue induced changes in the microstructure significantly before final failure occurs. Based on the LITs, constant amplitude tests (CAT) were performed to study the cyclic deformation behavior in the VHCF regime in detail, which is especially affected by the local microstructure. Fig. 1 exemplarily shows the development of the change of the specific electrical resistance ΔR in a wheel cross sections with different ferrite fractions. It is remarkable that the point of increase of ΔR is inversely proportional to the local ferrite fraction. The cyclic plastic deformation and the change of microstructure is more pronounced in volume areas with higher ferrite contents. Consequently the increase of ΔR occurs earlier in the specimen volume with the higher ferrite content. SEM investigations show that the increase of generator power, displacement amplitude and temperature correlates closely with the formation of slip bands and the initiation of fatigue cracks predominantly at ferrite – cementite phase boundaries of the test material. In TEM investigations, it could be shown that defined changes in the dislocation structure occur also in specimens running $10^9$ cycles without failure.

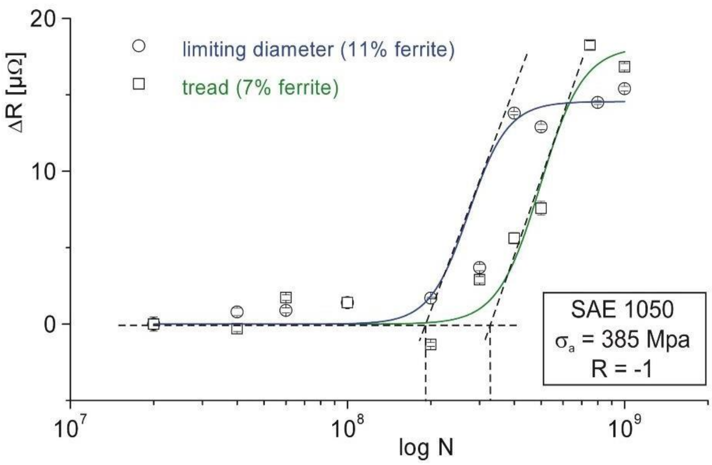


***Figure 1 -*** *Electrical resistivity analysis of a wheel steel in the VHCF regime*

# #043 A CTOD-based crack growth law for thermomechanical fatigue

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*fatigue crack growth*    *finite element simulation*    *TMF experiments*

**Abstract** Due to combined cyclic mechanical and thermal loading during operation, the material of exhaust gas conducting components of combustion engines is exposed to thermomechanical fatigue (TMF). This leads to formation and growth of cracks, especially at the most highly stressed points of these components. In order to better predict the service life of cracked components before failure, it is necessary to identify a crack propagation law for the material used. Isothermal crack propagation tests have been carried out at several temperatures with a typical cast iron to identify such a law. The crack length is measured by the potential drop method. The compliance method, fractography and thermographic camera measurements have been used to validate and calibrate the potential drop measurements. Each of the isothermal tests has been simulated using a specially developed FEM-algorithm based on remeshing and remapping. This algorithm has been implemented in python and ABAQUS. Thereby, the crack tip region is modeled by collapsed Quad8 elements. From the individual simulations, the cyclic crack tip opening displacement (ΔCTOD) is extracted and regarded as a potential fracture mechanics parameter which controls the crack growth rate. By combining the data from the experiments and the simulations, the crack propagation law has been identified. Finally, anisothermal crack propagation tests have been performed for validation of the crack growth law.

***Figure 1*** *– Experimental setup for crack propagation experiments*

# #044 Temperature evolution as a fatigue parameter of 42CrMo4+QT

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*Infrared thermography* *Fatigue analysis* *High cycle fatigue*

**Abstract** This study focuses on analyzing fatigue performance and temperature evolution during uniaxial cyclic loading. Fatigue specimens of four different geometries were machined from the 42CrMo4+QT bar produced in a single heat. Two sample types are of hourglass type, two are of dogbone type, all with the circular cross-section. Specimens of series A01 and A02 have 4mm diameter with the transition fillet of 24mm from the gripped head to the active cross section. The A03 and A04 samples have a diameter of 8mm and transition radius of 32mm. In contrast to hourglass samples of A01 and A03 types, series A02 and A04 have the 20mm prismatic part in the middle to enlarge the volume with the critical cross-sectional area.

All fatigue tests were carried out on the Amsler resonant pulsator with a load cell of 100kN under load control at the load ratio of $R$ =-1. The tests were monitored with the FLIR A315 thermal camera. To measure the temperature on the surface of the samples, LabIR black coat paint with high emissivity (HERP-LT-MWIR-BK-11) was applied.

The temperature response to cyclic loading was analyzed, and three parameters that can reflect fatigue behavior were focused on. It was found that the behavior of samples from this steel was different during cyclic loading from any expected response. The temperature response lacked the stabilized temperature region. Thus, the application of thermographic methods to estimate the fatigue limit and methods to predict the fatigue life performance on a single specimen (with variable amplitude of load) was not thus possible. This led us to analyze other parameters. For the estimation of the fatigue limit, the temperature increase rate in the first and second phases (see Figure 1) was used instead of the stabilized temperature from the second phase as proposed by (Luongo, 1997) and (La Rosa and Risitano, 1999.

Also, the analysis of the limiting energy (Fargione *et al.*, 2001), which is the area under temperature evolution during cyclic loading until failure (see Figure 1), relies on the stabilized phase, which is not observed here. This limiting energy is considered as a material parameter for a specific geometry and material. In the cases presented here, this parameter is highly dependent on the amplitude of the load; see Figure 2. It cannot be assumed that there is a constant available to predict the number of cycles to failure as Fargione postulated. As the last observed parameter, the cooling phase after failure of a specimen was analyzed so that the method proposed by Meneghetti (Meneghetti, 2006) could be applied.

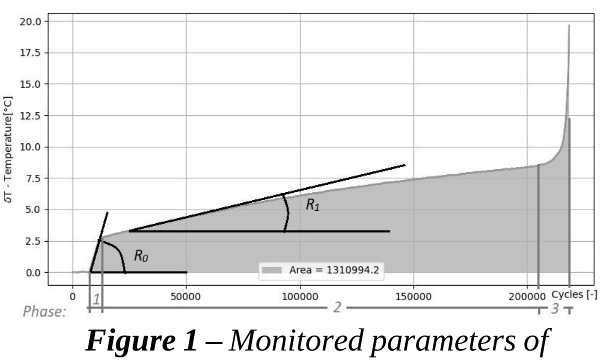


***Figure 1*** *– Monitored parameters of temperature evaluation during cyclic loading*

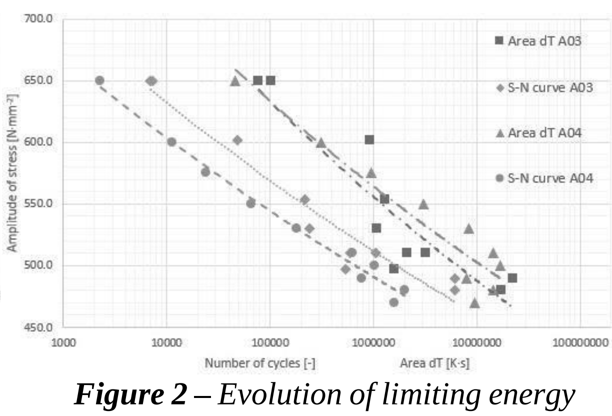


***Figure 2*** *– Evolution of limiting energy with S-N curves of A03 and A04 samples*

# #045 One-step dynamic calibration of strain measurement in a split Hopkinson pressure bar

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*SHPB* *Dynamic calibration* *Optical extensometer*

**Abstract** A new method for dynamic calibration of the bar instrumentation, i.e. the strain measurement, of a split Hopkinson pressure bar is proposed. The dynamic calibration is necessary to obtain the relationship between the measured voltages of the strain gauges attached to the bars and the respective strains in the bars that are eventually used to calculate forces and displacements within the specimen. The conventional measurement incorporates the striker velocity and the assumption of momentum conservation. These assumptions can be omitted by the proposed method.

The method applies an optical measurement of displacements of the bar/specimen interfaces. The measured time-dependent displacements are then compared with those displacements that are calculated from the (uncalibrated) voltage/time measurements. The calibration factors will then account for the actual sensitivity of the strain gauges at the incident and transmitted bars. Finally, two calibration factors, one for each bar, are obtained. The determination of a transmission factor is not necessary.

It was found that this method can be performed during an actual test, see Figure 1. Hence, it was neither necessary to rearrange the bars nor to use a rectangular incident pulse for calibration purposes. The amount of pulse shaping that is desired for the actual test can be used. The displacements calculated from the strain gauge readings in Figure 1a are given in Figure 1b. After the dynamic calibration according to this method, there is a very good congruence between the measured and calculated displacements. The dynamic calibration was then used to calculate forces from the strain gauge signals, the force/displacement relationship and, in this case, the stress/strain curve.

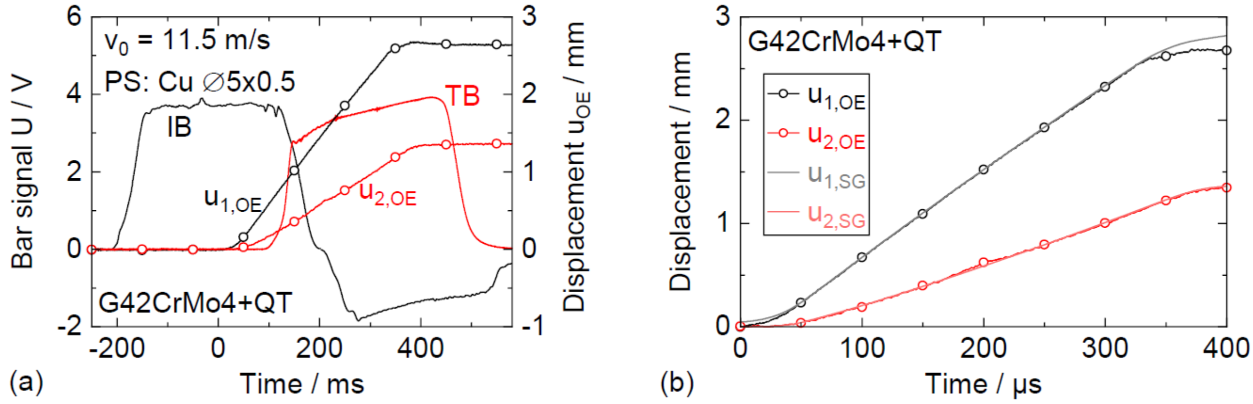


*Figure 1 - Measured and calculated signals (with pulse shaping (PS) and specimen):*

*(a) incident, reflected and transmitted pulses; optically-measured (OE) displacements at the interfaces incident bar (IB)/specimen (1) and specimen/transmitted bar (TB) (2).*

*(b) Comparison of optically-measured and calculated (from strain gauge (SG)) displacements after dynamic calibration.*

# #046 Numerical simulation of fracture behaviour of the shot-earth 772

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*FE numerical model* *homogenization approach* *cohesive law*

**Abstract** Earth building techniques have been around for thousands of years. Among them, it is worth mentioning: cut blocks, poured earth, superadobe, adobe, cob, rammed earth, compressed stabilised earth blocks, wattle and daub, shaped earth, and straw-clay. An innovative technique among the earth building ones, and named shot-earth technique, is the topic of the present paper. The technology employs a specific mixture of the shot-earth (named shot-earth 772) consisting of 7 parts of excavated soil, 7 parts of aggregates and 2 parts of cement (by volume): the mixture stream is projected at high velocity onto a surface, adding about 3% of water (by volume) at the spraying nozzle (Figure 1). The present research work deals with the numerical simulation of fracture behaviour of the shot-earth 772. More precisely, an experimental campaign performed to computed the fracture toughness of the material is here numerically simulated. To such an aim, a Finite Element macro-mechanical numerical model is used, where the material heterogeneity is considered by means of a homogenization approach. In fact, such a model is able to properly consider the effect of the void volume fraction on the macroscopic material properties, such as the elastic modulus, the compressive, tensile and flexural strengths, and the fracture toughness. The material fracture process is described by means of a cohesive-friction law which is introduced within the cracked zone, whereas an elastic law is adopted for the un-cracked region of the material. Finally, the numerical results are compared with the experimental ones.

***Figure 1*** *- Mixture stream projected at high velocity onto a surface.*

# #047 Medium carbon steels: when and why do low loads and holding times increase lifetime?

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*Variable Amplitude* *VHCF* *Strain aging*

**Abstract** With the onset of Very High Cycle Fatigue research, an anomaly in the Miner paradigm started occurring repeatedly: instead of decreasing the residual lifetime of a specimen, low load cycles just below the so-called endurance limit increase lifetime compared to constant amplitude tests even if only the cycles of the highest load block are counted; the low load cycles contribute a negative amount of damage in damage accumulation computations. We give a brief overview over related anomalies and discuss conditions of occurrence as well as possible mechanisms, identifying stress-enhanced static strain aging and oxide-induced crack closure as the most likely ones. We present experiments that show that holding a specimen at tensile stresses enhances static strain aging compared to holding the same specimen at zero stress

# #048 Phase field fracture modelling for 3D printed materials: a preliminary study

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*3D printing* *Carbon Fibre* *Phase Field*

**Abstract**

**Abstract** In recent years, Additive Layer Manufacturing (ALM) has captured more and more interest among both industrial and academic players due to the incredible opportunities that this technology offers. In this field, one particular branch seems to be promising for the possibilities offered from the design point of view: the continuous carbon fibre deposition. The possibility of deposing continuous Carbon Fibre (CF) along with common polymeric material allows the designer to give particular attention to regions of the component which could be subjected to higher stresses for whichever reason (notches, discontinuities, joints). The reinforcement of such areas with CF allows a better resistance to catastrophic phenomena like fracture which could lead to the failure of the component. Therefore, this deposition technique is of particular interest and object of study in this work. In the first part, a problem studied experimentally by Akasheh et al. [1] is analyzed numerically by means of the Phase Field fracture modelling, demonstrating the optimal capabilities of this approach to capture not only the experimental crack path but also the Stress-Strain response of the specimens tested. Validation of the material parameters is of particular importance especially for novel materials like the ones used in the experiments performed by the authors. Once both the capabilities of Phase Field and the material properties have been verified by means of the numerical simulations described above, these are now exploited to study a well know problem in the field of mechanics and aeronautics: structural joints. The aim is to use Phase Field as a tool able to predict failure load and failure mode of a component subjected to operating loading conditions, for instance. This could allow the designer to exploit the capabilities of continuous carbon fibre deposition to generate fracture resistance components, by means of accurate reinforcement of the most critical regions, where failure is most likely to occur. The Open Hole Tension test is simulated numerically by means of the same tools described above, taking into consideration different geometries for the reinforcement around the hole. The specimens with different reinforcements show different mechanical responses and crack patterns, thus highlighting the influence of the continuous carbon fibre reinforcement on the fracture scenario.

[1] Akasheh, F. and H. Aglan (2019). Fracture toughness enhancement of carbon fiber–reinforced polymer com- posites utilizing additive manufacturing fabrication. Journal of Elastomers and Plastics 51 (7-8), 698–711.

# #049 Strain-life testing as a probe of hydrogen effects on deformation in steel microstructures

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*Hydrogen* *Steel* *Strain-life*

**Abstract** The clearest conclusion that can be made after a century of inquiry into the phenomenon of hydrogen embrittlement is that the effect of hydrogen on a metal is complicated. Understanding the myriad of effects that hydrogen has on a metal, from its bonding strength to plasticity interactions, is further complicated by uncertainties in mechanical testing techniques due to both testing apparatus concerns and the statistical nature of phenomena such as fracture. The influence of hydrogen on plasticity means that separating elastic effects from plastic effects in tensile testing is difficult. Distinguishing and connecting the effects of hydrogen on these two regimes comprises one of the primary debates of the hydrogen embrittlement field.

One technique that shows promise for separating out the different effects of hydrogen on the elastic and plastic portions of the mechanical response is fully-reversed strain-life testing. This technique of mechanical testing is not trivial, particularly in a hydrogen atmosphere. The facilities at NIST have been adapted to accommodate these tests. Four different alloys were investigated in high pressure hydrogen gas under fully-reversed strain-controlled loading. Results on a 100% polygonal ferrite high strength low alloy (HSLA) steel will be compared with several pressure vessel martensitic steels: a currently used commercial 4130 alloy, and two higher strength steels which would be desired for hydrogen pressure vessel use. The strain-life results will be compared to demonstrate how the different steel microstructures respond to a hydrogen environment, particularly differences in elastic and plastic responses. Similarly, changes in microstructure evolution with different strain-life loading will be examined to ascertain the effect of hydrogen on damage accumulation. Implications as to the operating embrittlement mechanisms will be discussed.

# #050 Dimension-based failure analysis of formed internal threads in AlSi10Mg cast profiles using coupled DT/NDT testing methods

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*Fatigue* *Friction drilling* *Thread forming*

**Abstract** Production of detachable joints in lightweight components using friction drilling and internal thread forming processes could be considered as lightweight design strategy, which can reduce the material and time consumption. Innovative front face friction drilling perpendicular to the thickness of thin-walled cast profiles enables manufacturing a bore with a diameter larger than the profile thickness. Furthermore, tangentially shearing and radially expansion of material by a friction drill facilitates a chipless forming of the bores, utilizing the positive aspect of work-hardening. Afterward, using a cold thread forming for the tapping process instead of thread cutting enhances the thread's strength by imposing a further work-hardening into the subsurface of the formed threads.

Pre-study indicated that oversizing the friction drilled bores as a pilot bore can hinder the complete deformation of the thread profiles during the thread forming process. Subjecting an oversized internal thread to the static and dynamic load encourages bending of the thread profiles (nut dilation) instead of shearing them, which can decrease the static and dynamic strength of formed internal threads consequently. Determining the proper dimension of the pilot bores depends on material properties and manufacturing strategies. Adapting the manufacturing parameters of the friction drilling process according to material properties can enhance the quality of friction drilled bores and following formed threads, consequently.

In this study M6 internal threads were manufactured into thin-walled AlSi10Mg cast profiles. The specimens were manufactured with two different friction drill's diameters and speeds to find the proper process parameters. Pre-study indicated that a decrease in speed of the friction drill for 25% at the beginning of the process (penetration of the conical part in specimens) can decrease the expansion of the created bore. Computed tomography (CT) was chosen to measure the dimension deviation of manufactured bores and threads. Mechanical properties of manufactured M6-threads were investigated by subjecting the four initial thread turns to the static and cyclic loads. The results from conducted tensile and fatigue tests were compared and correlated to the CT-analysis. Dimensional analysis with CT declared that increasing the tool diameter for 0.1 mm increased the inner volume of the friction drilled bore, which led to an incomplete deformation of the thread profiles and decreased static and cyclic strength accordingly. Although friction drilling with an adaptive speed reduced the oversizing of the created bore in comparison to the friction drilled bores with a constant speed, measuring the volume of the formed threads into mentioned bores indicated an opposite trend. While the formed M6-threads into the friction drilled bores with constant speed showed a better strength in quasi-static and LCF regions, manufactured threads with an adaptive speed indicated a higher dynamic strength in HCF regions. The fatigue tests were monitored through NDT methods by measuring the change in deformation-induced temperature and potential (ACPD). The measured results were correlated to plastic strain up to failure corresponding to occurred softening, hardening or possible cracks initiation and propagation in thread profiles.

# #051 Effects of residual stress on fatigue crack growth rate in electron beam welded 316L pipes.

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*Fatigue Crack Growth Rate* *Residual Stress* *Electron Beam Welds*

**Abstract** Electron beam (EB) welding has the potential to reduce the cost of manufacturing processes due to its capability to be readily automated. It also has a smaller heat affected volume than other techniques such as gas tungsten arc welding and has a lower total heat input [1]. EB welding has existed for over seventy years, but the attention of safety critical industries has only recently turned towards it with a focus on its possible failure mechanics. This paper investigates the effect of residual stress created during the EB welding process on fatigue crack growth. EB welds create complex microstructure around the fusion zone (FZ) as well as multi-axial residual stress fields which can have a noticeable effect of the fatigue behaviour of the material. The project focusses on investigating 316L pipe sections.
First the residual stress present within the pipe near the weld is measured using a combination of contour method, x-ray diffraction, and incremental deep hole drilling. Contour measurements carried out by VEQTER Ltd shown in Figure 1 shows maximum residual stresses of approximately 400MPa [2]. Mechanical properties of the weld and parent are measured using a laser micrometre tensile test method. Compact test (CT) specimens were chosen to conduct the fatigue crack growth rate tests in line with ASTM E647. The CT specimens are cut from the parent material and weld region. The position of the CT samples cut from the weld region is determined by cutting three initial CT samples each with differing notch position, being on the weld centreline and around the FZ boundary. These tests help to identify the most critical location to carry out the full-scale tests.

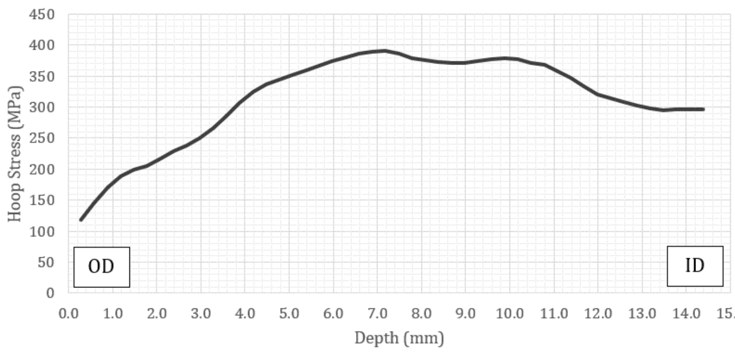


*Figure 1- Contour plot showing averaged hoop stress through thickness of the weldment, OD is outer diameter and ID is inner diameter*

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# #052 A multiscale model for predicting fatigue strength of bainitic steel considering grain boundaries effects by a generalised evaluation method

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**Keywords**

*Fatigue* *Multiscale model* *Microstructure* *Crack growth* *Steel*

**Abstract** A multiscale model for predicting fatigue strength of bainitic steel is proposed based on a generalised method for evaluating grain boundaries' (GBs) effects on fatigue crack growth. The proposed model is a modification of our previous works that extends the applicability from only low-grade ferrite steels to high-grade bainite steels. A microstructure model was developed considering the distances between GBs and misorientations between adjacent grains. The model was validated by comparing with experiments using two ferrite-pearlite and one bainite steel; results indicate the model predicted fatigue lives and limits of steels with microstructures from coarse ferrite to fine bainite grains.

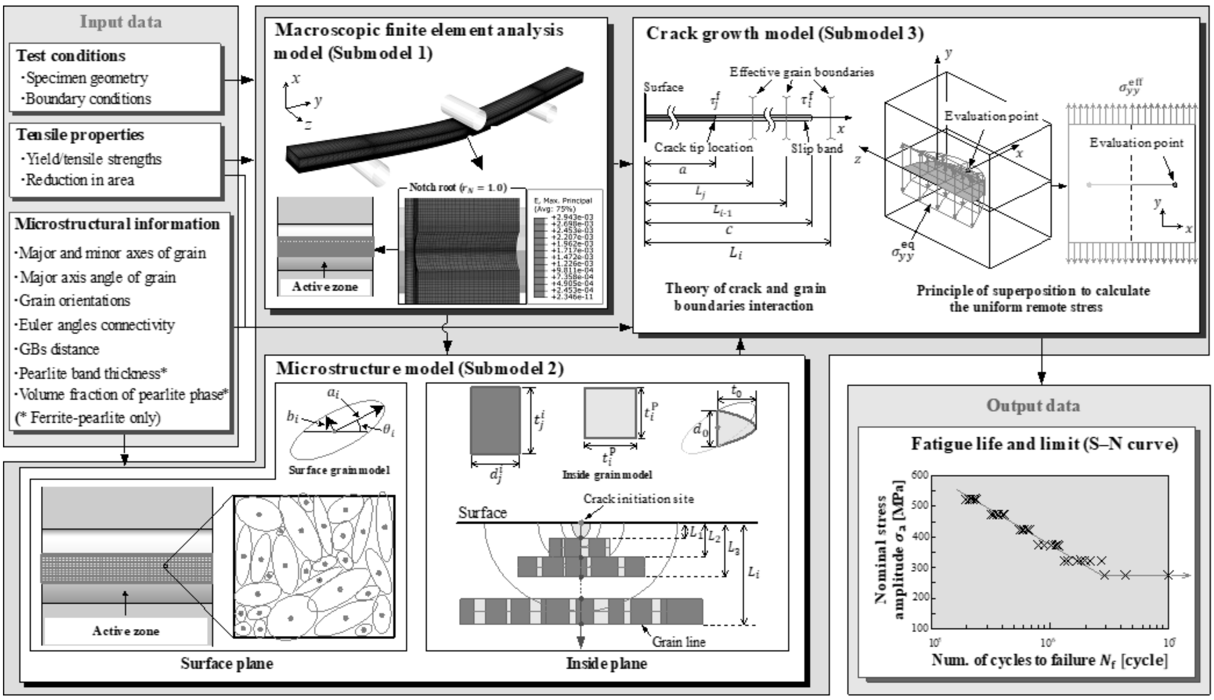


*Figure 1 - . Outline of proposed multiscale model for predicting the fatigue strengths of steel*

# #054 Delayed fracture susceptibility of a 1.5 GPa class dual phase steel evaluated by U-bend test

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*Hydrogen embrittlement* *Dual phase steel* *U-bend test,*

**Abstract** Advanced high strength steels (AHSSs) are used in structural applications and automobiles to achieve higher strength to weight ratio. However, the AHSSs which exhibit a tensile strength of 1.5 GPa are prone to hydrogen-induced delayed fracture. In general, the applied stress, diffusible hydrogen content, and microstructure are considered the determining factors for the delayed fracture. In addition, given that the automobile parts undergo forming operations, the plastic strain also plays a critical role in delayed fracture susceptibility and hence must be factored in. In this context, the U-bend test is an effective true-false test method to evaluate the hydrogen embrittlement behavior.

In the current work, we evaluate hydrogen embrittlement susceptibility of a 1.5 GPa class ferrite/martensite dual-phase (DP) steel using the U-bend test. The steel is initially bent in a U-shape and subsequently loaded by bolt-tightening. The applied stress was controlled by the extent of bolt-tightening. This was followed by galvanostatic hydrogen charging in a 3 wt. % NaCl aqueous solution containing $NH_4SCN$, wherein the hydrogen charging current density was increased in a stepwise manner until fracture. Fractography studies revealed a quasi-cleavage fracture. Furthermore, with an increase in applied stress, we observe that the crack initiation site reached the surface. We explain the role of plastic strain and microstructure in the formation of surface cracks.

# #055 Fracture toughness of the shot-earth 772

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*shot-earth* *soil* *sustainable practice*

**Abstract** The techniques used to build with soil are ancient and have made an impact all over the world. An innovative earth-based construction technique is the shot-earth technique. Such a technology employs a material, named shot-earth, composed by a dry mixture of excavated soil, aggregates and water, where the soil may be either unstabilised or stabilised by a chemical binder. The mixture stream is projected at high velocity onto a surface, where the impact compacts the material (Figure 1). In the present paper, the fracture toughness of a specific mixture of shot-earth (named shot-earth 772), consisting in 7 parts of soil, 7 parts of aggregates, 2 parts of cement (by volume) and about 3% of water (by volume) is computed by using the Modified Two-Parameter Model, recently proposed by the authors.

***Figure 1 -*** *Shot-earth technique.*

# #056 Estimation of the residual life of composite structures with impact damage based on ultrasonic testing and numerical simulations

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*Impact damage* *Ultrasonic testing* *Numerical simulations*

**Abstract** Polymeric composite materials, such as carbon or glass fiber reinforced polymers, are widely used in the aircraft industry owing to their numerous advantages, especially low weight, which is critically important for the construction of aircraft components. One of the most important and currently investigated problems is the susceptibility of composites to impact damage. Aircraft may suffer from impact damage as a result of hail, runway debris impacts, bird strikes in flight, or dropped tools during maintenance procedures. A so-called Visible Impact Damage (VIS), like damage caused by a bird strike, is less of a problem since it is detectable during routine vision inspections and it often qualifies the component for a repair or replacement. A more complicated is the occurrence of Barely Visible Impact Damage (BVID), which appears as a result of low-velocity impact and is detectable only during inspections with the use of a specialized equipment that allows to detect internal damage. According to the damage tolerance methodology, aircraft has to be included in appropriate maintenance program based on performing periodic inspections using non-destructive testing (NDT) methods, which ensures detecting damage before it propagates to the level causing reducing the strength of the structure below an acceptable limit. One of the most widely used NDT method applied for the aircraft inspections is ultrasonic testing (UT) owing to the high ability of this method to detect and localize internal damage as well as identify its size and depth location. Through such inspections, it is possible to monitor the propagation of the detected damage and make decisions about admission of the aircraft to operation or the necessity to take an intervention. The purpose of the studies performed by the research team was to develop a methodology making it possible to predict the residual life of composites based on data acquired from UT and numerical evaluation of structural degradation. A main concept of the proposed approach was based on reverse engineering by a reconstruction of the real shape of BVID in three dimensions using image processing and image analysis methods. For this purpose, data extracted from ultrasonic scans were processed and numerical models were prepared, which reflect with a high accuracy the current technical condition of the composite specimens. The specimens were tested also using X-ray computed tomography (XCT), which allowed obtaining reference data and adjusting the models. The residual strength was investigated based on experimental and simulated Compression After Impact (CAI) tests. This study summarizes the obtained results of the ongoing research project, which indicated that the proposed methodology is promising and may be used as a tool of an enhancement of BVID identification as well as prediction of the structural residual life

# #057 Fracture surface analysis of undermatched welded joint of martensitic steel

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*SEM* *Undermatching* *Martensitic*

**Abstract** Fracture surfaces on welded joints made of martensitic steels X 10 CrMoVNb 9-1 and Armox 500T were analyzed. Welding was performed using a combination of nickel based and austenitic ferritic additional material, which achieved an undermatching effect. The fractures of four test specimens were analyzed, two of which were made from tube and have a rectangular cross-section, while the other two test specimens were made from plate and had a square cross- section. Fractures of all specimens occurred in the weld metal zone. A scanning electron microscope (SEM) was used to analyze the fracture surfaces. The obtained results showed that the fracture was caused by the mechanism of microvoids coalescence in the presence of different inclusions and with different degrees of plastic deformation on the face and root of the weld metal. The presence of a large amount of chromium in the additional material contributes to increasing the strength of the welded joint and its resistance to work at high temperatures, but also the formed chromium inclusions are the initial sites for the formation of secondary cracks.

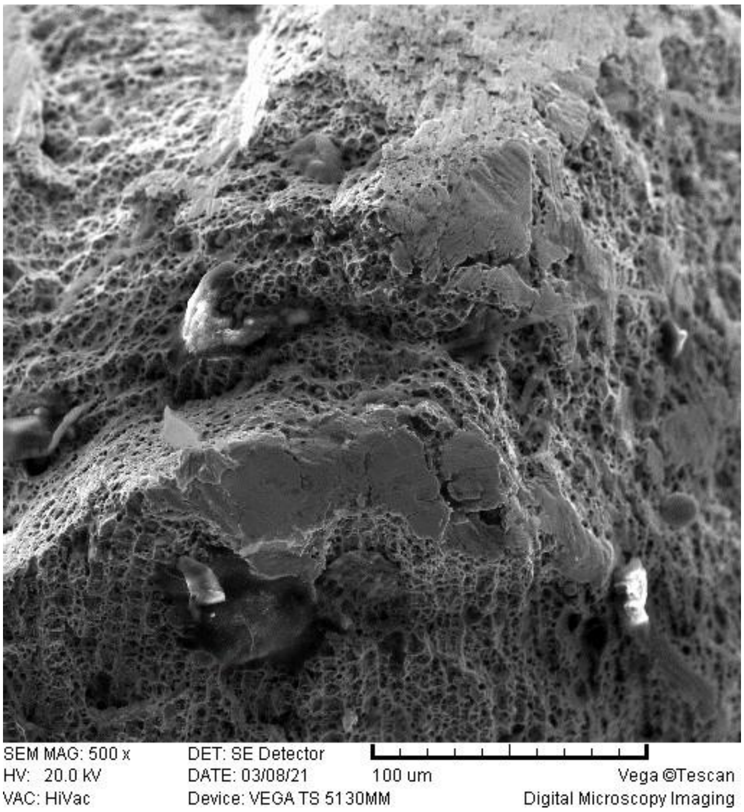


***Figure 1*** *– Fracture surface of the specimen C1-1*

## #058 Solidification of a water drop – A paradox when multi-cracking

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*Multi-cracking* *Thermal residual stresses* *Coupled Criterion*

**Abstract** When a liquid water drop falls on a very cold plate, ice is formed almost instantly after the impact on the cold surface. If the plate is cold enough, cracks may appear in the ice layer. Depending of the temperature $T_c$ of the plate, three cracking regimes were observed in experiments. For $T_c > -20$ °C, a first regime shows that the water solidifies into ice without creating cracks. A second regime appears around $T_c = -30$ °C, the water solidifies entirely into ice, then suddenly closely spaced cracks are formed. A third regime is presented for $T_c < -30$ °C, cracks appear following a hierarchical order while the water is still solidifying, these cracks are significantly more spaced than in the second regime.

These three mechanisms are paradoxical. Indeed, the plate exerts a thermal loading, the colder the plate, the more intense the loading. We would therefore expect multi-cracking to be more dense for higher loadings, and the opposite is observed. Based on a simplified 2D model, the Coupled Criterion is able to explain this surprising phenomenon.

# #059 Influence of recyclates on mechanical properties and lifetime performance of polypropylene materials

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*polyproylene* *recyclate* *slow crack growth*

**Abstract** Recycling of plastics has already gained increasing attention in many sectors, including science, industry and commerce, due to the economic and technological importance of the materials, as well as the environmental and social challenges associated with the circular economy of plastic products. In Europe, the amount of plastic waste which is recycled and further processed into new products is currently only about 13% in 2018. One option to process higher volumes of post-consumer recyclates into new products is blending with virgin materials. In order to investigate the effect of recyclates on structural material properties, a post-consumer polypropylene recyclate (PP-r) was added to a virgin polypropylene (PP-v) in different contents – 10%, 25% and 50%, respectively. Mechanical and fracture mechanical properties were analyzed and compared with initial conditions of the original materials (virgin and recycled). In addition, the influence of qualitatively different recycled PP-r types (PP-r1 and PP-r2) were examined by using grades of a low and high melt flow rate (MRF). Results demonstrate that the blending of virgin material with recyclates had a clear influence on the material properties. MFR values increased with higher recyclate content. Tensile tests showed a reduction of the Young’s modulus and the yield strength with increasing recyclate content, while the elongation at break decreased and increased depending on the used recycled PP grade (PP-r1 or PP-r2). While for the tensile test properties the values already changed significantly at a recyclate content of ≥10%, Charpy impact strength was affected only above a recyclate content of 25% and 50% for PP-r1 and PP-r2, respectively. The resistance against slow crack growth (SCG) of the materials was analyzed by the crack round bar (CRB) test. Results indicate that a small recyclate amount of 10% does not significantly reduce the SCG resistance of the blend compared to the virgin material. However, the SCG resistance decreases dramatically with higher recyclate content.

# #060 Optimal sensor placement techniques for modal identification of historical masonry structures

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*Structural health monitoring*     *Optimal sensor placement*     *Historical masonry structures*

**Abstract** Since destructive tests cannot be performed on historical structures, numerical model updating using accelerometers has gained attraction in the last decade. Furthermore, another application of structural health monitoring is damage detection for near-real-time monitoring of cultural heritage assets that can also be as infrastructures such as masonry bridges. High cost is the main problem that discourages the use of large-scale structural health monitoring systems and modal pretest analysis is required to plan and optimize the modal tests. For this purpose, various optimal sensor placement (OSP) techniques have been developed to derive the operational modal analysis results with a minimum number of sensors, leading to a lower cost.

In this light, various OSP techniques have been applied on two case studies. The first case study is a masonry tower located in Tønsberg, Norway and the second one is a two-span masonry arch bridge in Rhodes, Greece. Baseline finite element models were developed before performing the ambient vibration tests and model updating process. The optimum sensor locations were detected using various techniques, and a comparative study was conducted on the results. Furthermore, a sensitivity analysis was done on each model to investigate the effect of material properties' uncertainties on the OSP results.

# #061 Effect of Thermal Shock Cycles on the Shear Strength of Carbon Composite Adhesive Joint

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*Adhesive Joint* *Shear Strength* *Surface Free Energy*

**Abstract** In recent years, significant advances in the field of adhesive materials chemistry have led to the constant development of bonding technology. The effectiveness of bonding depends to a large extent on the suitable selection of the adhesive and the use of appropriate surface treatment technology. It is difficult to imagine virtually any modern industry without adhesive joints, be it the aircraft, aerospace or automotive industries; which simultaneously highlights the great importance of adhesives and adhesive materials for the present day economy. Adhesive joining is a typical method for joining structural materials (including composite substrates) in crucial machines and devices operating in various conditions of thermomechanical loads. However, the phenomena occurring at the interface between the substrate and the adhesive are so complex that it is not possible to develop an effective general purpose adhesive for all materials.

The influence of cyclic thermal loading on the strength, both static and dynamic, of lap joints is relatively poorly known, especially in the aspect of the mechano-chemical changes occurring within the adhesive. For the most reliable prediction of the adhesive joint performance of carbon composite substrates under variable thermomechanical loading conditions it is necessary to understand the behaviour of the adhesive subjected to shock changes in the operating temperature. Thermal fatigue of cured adhesives may imply aging processes and thus change the mechanical properties.

The prepared adhesive joint specimens were subjected to cyclic thermal loading, following a specific program, in the thermal shock chamber at the temperature range from -40°C to +60°C, in a specified number of cycles (200, 500 and 1000). The assumed temperature range for tests is typical for the operation of machines, including aircrafts.

The primary aim of the study was to determine the influence of thermal loading (fatigue) as a function of shear strength of adhesive joints of carbon composite substrates. The results of the tests were analysed statistically, observing the appropriate scientific standards.

# #062 Microstructures and HE fracture mechanisms in 17-4PH martensitic stainless steel


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*Hydrogen embrittlement* *Martensitic stainless steel* *Microstructure*



**Abstract** Martensitic stainless steel 17-4PH is a precipitation hardening material with a combination of high strength and good ductility and widely used in various modern industries. However, this material is susceptible to hydrogen embrittlement, HE, in some environments and applications. In this study, the correlations between the microstructures in the solution annealed condition and different tempering conditions were investigated, when exposed to hydrogen. The different embrittlement mechanisms in 17-4 PH stainless steel in the various heat treatment conditions were identified. In-situ electrochemical hydrogen charging and slow strain rate tensile tests, SSRT tests, were used to evalaute susceptibility to hydrogen embrittlement and fracture mechanisms. Fracture morphology and microstructures of the steel were studied using scanning electron microscope techniques such as EBSD and ECCI. It was found that 17-4 PH steel in the solution annealed condition is susceptible to hydrogen embrittlement. Intergranular cracking and transgranular cleavage are two main mechanisms. Tempering at 510-621°C reduces the susceptibility to hydrogen embrittlement, mainly by the precipitation of nano austenitic phase and change of dislocation structures. This has also caused fracture mechanism transitions from intergranular cracking to transgranular cleavage, and finally a ductile cracking mode. This work will increase the knowledge to reduce and finally avoid the susceptibility to hydrogen embrittlement in 17-4PH material.


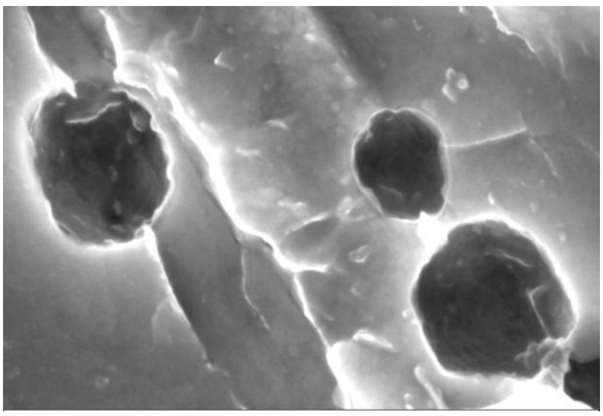

***Figure 1 – Fish eye at HE fracture***

# #064 Adapted multiaxial fatigue models based on the critical plane approach to consider the presence of small defects in steel

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*Multiaxial fatigue* *Small defects* *Out-of-phase loads*

**Abstract** Non-metallic inclusions can often be seen in the fatigue crack initiation site in high-strength steels (Fig. 1(a)). These inclusions are known to be detrimental to the fatigue strength, as they behave as stress concentration elements. The same is valid for small defects such as notches, holes and scratches. The goal of this research is to investigate not only the effect of non-metallic inclusions but also of small artificial defects on the fatigue strength of the AISI 4140 steel under multiaxial loading conditions. In order to do so, two critical plane based multiaxial fatigue models are coupled with Murakami's $\sqrt{area}$ parameter. This is an empirical parameter, which is used to estimate the uniaxial fatigue strength of metals containing small defects (or inclusions). One of the major merits of $\sqrt{area}$ parameter is the fact that the material fatigue limits (under push-pull or torsion) can be estimated by considering only the material hardness and the geometry (area) of the small defect, i.e no costly and lengthy fatigue tests are required. To validate the analysis, experiments under combined push-pull and torsional loading in and out-of-phase have been conducted in smooth and also in specimens containing an artificially produced micro hole. Comparison between the estimates provided by the coupled critical plane-$\sqrt{area}$ parameter multiaxial criterion and data provided very good results, with errors around 20%. Fracture surface analyses were also carried, as seen in Figure 1.

***a*** ***b***

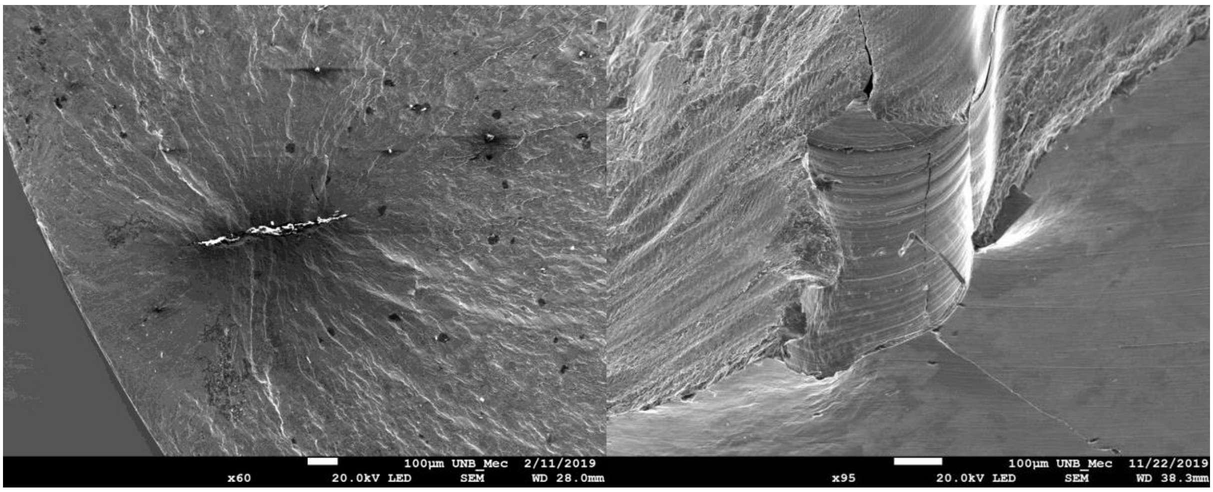


***Figure 1 –*** *Crack initiation in non-metallic inclusion (a) and in artificial micro hole (b) seen on the fracture surface of AISI 4140 steel specimens.*

# #065 Finite Element Modelling of Hydrogen transport in a multimaterial component under complex thermomechanical loadings

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*Finite Element* *Hydrogen transport and trapping* *Thermomechanical loading*

**Abstract** In a future hydrogen-based economy, component reliability is a key prerequisite as hydrogen can contribute to a structure's early failure (due, e.g., to hydrogen embrittlement). Hydrogen permeation, in conjunction with applied thermomechanical fields, has to be controlled to ensure the safety of in-service structures. In the specific case of nuclear fusion devices, hydrogen permeation and retention in components is also linked to safety issues.

In ITER, the divertor plasma-facing components are actively cooled monoblocks. They consist of tungsten armor and CuZrCr cooling pipes in which pressurised water evacuates the heat deposited by the plasma power loads. A significant part of the plasma load is carried by energetic tritium ions that impact on the components, of which a fraction permeates in the monoblock to remain trapped or even enter the coolant flow. The related tritium retention and permeation must be understood.

For a better understanding of this permeation process, a simulation of monoblock plasma exposure is conducted by means of the Abaqus finite element software. Hydrogen diffusion and trapping, assisted by thermomechanical fields, is modelled, using specific developments which permit the simultaneous resolution of transient heat transfer, mechanical stresses (including expansion) and diffusion and trapping problems. In the specific case of multimaterial components, chemical potential continuity is assumed to be linked only to the ratio of hydrogen concentration and solubility. Then, a parametric study is conducted to capture the influence of the boundary condition on the hydrogen retention and permeation in monoblocks.

# #066 An investigation of the effectiveness of the different constraint parameters for brittle steels

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*In-plane constraint* *Out-of-plane constraint* *Brittle fracture*

**Abstract** Crack-tip constraint can have a significant effect on fracture toughness. Generally, a loss of crack-tip constraint can cause an increase in fracture toughness. This means through a fracture test with standard specimens which have a high level of crack-tip constraint, only the lower bound toughness of the material is obtained. Therefore, to make the best use of the low constraint effect and reduce over-conservatism in structural integrity assessment, it is important to quantify the constraint level and to correlate it with fracture toughness variation.

Constraint is often divided into in-plane and out-of-plane. Currently, there are many parameters that are used to characterize in and out of plane constraint separately. The $T$-stress and $Q$, which were adopted by R6 and BS 7910 flaw assessment procedures, are used to assess the in-plane constraint level, while $T_Z$ works as an out-of-plane constraint. However, it can be difficult to quantify the combined effects of constraint in different directions in a real case. Thus, some unified measurement parameters have been introduced to characterize such combined effects. For example, the Anderson–Dodds method, $\varphi$ and $A_P$. Although these parameters were validated by many numerical studies, applications to comprehensive experimental data of materials with different yield to elastic modulus ratios are far and few between. The lack of large-scale experimental validation has limited their application in safety critical industries such as nuclear.

In this study, the effectiveness of several well-known constraint parameters was investigated for two different materials: Al7075 T651 and BS1501-224 28B steel. Al7075 T651, a grade of aluminum prone to brittle fracture, was tested at room temperature, while BS1501-224 28B steel, a ferritic steel, was tested at -160°C. A series of SEN(B) and C(T) specimens with different thicknesses and a/W, which ensure a large range of in-plane and out-of-plane constraint conditions, were tested to establish a detailed experimental database of fracture tests which was then analyzed by finite element modelling. All simulations were conducted with ABAQUS 6.14. Then, those constraint parameters were calculated by the simulation results and compared to evaluate their effectiveness.

It is found that, for Al7075 T651 and BS1501-224 28B steel at brittle fracture, $T$-stress and $T_Z$ can only quantify in-plane and out-of-plane constraint, separately. The parameter $Q$ can partially characterize both constraint levels, but it is not possible to establish a monotonic correlation with fracture toughness. The unified parameters are shown to be sensitive to both measures of constraints, and there is a high order relationship between them and fracture toughness.

# #067 Evaluation of the effectiveness of *Q* and unified constraint parameters on the uniaxial and biaxial bending specimen

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*Biaxiality* *Uniaxiality* *Constraint level*

**Abstract** Crack-tip constraint is defined as the resistance of a structure against crack-tip plastic deformation. A loss of crack-tip constraint can cause an increase in fracture toughness. Therefore, the standard test geometries such as compact tension specimens are designed to have high levels of constraint so they can be used to measure the lower bound level of toughness. The factors that can affect the constraint level are often considered to be component thickness, crack and ligament length, geometry, and type of loading. Currently, widely accepted constraint parameters such as $Q$ and $A_P$ are used to quantify their effect on toughness. The effectiveness of such parameters has been validated using specimens with uniaxial loading such as C(T) and SEN(B). However, a large number of industrial assets experience modes of loading other than uniaxial. While multi-axiality has been considered an important effect in various standards and assessments, its effect on the toughness has often been considered separate from constraint.

In this study, a number of cruciform, 5 Point Bend biaxial specimens as well as 3 Point Bend specimens of BS 1501-224 steel were tested at lower shelf (-160℃). The results were included in a dataset which includes results of 25 mm thick C(T) and 10mm thick SEN(B) tests carried out previously. Finite element analysis of all tests was conducted with ABAQUS 6.14, and essential results were extracted to calculate $Q$ and a unified measure of constraint.

It was found that the effect of biaxiality is captured successfully on cruciform specimens using a unified measure of constraint. The constraint levels of cruciform and rectangular specimens are lower than those of C(T) and SEN(B) specimens. Parameter $Q$ and the unified measurements quantify toughness variations in C(T) and SEN(B) specimens but cannot be used for combining uniaxial and biaxial bending conditions.

*Figure 1- Photograph of cruciform specimen experimental setup*

# #068 Probabilistic approach and fault-tree analysis for increased bucket wheel excavator welded joints reliability

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*bucket wheel excavator* *welded structure* *fault-tree analysis*

**Abstract** The main part of this paper is consisted of presentation of a new method for determination of reliability of the structures. Presented method provides more knowledge and confidence when evaluating the construction of vital welded structures and determining the cause of their failure in service. The probabilistic and semi-probabilistic approaches have been defined for expressing the coefficient of validity (ν) and the coefficient of the welded joint weakening (η), while reliability (R) has been defined as a measure of quality of installed vital welded structures on bucket wheel excavators in service (Fig. 1).

The applied "fault-tree" analysis enables quantitative and qualitative analysis of the failure causes, diagnostics of behavior and structural degradation, evaluation of integrity and estimate of the service life of the vital welded structures that have a flaw in the welded joint, as well as creating a data base, by which the reliability of the bucket wheel excavators can be increased. The method also makes possible to efficiently test the welded joints, during the manufacturing, acceptance and assembling the new welded structures of the bucket wheel excavators, cranes or bridges.

***Figure 1 -*** *The bucket wheel excavator SRs 2000 20/5 in exploitation, Kostolac (Serbia)*

# #070 Effect of the manufacturing process on the bending characteristics of hybrid structures in Titanium-Lattice/FRP

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*EBM printing* *Composite material* *Bonding*

**Abstract** Higher performances in terms of mechanical properties, lightweight, and reliability are increasingly required to materials used in the transportation field, due to the need of reducing pollutant emissions and increase the safety level. A solution to meet these requirements is the adoption of innovative hybrid structures made of metallic lattice core and composite material skins, because both of them are characterized by high specific strength and stiffness. These peculiarities are synergically increased when they are combined together, giving rise to a more performant material. Compared to other commercial cores, like honeycomb, lattice core is more rigid, but the loads applied to the structure are not uniformly distributed, due to the particular topology of the lattice. For this reason, skins are required. The simpler approach for achieving this objective consists in producing both the skin and the lattice core together; in such a manner, both the skin and the core should be made of the same material. This represents a very practical solution from a manufacturing point of view since the whole part can be produced within a single process; however, it may not be the best one in terms of performance, especially in terms of strength/weight ratio. For this reason, lattice structures with FRP (fibre reinforced polymer) have been proposed. In fact, composite material is more lightweight compared to metal, without decreasing the mechanical performance. At this point, a question arises: what is the best technological process to produce such hybrid structures?

In this work, two different processes are analysed and compared: co-curing and bonding. In the former case, the prepreg layers are laid up directly on the lattice, which acts as a mould. Instead, in the latter case, a composite material laminate is cured alone, and then it is bonded to the core. The former results to be more convenient since a single step is sufficient to obtain the part, especially in the case of complex shape parts. On the other hand, the latter allows the cure of the laminate on a dedicated smooth mould, improving the quality of the laminate itself. The aim of the work is to compare the flexural properties of the laminates obtained through the two abovementioned processes. After the production of the laminates, specimens were extracted and tested according to the three-point bending procedure. Both types of specimens demonstrated a similar stiffness, but the co-cured one presented a higher strength, with an improvement of about 10%. This finding, coupled with the greater process ease, makes co-curing the best technological solution.

# #071 The circularly truncated Brazilian disc

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*Brazilian Disc Test* *Truncated Brazilian Disc* *Tensile strength*

**Abstract** Since its introduction, almost eight decades ago, the Brazilian Disc test is still drawing the interest of researchers being a challenging topic both experimentally and analytically. In this direction, several alternatives are proposed from time to time to improve the procedure and the reliability of the respective results (Ring test, Flattened Brazilian Disc test, Circular semi ring test, etc.). In this context, a new configuration is here proposed: the Circularly Truncated Brazilian Disc (CTBD) test (Fig.1a). The CTBD test aims to alter the biaxiality ratio of normal stresses at the center of the disc, in favor of central fracture against potential premature cracking at the disc-platen contact region. In this context it is believed that CTBD could further guarantee the reliability of the test results providing accurately the tensile strength of brittle materials. The solution for the respective 1st Fundamental problem of the CTBD is obtained with the aid of Muskhelishvili's complex potential technique [1], as recently applied in the case of the Flattened Brazilian disc [2]. Namely, first the contact arc and the contact stress (boundary conditions for the 1st problem) are defined from the CTBD-semicircular intender contact problem (Fig.1b), and then the 1st problem for the isolated CTBD is solved (Fig.1c) using conformal mapping. The complex potentials solving the problem are sought as:

$$\begin{aligned}
\varphi(z) &= \frac{-1}{2\pi(1+\kappa)}\sum_{j=1}^{n}(X_j+iY_j)\log(z-z_j)+\varphi_o(z) \\
\psi(z) &= \frac{\kappa}{2\pi(1+\kappa)}\sum_{j=1}^{n}(X_j-iY_j)\log(z-z_j)+\frac{1}{2\pi(1+\kappa)}\sum_{j=1}^{n}(X_j+iY_j)\frac{\overline{z}_j}{z-z_j}+\psi_o(z)
\end{aligned} \tag{1}$$

$\kappa$ is Muskhelishvili's constant for the CTBD, and $\varphi_o(z)$, $\psi_o(z)$ are subjected to determination.

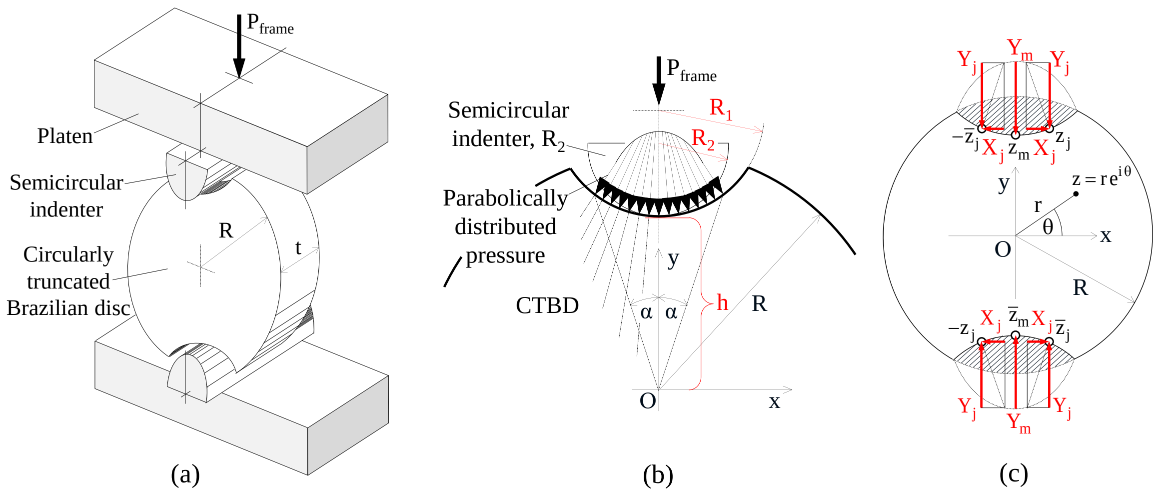


***Figure 1 -*** *(a)The CTBD test; (b) The contact problem; (c) the 1st problem for the CTBD.*

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# #072 Cyclic response and low-cycle fatigue strength of a Laser Powder Bed Fusion (L-PBF) additive manufactured AISI 316L steel

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*L-PBF AISI 316L* *Low-cycle fatigue* *Cyclic response*

**Abstract** While the Low-Cycle Fatigue (LCF) behaviour of wrought AISI 316L stainless steel is generally well documented in the literature, less studied is the behavior of the same steel made by Laser Powder Bed Fusion (L-PBF) additive manufacturing. This works aims at comparing the cyclic response and LCF strength of an AISI 316L steel in both wrought and L-PBF additive manufactured (AM) state. AM samples were obtained by scanning bi-directional tracks melted in layers of 0.025 mm with a 0.12 mm laser beam moving at 600 mm/s and providing 180 W of power. The exposure pattern consisted of 5x5 mm alternating islands. During testing, AM material shows an initial cyclic hardening followed by softening until failure; the wrought material also reveals a significant secondary hardening in last part of test. The wrought material exhibits a strain-induced martensitic transformation of the austenitic phase, whereas in the AM material the bi-phasic microstructure undergoes only the activation of dislocations (local micro-plasticity). At each strain amplitude, the cyclic stress values of L-PBF AISI 316L are almost always above those of wrought material. Despite the different elastoplastic response, the two materials show a comparable LCF strength. A fractographic analysis was also conducted on broken specimens to detect the microstructural defects responsible for crack initiation.

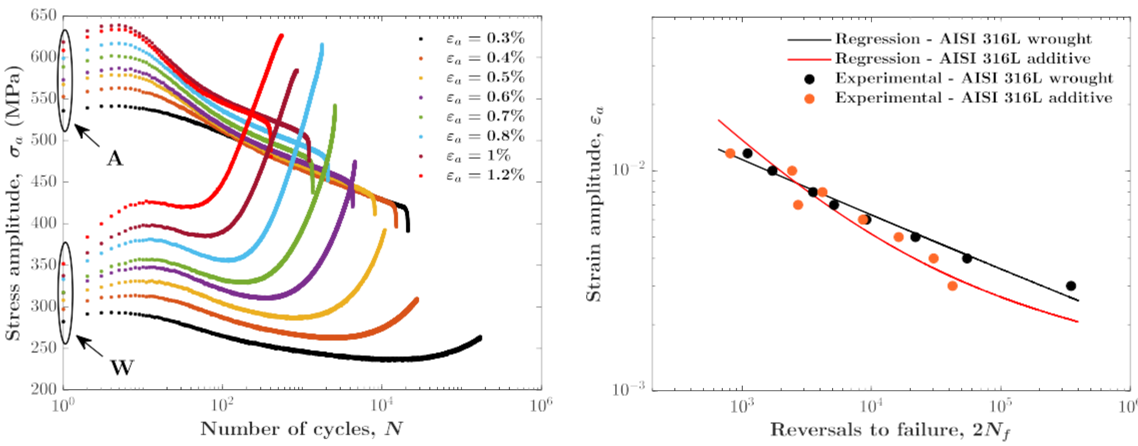


***Figure 1** - Cyclic stress response and strain-life curves for wrought (W) and L-PBF (A) AISI 316L stainless steel.*

# #073 Evaluation of tire vehicle stiffness under drift or cornering forces

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*Tire radial stiffness* *Tire lateral stiffness* *Vehicle Drift*

**Abstract** The tire is an essential component for safe vehicle functionality in people or goods transport. A vehicle tire is subjected to complex dynamic loads. In tire dynamics, there are three dominant force directions that must be scrutinized: the circumferential, the radial and the transverse. Attention is focused on the effect of transverse forces on tire structure. This type of forces has a major influence on vehicle behaviour, once transient lateral actions affect the evenness of the vehicle trajectory, eventually potentiating its loss of control. The present work proposes a simplified model for tire lateral stiffness calculation. The solution is based on the balance of the internal energy of the compressed air volume by tire deformation, versus the external work due to transverse force, thereby distorting the tire at the tire/soil contact surface. The study considers only the effect of lateral forces but includes also the coupling with radial loads, as these affect the tire shoulder dimension by radial compression as described.

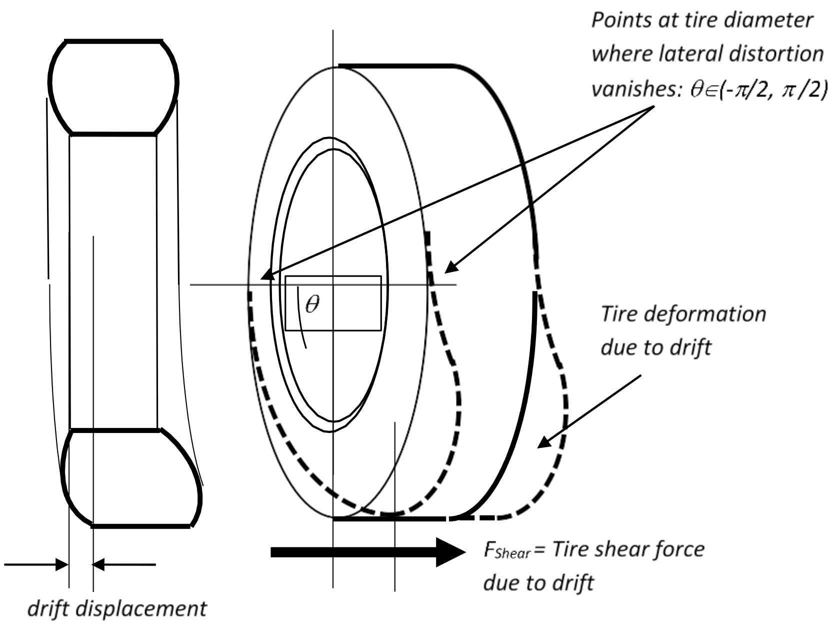


***Figure 1** – Tire distortion by lateral force due to cornering.*

# #075 Heat treatment effect on stress-life curve of additively manufactured MS1 maraging steel under push-pull loading

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*Fatigue life* *Additive manufacturing* *Effect of heat treatment*

**Abstract** Additive manufacturing (AM) is a rapidly developing technology with the advantage to produce structural parts of complex shapes directly from 3D digital models without further machining. The post-heat treatment of AM metallic material is one of the factors influencing its mechanical properties. The influence of the temperature of age treatment on the fatigue life of AM maraging steel (MS1) is not fully recognized. A few studies reported that the age-treated specimens at 490°C exhibited increased fatigue life compared to specimens without the heat treatment. The temperature of 490°C for age treatment of AM maraging steel (MS1) is a standard applied value deduced from previously reported research on its positive effect on tensile strength. The aim of the present research is to analyze the effect of the ageing treatment conducted at 450°C, 470°C, and 490°C on the fatigue lives of AM maraging steel (MS1) under fully reversed axial cyclic loading. The stress-live curves were identified through the non-linear Kohout-Věchet model. The influence of age treatment temperature on the tensile yield and ultimate strengths is evident (Fig.1a). But their influence on fatigue life is not statistically significant (Fig.1b). Though the median stress-life curves are shifted approximately up to 8%, the life scatter is higher and the estimated 95% confidence bounds for data at 470°C include all median curves (Fig.1b.).

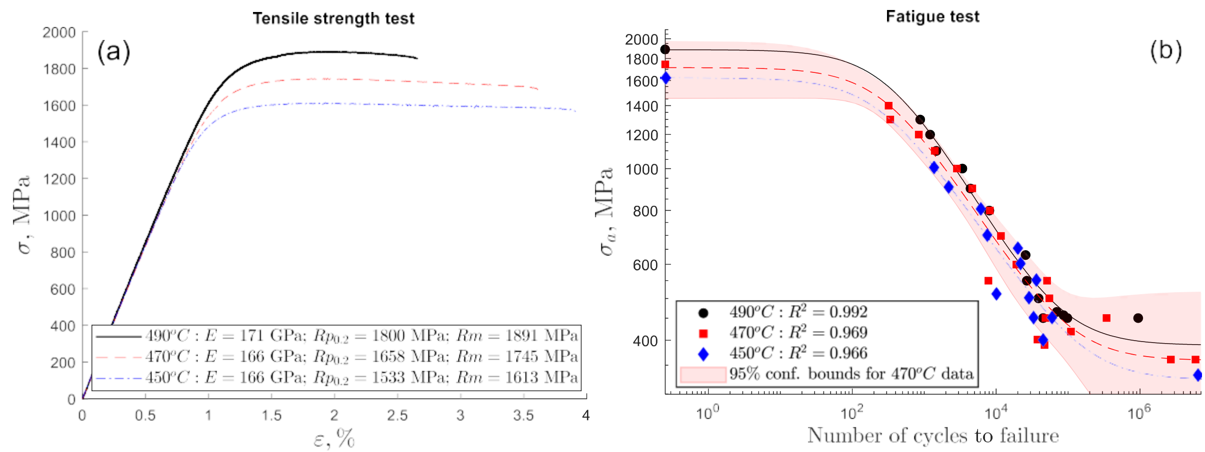


***Figure 1** – Tensile stress-strain and stress-life curves of additively manufactured MS1 maraging steel under different post heat treatments*

## Funding

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# #076 Influence of DMLS printing orientation on the strength of materials before and after heat treatment

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*DMLS printing* *Heat treatment* *Anisotropy*

**Abstract** The basic mechanical properties are determined on the basis of appropriate experiments carried out on samples cut from the test material. In most cases, neither the place nor the direction of sampling affects the mechanical properties of the sample. In such a case, we say that the material tested is homogeneous and isotropic. However, for additively manufactured materials it is different. The material analyzed in the paper will be 3D printed by the EOSINT M280 metal 3D printer using the DMLS/SLM (Direct Metal Laser Sintering) method. This technology enables the direct production of high quality metal parts based on 3D CAD models. However the specimens prepared in this technology are characterized by anisotropic properties [1]. The strategy of printing specimens involved printing at different orientations. It has already been proven that the direction of print buildup of the printing layers has an impact on the strength of the tested materials [2].

The paper presents the results of a static tensile test for specimens printed before and after heat treatment. The aim of the paper is to investigate the influence of the print orientation on the mechanical properties and cracking curse of the tested material, including heat treatment.

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# #077 3D analysis of HR-EBSD fields of indentation micro-cracks in (001) Silicon

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*HR EBSD* *Stress Intensity Factor* *Indentation*

The residual strain fields of cracks initiated at a Vickers micro-indentation in a (001) Silicon mono-crystal wafer have been investigated (Figure 1a). The symmetrical elastic deformation field surrounding the indentation was calculated by HR-EBSD (high-resolution electron backscatter diffraction) (Figure 1b) and integrated into the equivalent 3D displacement field (Figure 1c). The out-of-plane displacements were consistent with the topography measured by AFM (atomic force microscopy). The 3D stress intensity factors (SIFs) were calculated via the *J*-integral and the interaction integrals (without requiring knowledge of the loading or the crack geometry) in an anisotropic linear elastic finite element model that used the 3D displacement field as a boundary condition. This found an opening mode I SIF for a {110} crack that was orthogonal to the surface, and in-plane shear mode II SIF for an inclined {111} cleavage crack (Figure 1d). The analysis method applied here to ex situ measurements of the residual fields could be applied to in situ studies to determine the critical SIFs.

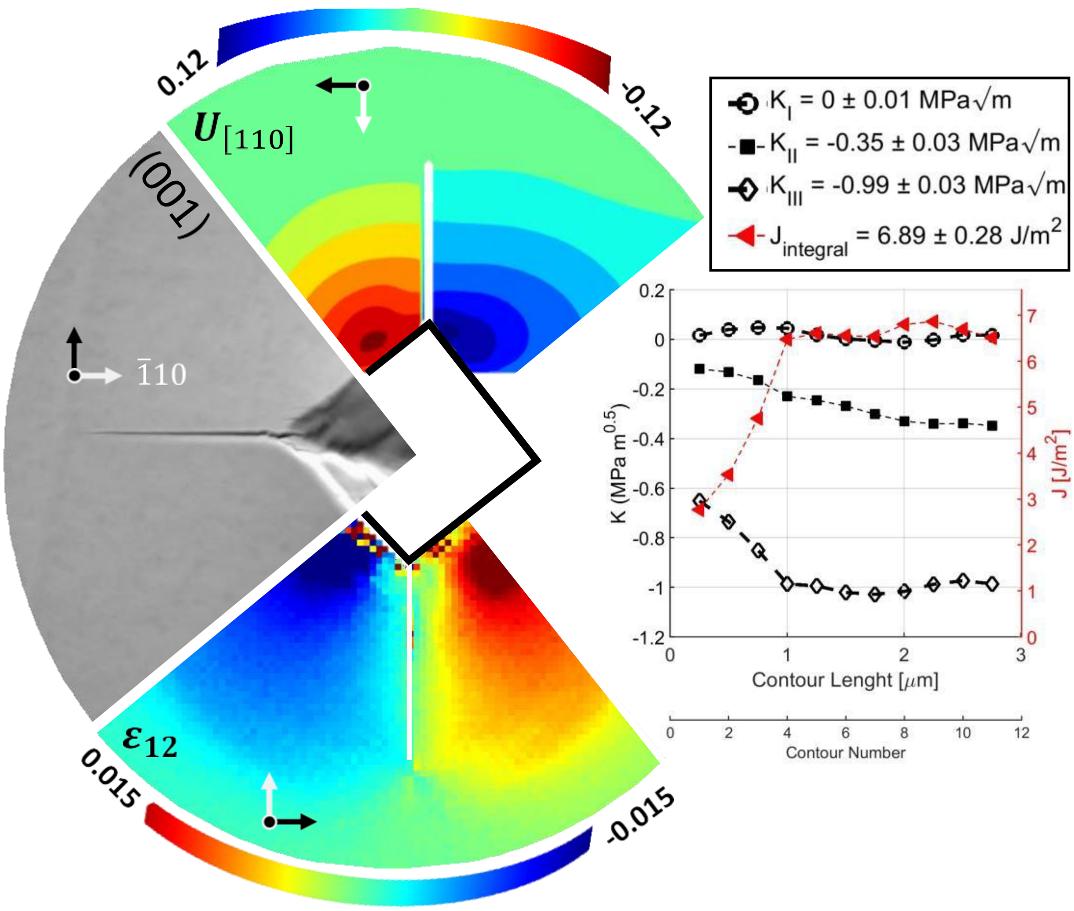


***Figure 1*** – (a) $(11\bar{1})$ cleavage crack due to Vickers indentation in (001) Silicon. (b) In-plane shear strain ($\varepsilon_{12}$). (c) Integrated displacement field in the [110] direction ($U_y$). (d) *J*-integral and 3D SIFs (the sign of the shear modes has no physical meaning).

# #078 Optimal placement of coupling elements of RC shear walls using endurance time method

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*Structural fuse* *Endurance time method* *Hybrid coupled wall*

**Abstract** One of the common lateral bracing systems in reinforced concrete structures is shear walls. A coupling beam can be used due to architectural limitations for connecting two or multiple separate walls. The behavior of coupled shear walls is governed by coupling beams which are the most vulnerable parts of coupled shear wall systems. Therefore, beams could be designed to act as replaceable fuses in the system. In this paper, the application of viscoelastic coupling dampers (VCD) and replaceable steel coupling beams in a high-rise building located in a high seismicity region is investigated. A parametric study has been conducted to determine the optimal number and placement of the dampers to achieve enhanced seismic performance of the structure. The endurance time analysis method has been utilized to compare the seismic performance of a conventional steel coupled wall building to alternative designs incorporating VCD. The results show that the structure's capacity with VCD is 17% higher than the structure with steel link beams. The natural period of the structure increases by employing VCDs. By replacing the steel coupling beams with less stiff VCDs, the lateral stiffness of the structure is reduced, and the natural period is shifted beyond the predominant periods of typical earthquakes. The added damping provided by the VCDs dissipates seismic energy and effectively controls excessive drifts.

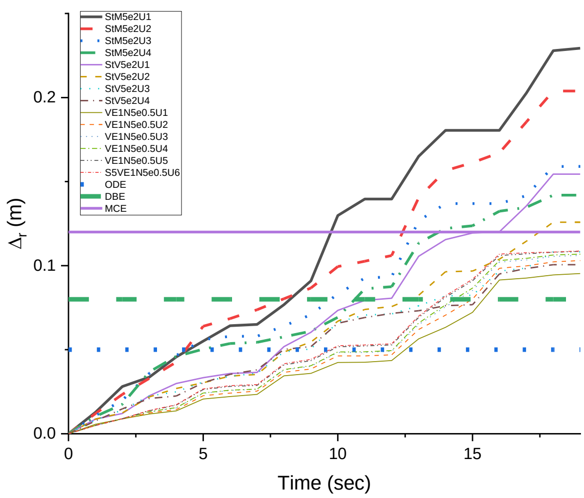


***Figure 1 -*** *Performance curve (ET curve) for a five-story frame*

# #079 20kHz cantilever VHCF bending fatigue of high strength strip steels

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*Very high cycle fatigue* *Cantilever test* *Strip steels*

**Abstract** During the past decades, Very High Cycle Fatigue (VHCF) research has developed into an active and prioritized research area since the number of cycles up to $10^7$-$10^{10}$ can be reached within a reasonably short amount of time by the development of 20-30 kHz ultrasonic fatigue testing equipment. However, testing of strip steels has not been conducted on a great scale due to their low thicknesses, which create difficulties especially when it comes to the gripping of the specimens. In the present effort, cantilever bending fatigue studies of cold-rolled strip steels were performed in the VHCF life region. An experimental set-up including the load chain ultrasonic horn and specimen was designed for resonance. The design of the specimen along with the FEM calculation of eigenfrequency are presented. Fatigue testing was performed at 20kHz in the cantilever bending conditions up to fatigue life of $10^7$ to $10^9$ cycles. Three martensitic stainless steel grades and one carbon steel grade were evaluated, and their nominal composition, thickness and tensile strength are presented in Table 1. Microstructural characterization of the different grades was performed by SEM. Finally, the effect of microstructural features on VHCF behavior and SEM fractography results are discussed in detail.

***Table 1.*** *Nominal composition, thickness and tensile strength of the tested grades materials.*

| ***Grades*** | ***Nominal chemical composition (wt. %)*** | | | | | | | ***Thickness (mm)*** | ***Tensile strength (MPa)*** |
|---|---|---|---|---|---|---|---|---|---|
| | ***C*** | ***Si*** | ***Mn*** | ***Cr*** | ***Mo*** | ***Ni*** | ***V*** | | |
| ***A*** | *0,40* | *0,20* | *0,55* | *13,3* | *0,35* | *1,35* | *0,35* | *0.60* | *1810* |
| ***B*** | *0,40* | *0,20* | *0,50* | *12* | *2,30* | *-* | *0,50* | *0,381* | *1910* |
| ***C*** | *0,38* | *0,45* | *0,55* | *13,5* | *1,0* | *-* | *+* | *0,381* | *2100* |
| ***D*** | *1* | *0,30* | *0,40* | *0,15* | *-* | *-* | *-* | *0,381* | *2100* |

# #080 A microstructure image-based numerical model for predicting the fracture toughness of alumina trihydrate (ATH) filled poly(methylmethacrylate) (PMMA) composites

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*Particulate composite* *Fracture toughness* *FEA model*

**Abstract** Particulate reinforced polymeric materials are a class of materials which appear in numerous applications in our lives, such as in automotive parts, building materials and various consumer products. On a macroscopic level they appear as continuous materials but when examined on a smaller scale, the particulate reinforcement dispersed into the continuous polymeric matrix marks the crucial link between structure and mechanical performance. The particles can have a wide size and shape distribution; they may be well dispersed in the polymeric matrix or agglomerated into localised regions. They could be well or poorly bonded to the continuous polymeric matrix. In addition, their relative amount by volume and the contrast in their properties in comparison to those of the matrix can greatly affect the composite's bulk response. We have developed a modelling methodology which considers all these parameters and provides accurate predictions of the composite's bulk response, hence providing a powerful design tool for optimising the performance of these materials in their respective applications. In our study, we use microstructural images of such a composite - Alumina trihydrate filled poly(methyl methacrylate) – and we feed these into a Finite Element model of a representative material volume. Our model is capable of simulating several failure micro-mechanisms and not only predicts well the modulus and the strength of the composite but also gives accurate estimates for the fracture toughness of the composite using a novel and simple approach, as a function of particle volume fraction and particle size. The estimation of the fracture toughness in particular from models has been a long-standing gap in the composites literature. For example, the model is able to predict the effect of crack arrest caused by larger particles associated with higher toughness, and the agglomeration of small particles leading to matrix cracking associated with lower toughness (see Figure 1). This work enables material manufacturers to cost effectively develop tougher, hence safer and more durable, particulate composites.


***Figure 1** Typical crack growth path (a) without arrest nor agglomeration-induced matrix crack, (b) with arrest, marked by the red circle and (c) with agglomeration-induced matrix crack, marked by green circle.*

# #081 Master curve evaluation of ANP-5 steel by using mini-CT specimens

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*ANP-5* *Miniature Compact Tension* *Master Curve*

**Abstract** The nuclear industry demands analyses that make possible the long-term operation of nuclear power plants (beyond 40 years). In this sense, one of the main challenges to overcome is the restricted amount of material available to extend the surveillance programs. To mitigate this issue, mini-C(T) specimens have been proposed to evaluate the fracture properties of reactor pressure vessel (RPV) materials, and particularly, the corresponding Master Curve. These specimens can be taken from the broken halves of previously tested Charpy specimens. In this work, mini-CT specimens have been employed to evaluate the reference temperature of the RPV ANP-5 steel in non-irradiated conditions. The obtained results were compared with those obtained by means of conventional fracture tests.

***Figure 1** – Comparison between mini-CT and standard CT specimens.*

# #082 Numerical analysis of CuMg alloys susceptibility to cold working processes

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*Copper alloys* *CuMg* *Finite Element Method*

**Abstract** Modern industry is focused among others but not limited to the efficiency of the manufacturing process. Which is why, when a new material is being designed it is necessary to assess its susceptibility to prospective cold working processes to the form of a final product. Conductive materials with copper matrix usually find their origin in various casting lines and the obtained cast rods or ingots are used as batch material for further drawing or cold/hot die forging processes. The study presents results concerning numerical analysis of the cold working processes of CuMg alloys with various Mg content (2 - 4 wt. %). Using Finite Element Method (FEM) simulations possibility of fracture occurrence was determined during plastic working. The analysis of the obtained results made it possible to verify the best geometry of the tools,

i.e. the drawing half angle and the bearing length of the drawing die, as well as the optimal shape of the forging die limiting the flash. All the analysis were based on the experimental data regarding the Ultimate Tensile Strength of the alloys in order to estimate whether or not the fractures would occur and thus the possibility of subjecting the designed materials to metal working processes.

Acknowledgements

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# #083 Susceptibility to deformability of novel CuMg alloys characterized with high wt. % of Mg

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*Copper alloys* *CuMg* *Deformability*

**Abstract** An increasing demand for electricity conducting materials caused by growing demand for electrical energy made it necessary to improve existing materials and develop a new type of alloys such as CuMg alloys with high wt. % of magnesium. The obtaining of such alloys using metallurgical synthesis have been proved to be possible in several scientific publications, however, processing of the obtained ingots or cast rods is still to be questioned. The proposed paper is dedicated to the susceptibility to deformability during cold working of CuMg alloys with Mg content ranging between 2 and 4 wt. %. The conducted uniaxial compression tests determined at what Mg content and with what amount of deformations fractures occurred. The materials were analyzed in four various states, i.e. as-cast state, after homogenization and supersaturation, after drawing process in a single draw with $\lambda$=1.2 and after drawing and recrystallization. The obtained results made it possible to analyze basic properties such as hardness and electrical conductivity and their evolution as the material changed due to the tests it was subjected to. The analysis of the results made it possible to determine the possibility of fracture occurrence during the deformation process and the prospective final properties of the designed material.

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# #085 Single-Point Laser Scanning Strategy for the Slm Fabrication of Ti-6al-4v Micro-Strut Lattices: Influence of Strut Size and Orientation

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*Keyword 1: Additive Manufacturing* *Keyword 2: Ti-6Al-4V* *Keyword 3: Lattice Structures*

**Abstract** Porous titanium scaffolds fabricated by additive manufacturing (AM) techniques such as Selective Laser Melting (SLM) offer many benefits which have been identified as advantageous over traditional biomaterials for bone reconstruction and osteochondral tissue engineering strategies consisting of metal and in vitro engineered cartilage.

The mechanical properties of the individual struts making up these lattices can be significantly different to the bulk material. These changes have been related to features inherited from the SLM process; among which are deviations in the as-built geometry from the as-designed. In this regard the 'single-point' (SP) based laser scanning strategy has been suggested as more suitable for the fabrication of such lattice structures than more traditional contour-and-hatch (C&H) based approaches. In the SP approach strut thickness is determined by melt pool thickness defined at a single exposure point for each build layer; offering the potential for a smaller minimum feature size.

Here we are seeking to 1.) define the SP scanning strategy for the fabrication of a range of strut sizes and orientations via the control of laser spot size, power and exposure time and 2.) characterize changes in mechanical properties of the induvial struts across this range. Special attention is paid towards relating these properties back to deviations in the as-built geometry; as has been done with C&H based approaches. Furthermore, we extend this work to draw further conclusion from other strut-size dependent, process inherited factors including surface roughness and microstructure. This knowledge will improve our understanding of how the properties of micro-lattices are influenced by the SLM process.

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# #086 Simulation of crack propagation in a thick walled cylinder using XFEM

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*Thermal Shock* *Crack propagation* *Thick walled cylinder*

**Abstract** For a safe operation of nuclear power plants, the integrity of their reactor pressure vessel (RPV) must be assessed. Experiments on real scale RPVs are expensive and almost unfeasible. One way to overcome this difficulty is to use thick walled cylinders (mock-up). At PSI, experiments on downscaled mock-ups are currently planned to be carried out. At the same time, simulations of crack propagation with the implemented extended finite element method (XFEM) in ABAQUS are performed but validation is required. In this contribution, the simulation of crack propagation in a mock-up subjected to a thermal shock transient similar to a pressurized thermal shock occurring in a loss of coolant accident is presented. The experimental conditions (geometry, loads and materials) are taken from the FALSIRE project, where the experiment was well documented. The results of the simulation are compared against the corresponding experimental data, with the future view on the applicability of XFEM on the planned downscaled mock-ups.

The material used in the finite element model corresponds to a specially heat-treated ferritic steel and mimics the fracture-mechanical behavior at the end-of-lifetime of the reactor, i.e. it exhibits a high ductile-to-brittle transition temperature (DBTT) as a highly irradiated RPV steel. Correspondingly, this high DBTT is considered in the simulation approach. The temperature dependence of material fracture toughness is described following the ASME models and is related to the maximum principal stress criteria for the initiation of crack propagation and crack arrest, where linear elastic fracture mechanics (LEFM) is applied. Thus, the modified temperature dependent stress criteria are included in the ABAQUS simulation by means of a subroutine UMDGINI.

The mock-up under investigation contains a fully circumferential initial crack. Both the loads and geometry of the cylinder are axisymmetric, however in the implementation of XFEM in ABAQUS, axisymmetric elements are not available. To avoid a full 3D finite element model and taking advantage of this symmetry, we proposed a model based on a cyclic symmetry of the cylinder. The results show that the crack propagates through the cylinder but comparison against the experimental results shows an overestimation of the final crack depth. The quality of the solution is demonstrated by a parameter analysis.

# #087 Effects of recycling on microstructure and defects in Ti-6Al-4V samples fabricated by Electron Beam Melting process

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| | | |
|---|---|---|
| *Electron Beam Melting* | *Recycling powders* | *Microstructure* |
| *Ti-6Al-4V* | *Defects* | *Plasma atomization process* |

**Abstract** Electron Beam Melting (EBM) is an additive manufacturing process that forms part of the Powder Bed Fusion (PBF) category. All the PBF processes share the same basic printing steps and use as material feedstock the metal powder which is previously atomized according to several existing methods. After the printing cycle, the powder in excess may be reused following a suitable sieving procedure to lower the production costs, otherwise, a large percentage of unused powder would be lost. The waste powder may differ in several respects compared to the starting virgin ones, depending on how many times it has been reused. Moreover, degradations in powder properties and its chemical composition can lower the quality and the mechanical performances of the components fabricated by Electron Beam Melting. The aim of this work is to investigate the microstructure variations in two batches of Ti-6Al-4V powder: virgin powders produced using a plasma atomization process and recycled powders more than one hundred times. Printed with the two batches of powder feedstock, 6 EBMed cylindrical bars were analyzed both from the point of view of microstructure and internal defects using an Optical Microscope. The bars were firstly cut and then embedded in resin, polished and etched with a Hydrofluoric acid (HF) solution. The experimental results show several types of internal imperfections including macropores, micro voids, Lack of Fusion (LOF) defects, which are directly dependent on process parameters and quality of the material feedstock. While for the microstructure few changes were found both in powder particles and in their printed bars.

# #088 Damage mechanisms in additively manufactured 316L stainless steel subjected to thermomechanical fatigue

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*Additive manufacturing* *Thermomechanical fatigue* *Damage mechanisms*

**Abstract** The aim of this work was to study the damage mechanisms in additively manufactured 316L stainless steel subjected to thermomechanical fatigue. Both vertically and horizontally built specimens were printed and tested. Cylindrical specimens were machined out of bars and were cycled in in-phase and out-of-phase loading modes in the temperature range of 550–750 °C. The tests were strain-controlled with mechanical strain amplitudes of 0.2, 0.3 and 0.5 % (in-phase tests) and 0.3, 0.5 and 0.6 % (out-of-phase tests). The material was characterized both prior to and after testing by means of visible light microscopy, computed tomography (CT), scanning electron microscopy and transmission electron microscopy. The grains in the initial microstructure exhibited elongation along the building direction. No lack-of-fusion defects larger than 5 μm were revealed by CT analysis, however fine round defects in the micron scale were present. The internal structure after cycling comprised dislocation cells elongated in <100> direction. Under in-phase loading conditions, the vertically built specimens exhibited higher fatigue lifetimes. The dominant damage mechanism was a creep mechanism starting with the nucleation of cavities along grain boundaries, followed by their growth and coalescence, which can be attributed to the relatively high stresses at high temperatures. As a result, intergranular damage was dominant. Under out-of-phase loading conditions, again the vertically built specimens exhibited higher lifetimes, however at notably lower stresses. The dominant damage mechanism was oxidation-assisted crack initiation, which resulted in numerous short, shallow cracks running approximately perpendicular to the surface. As a result of absent or relatively low creep damage at high temperatures, the character of damage was transgranular and there were striations at the fracture surface. The obtained experimental results are discussed in relation to the lifetime behavior of the tested material.

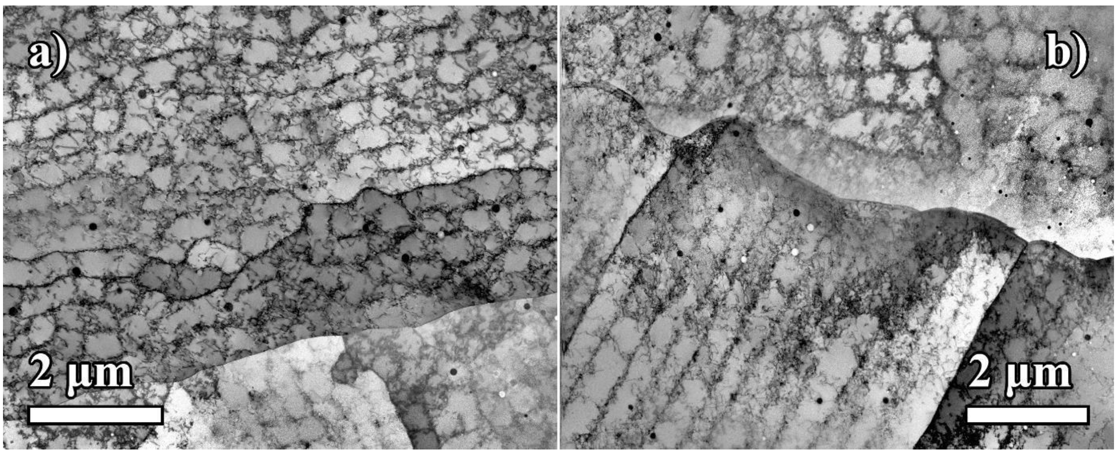


***Figure 1 -*** *STEM micrographs (BF contrast) of the transversal foils revealing dislocation cells present prior to the testing. a) Vertical and b) horizontal building direction.*

# #090 Reliability based structural analysis of a bucket wheel excavator's load-bearing steel structure

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*bucket wheel excavator SchRs 630* | *structural reliability* | *reliability index based on stress*

**Abstract** Structural analysis of large structures such as bucket wheel excavators (BWE) are generally performed using the finite element analysis and assessed according to the portion of the material's yielding limit. Consequently, a structure is evaluated just by the maximum stress at the specific location. In order to address the whole structural response of the object, this paper introduces a structural reliability-based evaluation presented on a case study of the BWE SchRs 630. Although the BWE reliability has been explored in the literature, most of the research was based on the obtained failure of systems and structure over the years. Nevertheless, this investigation is dividing the pure structural from the system failure by mapping and analyzing the specific structural zones of the BWE. Finite element method obtained range of randomized stresses (i.e., D – demand of the structure) in a structure is categorized as independent variables and modeled using probability density function. The same is performed in case of the criterion – yield strength of the structure's material (i.e., C – capacity of the structure), see figure below. Furthermore, yield strength distribution itself is evaluated according to the industry's practice meaning that mean value of the yield stress is to be reduced when used as a criterion for the stress assessments. Therefore, a margin function is analyzed according to the equation: M = C – D. Consequently, the structure is assessed as a whole through the introduction of the reliability index based on stresses. Such evaluation could enable comparison between the corresponding and similar structures in terms their structural response in more holistic manner.

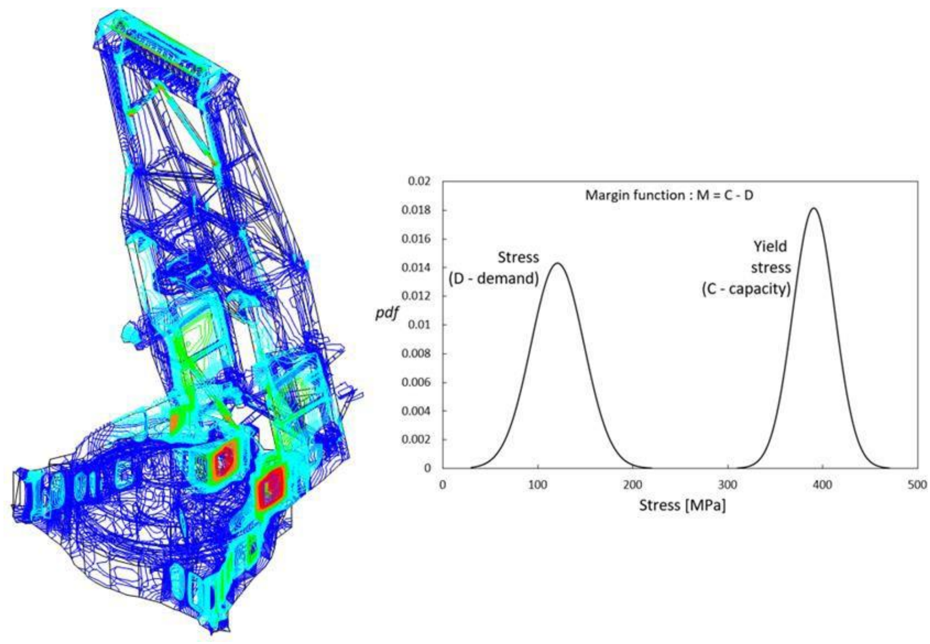


***Figure 1** – stress distribution (static load) and probability density functions, BWE.*

# #091 Wall thickness and scale effect on the quasi-static compression and fatigue performance of AlSi10Mg sheet-based lattice structures fabricated via Selective Laser Melting

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*Thickness and scale effect* *Selective Laser Melting* *Sheet-based lattice structure*

**Abstract** Additive Manufacturing (AM) has demonstrated significant advancements in fabricating metallic components recently since it has gained popularity due to the invention in the 1980s. It has been providing new possibilities in industries with complex geometries such as lattice structures, which are considered as excellent candidates for numerous applications from relatively small to large scales such as biomedical implantations, energy absorption, and heat dissipation. According to the recent literature studies, the mechanical properties of components fabricated AM technique are highly dependent on the thickness and scales of the parts. For metallic structures, the importance of the thickness and scale effect on lattice structures has not been fully investigated yet. Therefore, this research aims to evaluate the wall thickness and scale effect on the mechanical properties of uniform sheet-based gyroid lattice structures under quasi-static compression and cyclic loading conditions. First, specimens were designed and divided into three categories with the dimensional constraints of keeping the constant porosity, wall thickness, and cubic size in each category. Then all the lattice structures were fabricated via selective laser melting (SLM) technique with the material of AlSi10Mg powder. All the manufactured specimens are subjected to quasi-static and cyclic compressive loading conditions to evaluate the mechanical strength and fatigue properties. The experimental results from the compression tests are compared under each category and further investigated with scanning electron microscope (SEM) to observe the fracture locations in a more detailed manner, as well as analyze the overhang regions and surface roughness. In addition, the chemical etching technique is also introduced for the analysis of microstructure and grain size distributions through optical microscopy. Furthermore, CT scans will also be used for the purpose of measuring geometrical deviations of the lattice structures. Finally, conclusions are obtained based on the analysis of surface roughness, failure locations, internal porosities as well as geometrical accuracy.

# #092 Wall thickness effect on the quasi-static compression and fatigue properties of Inconel 718 uniform sheet-based lattice structures fabricated via Selective Laser Melting

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*Thickness effect* *Inconel 718* *Selective Laser Melting*

**Abstract** Additive manufacturing (AM) technology has unlocked the possibilities of fabricating complex structures of components such as lattice structures, which are preciously unattainable through traditional manufacturing techniques. According to the recent literature review, the mechanical properties of traditionally designed components fabricated via AM technology are significantly dependent on the thickness of the components. The significance of the thickness effect on more complicated structures such as lattice structures has not been completely investigated yet, especially for metallic lattice structures. Therefore, this research aims to study the wall thickness effect on the mechanical performance of sheet-based lattice structures under quasi-static compression and fatigue loading conditions. All the lattice structures were fabricated via selective laser melting (SLM) technology with the material of Inconel 718 power where the nominal relative densities of 12.5%, 25%, 37.5%, and 50% were considered, which resulted in different wall thicknesses of each geometry. First, all the specimens were heat treated and then tested under cyclic compressive loading conditions to obtain the fatigue data for each respective relative density. In addition, the experimental results from the compression fatigue tests were compared among each relative density and further analyzed with Scanning Electron Microscope (SEM) to observe the fatigue failure locations in a more detailed method, as well as the surface roughness and overhangs regions. Furthermore, metallurgical samples extracted from the SLM lattice specimens were subjected to chemical etching to analyze microstructure and grain size distributions through both optical and digital microscopy. CT scans were performed in order to have a clear understanding of the geometrical accuracy and possible internal defects in the components. Conclusions are drawn on the thickness dependency of the fatigue performance of SLM Inconel 718 lattice specimens based on the analysis of surface roughness, internal porosity as well as dimensional accuracy.

# #093 Numerical investigation of laser beam-welded AA2198 joints under different artificial ageing conditions

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*Al-Cu-Li alloy* *Laser beam welding* *Finite element method*

**Abstract** Nowadays, aircraft industries mainly focus on the development of lightweight structural materials with high specific mechanical properties and good weldability. Lithium (Li) is the lightest metallic element with low density therefore it was introduced to aluminum alloys to reduce structural weight. It is estimated that by using high strength Al-Cu-Li alloys such as AA2198, the structural weight can be reduced by about 10-15 % while its stiffness can be increase by 20 %. A further reduction in structural weight and manufacturing costs can be achieved with the introduction of advanced welding methods, as alternative-joining processes to replace conventional rivets. Laser beam-welding (LBW) as a joining technique is already established in the aerospace industry, due to higher buckling strength and lower weight by replacing the conventical riveted differential structures.

In the present work, local tensile mechanical properties of the laser beam-welded joints of Al-Cu-Li AA2198 alloy with Al-Si AA4047 filler wire were experimentally investigated using micro-flat tensile (MFT) specimens. The MFT specimens were extracted from the fusion zone (FZ) and heat-affected zone (HAZ). The effect of post welding heat treatment (PWHT) on the local tensile mechanical behavior of the welded joints was also studied under different artificial ageing conditions at 170 $^{o}$C, i.e., under-ageing (UA), peak-ageing (PA) and over-ageing (OA). The experimental results were used as an input to a finite element model to investigate the effect of weld geometry and geometrical imperfections on the developed stress and strain fields in the welded joint under axial loading.

The experimental results showed that the chemical composition of the filler wire affects the local mechanical properties in the FZ, which present a decrease by about 26 % in yield strength from the radiation exposure side to the weld root side. The FE results show that the maximum strain was observed in the lower region of the FZ for the weld angles of 90$^{o}$ and 85$^{o}$, while for lower weld angle 80$^{o}$ the position of the maximum strain was observed between the upper and the middle region of the FZ, which can be attributed to the change of the weld width that is smaller in the lower region due to the respective effect of the angle. By applying PWHT, maximum strain concentration can be noticed in the upper region of the FZ for all the ageing times independently the geometrical imperfections

# #094 Experimental research on high cycle fatigue failure of hot forging tool steels

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*Hot forging tool steel* *High cycle fatigue* *Corrosion fatigue*

**Abstract** Hot forging tool steels are extensively utilized for manufacturing of die casting tools because of their outstanding mechanical properties. Nevertheless, these components are subjected to remarkable thermal and mechanical stresses, which limit their service life and therefore inflate the money invested in tool upkeep by many different sectors. This fact is further aggravated when these steels operate in contact with a corrosive medium or under an aggressive environment. The present study deals with the analysis of high cycle fatigue (HCF) behavior of H13 steels under normal conditions and in presence of a saline solution.

The H13 steel resultant from an electroslag remelting (ESR) manufacturing process was heat treated, machined and polished. Axial fatigue tests were performed on the obtained specimens applying different load ranges with the same stress ratio and loading frequency in order to get the Wöhler diagram. Likewise, fatigue tests were developed on specimens while they were put in contact with a NaCl solution. Fracture surface analysis was carried out to assess the mechanisms that lead to the failure of the specimens.

The results showed that fatigue behavior of this steel is significantly weakened in a corrosive environment. The S-N diagram obtained from the corrosion fatigue tests was steeper. As a result, differences in fatigue lives were greater at lower stress levels than at higher ones. Under normal test conditions, most fracture surfaces presented a single crack initiation point located at the surface of the specimen. However, SEM images revealed the presence of non-metallic inclusions that promoted internal crack initiation in few specimens. These inclusions are defects originated through the ESR process, that act as stress concentrators and likely worsen fatigue behavior of the steel. In corrosion fatigue tests, crack initiation is advanced due to the generation of corrosion pits, which require a certain amount of time to be formed. Therefore, cycles to failure are expected to increase with higher loading frequency and lower salt concentration.

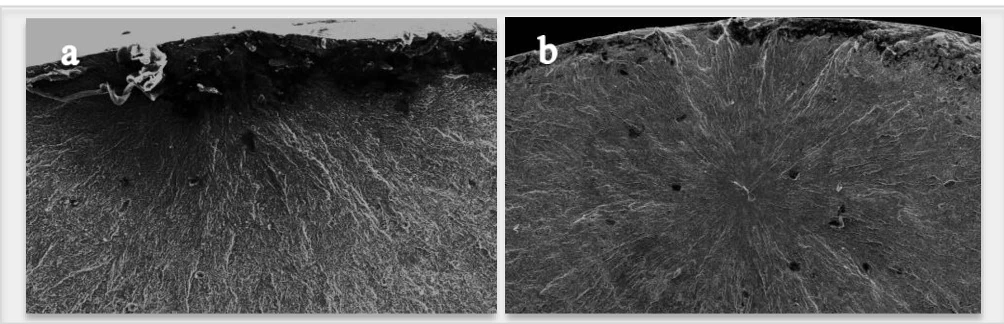


***Figure 1*** *– SEM images of crack initiation (a) at the surface and (b) inside the H13 specimen*

# #095 Experimental study of strength and fracture toughness of laser-blasted glass

Erik Calvo-García[1,2], Rafael Comesaña[1,2], Antonio Riveiro[1,2], Jesús del Val[1], Aida Badaoui[2], Félix Quintero[1,3], Mohamed Boutinguiza[1,3], Fernando Lusquiños[1,3], Juan Pou[1,3]

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*Keywords: Glass laser blasting fracture toughness, strength*

**Abstract** The use of glass in structural applications has been increasing during last years. Nevertheless, the generalized use of surface-modified bearing glass is precluded by the lack of knowledge about their mechanical performance. This experimental investigation carries out the assessment of the fracture toughness and strength of glass subjected to laser blasting.

Annealed glass and heat strengthened glass plates were subjected to mid-infrared laser surface treatment to increase the surface roughness and improve the slip resistance in wet conditions. The fracture toughness and fracture surface energy was experimentally determined from the observed radial cracks after micro-indentation with a pyramidal diamond indenter, and the results were analyzed in correlation to the laser processing conditions and the obtained surface roughness. The Weibull graph and the cumulative failure probability of the as-received and laser-modified glass were obtained by the four-point bending test with fifteen repetitions.

It is observed that the fracture toughness of the laser-blasted annealed glass is clearly reduced by increments of the laser optical density on the sample surface. A maximum value of 0.95 $MPa \cdot m^{1/2}$ and minimum value of 0.43 $MPa \cdot m^{1/2}$ were obtained. On the contrary, the fracture toughness of the heat strengthened glass within the explored laser-blasting processing window remained constant around 1.12 $MPa \cdot m^{1/2}$ . Regarding the obtained parameters of the Weibull distribution, it is observed 33 % and 26% reduction of the characteristic strength of the annealed and heat strengthened glass, respectively. The Weibull modulus was increased, resulting in a narrow distribution of failure stress after laser processing.

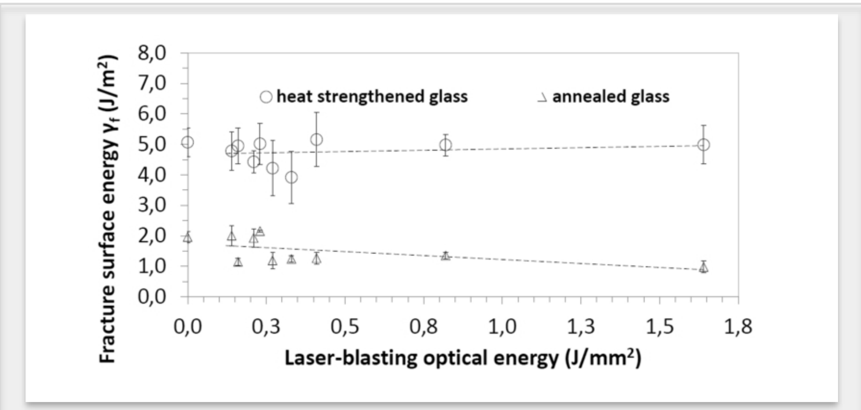


***Figure 1*** *– Experimental fracture surf. energy as a function of the laser-blasting energy.*

# #096 3D Computational Welding Mechanics applied to IN625 Nickel-Base Alloy

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*Inconel 625* *Multi-run arc welding* *Welding simulation*

**Abstract** Design for sustainability asks for higher and higher performance materials and enhanced techniques devoted to realizing their joints. For Advanced-Ultra Supercritical applications, the emphasis is on high-temperature strength, long-term creep life, phase stability, oxidation resistance, and robust and flexible welding processes. In this scenario, Ni-based superalloy Inconel 625 is successfully used for mechanical components operating at high temperatures and stresses, conditions that however may cause surface cracks. In the frame of circular economy, fusion welding is therefore used as a convenient repairing technique, as well. However, correct process parameters avoiding metallurgical and mechanical defects need to be known for each case-study. Computational welding mechanics is a proper tool used to reach that goal, provided that the model is able to capture the main phenomena involved in the welding process. In this work, a 3D numerical model of Inconel 625 multi-pass welding process is developed and validated through residual stresses X-Ray diffraction measurements. The model showed a good accuracy (Fig. 1) and was therefore proved to be a powerful tool for welding process design of such alloy.

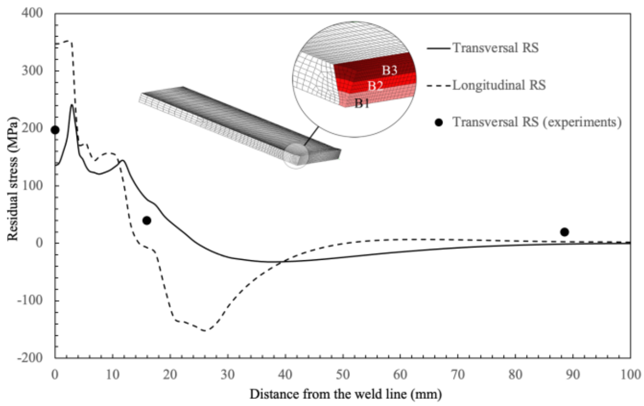


***Figure 1*** *– Residual stress: comparison between experimental and numerical results.*

# #097 Probabilistic Reliability Assessment of Laser Beam Welded Ti-6Al-4V Components in the Presence of Internal Defects

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*Internal Defects* *Probabilistic Modelling* *Laser Beam Welding*

**Abstract** Laser beam welded joints or laser additive manufactured structural components always contain metallurgical defects as a result of a manufacturing process. Typical examples of defects are pores, non-metallic inclusions, cavities, lack of fusion or corrosion pits. These metal discontinuities act as stress raisers (notches) and lead to premature crack formation in the early stages of fatigue life. Therefore laser-based manufactured structures are particularly susceptible to fatigue cracking due to stress concentration at the surface and internal material defects. Despite significant benefits provided by the laser-based manufacturing techniques, there is still a lack of understanding, how these parts fail under cyclic loading. Therefore, this study aims to investigate the effect of internal material defects on the high cycle fatigue behaviour of laser processed Ti-6Al-4V. It is shown, that internal fish-eye fatigue fracture is a dominant failure mode if a subsequent surface treatment technique is applied. A probabilistic lifetime assessment framework for predicting the joint durability and its scatter in the high cycle fatigue regime is developed (Figure 1). A good agreement between the modelling and experimental results is achieved.

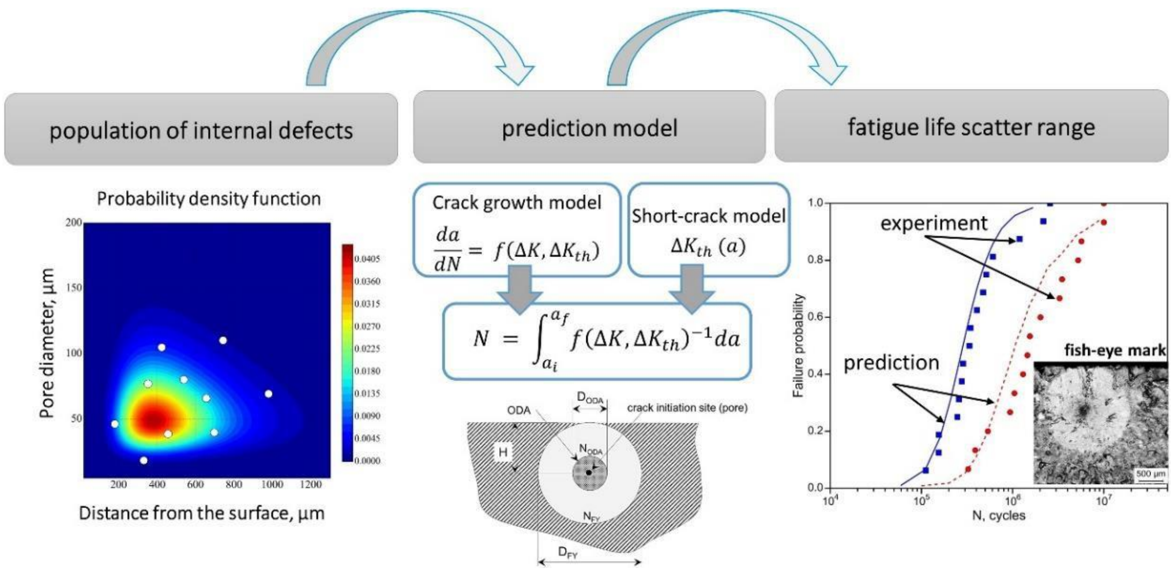


***Figure 1** - Schematic illustration of the probabilistic modelling for assessment of the lifetime scatter.*

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# #099 Lifetime predictions of notches with small radii in the field of high and very high cycle fatigue

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*Lifetime predictions* *Notches with small radii* *Very high cycle fatigue*

**Abstract** This research deals with the formulation and application of a method for fatigue lifetime predictions of notched components in the field of high and very high-cycle fatigue. An ultrasonic fatigue testing machine was used for experimental part of the study to perform fatigue tests at a frequency of 20 kHz. The method for lifetime predictions is based on the theory of critical distance, specifically the line method [1, 2], and uses numerical calculations for axial stress distribution over the narrowest cross section of specimens. The introduced method for lifetime predictions of notched components uses the critical length parameter $l$. This parameter $l$ depends on the number of cycles to fracture. The lifetime predictions were compared to experimental fatigue data of specimens with various notch radii. The smallest difference between predicted fatigue data and experimentally obtained values is observed for notches with small radii, where the critical length parameter is most stable over the range from $10^6$ to $10^{10}$ fatigue cycles. Detail comparision is shown in fig. 1.

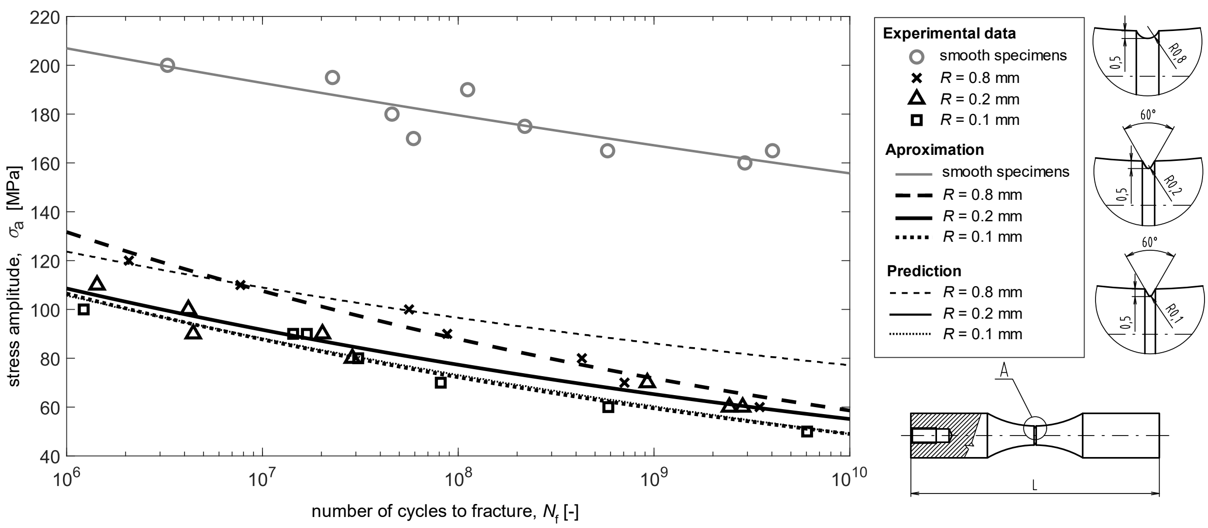


***Figure 1** – Experimental data and predictions*

**Acknowledgment** The research was supported by the Czech Science Foundation, project No. 21-14886S.

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# #100 CTOD Evaluation Of Api X80mo Psl2 Tmcp Steel Welded Joints Used In Offshore Structures Based On Api Rp 2z

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*APIX80MO TMCP Steel* *Heat affected zone* *CTOD*

**Abstract** Offshore structures and equipment, used both for oil extraction and wind power generation, are constantly exposed to extreme application conditions, such as low temperatures, corrosion and cyclic loading. Thus, to ensure the integrity of such components, the use of materials with excellent mechanical properties together with good weldability is required. In this sense, the main committees, institutes and normative societies created pre-qualifications, codes and programs to evaluate and certify the weldability of steels applied in the offshore industry. API RP 2Z prequalification is one such standard and is designed to ensure that steels developed for these applications have excellent fracture toughness in the heat affected zone (HAZ). In this context, the effect of heat input and post-weld heat treatment (PWHT) on the HAZ toughness of welded joints of API X80MO steel plates was evaluated, using the CTOD (Crack Tip Opening Displacement) parameter. It was found that this steel, of 37 mm thickness, welded with heat inputs of 0.8 and 4.5 kJ/mm, with and without the application of PWHT, presented weldability characteristics and results fracture toughness suitable for APIRP2Z standard requirements. Therefore, API X80MO steel plates, produced by controlled rolling followed by accelerated cooling, is an option for application in the construction of offshore structures and components.

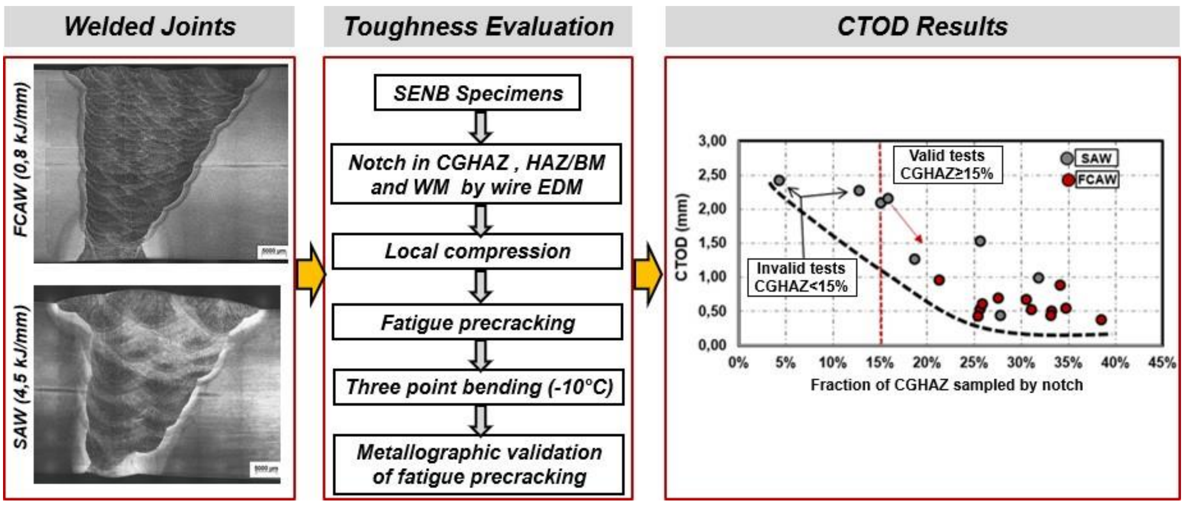


***Figure 1*** *- Summary flowchart of the work.*

# #101 Investigation into Mechanical Properties and Failure Mechanisms of Novel Sandwich Composite Material with Carbon Fibre/Epoxy Facesheets and PVC Foam Core

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*Sandwich Composites* *Failure Mechanisms* *Carbon Fibre/Epoxy Laminates*

**Abstract** Sandwich composite materials have seen a significant increase in use across various engineering fields and applications due to their exceptional mechanical properties, including high specific strength and bending stiffness values. Because of their high strength properties, the use of sandwich structures is preferred in different industries. It is crucial to investigate material properties of novel composites in order to estimate their failure mechanisms under different loading types. In this study, a Carbon Fibre/Epoxy Facesheets with two different dimensions and PVC Foam Core sandwich composite was designed and fabricated. The selection of PVC foam for this study is motivated by its wide use in load bearing components in different industries. The sandwich composite material used for the experiments was manufactured by using vacuum-assisted resin infusion moulding process (VARIM) by IZOREEL in Izmir, Turkey. Failure styles of the structure in compression, shearing and bending were revealed by sandwich flatwise tension, core flatwise compression, sandwich edgewise compression tests. Facesheet bending of manufactured composites have been investigated experimentally. Tensile strength of the facesheets and sandwich material have been presented separately. The analytical solution is derived to calculate the flexural rigidity, shear stresses and maximum tensile, compression stresses in three-point bending specimens for the sandwich composite. The detailed formulations and procedures were provided. The obtained results are discussed, and it is seen that maximum tensile and compression stresses in the three-point bending test depend on the direction of the loading with respect to different facesheet thickness.

# #102 Usage of Nanomaterials on Carbon Fibre/Epoxy Composites for Improvement on Their Material Properties

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*Carbon Fibre Cloth* *Carbon Nanotubes* *Nanomaterials*

**Abstract** Composite materials are mostly chosen due to their high strength to weight and stiffness to weight ratios and widely used by different industries. On the other hand, smart materials have created their own importance in all areas of science and technology especially as design materials for civil engineering applications. Carbon Fibre composites provide civil engineers with an extensive use of construction materials for construction of numerous structures and engineering applications. The widespread adoption of composites in addition to advanced technology allows engineers to maximise on reduced failure. However, failure reasons in these composite materials should not be ignored and should be studied ambiguously and thoroughly. This study presents the study of several Carbon Fibre/Epoxy composites with and without nanomaterials obtaining their material properties and studying their flexural and tensile strengths.

First of all, 200g 2x2 Twill 3K Black Carbon Fibre cloth with EL2 Epoxy neat resin and 450g 2×2 Twill 12k Carbon Fibre cloth with EL2 Epoxy neat resin were used in order to manufacture two different composite materials due to their high usage in construction industry. Hand lay-out technique was used for all manufacturing process of composite materials. A vacuum is applied between the mould and bag to squeeze the resin/reinforcement together and remove any air. Tensile testing and 3-point bending testing procedures were applied to both composite materials. Elasticity Modulus of composites were presented.

Second, EPOCYL 128-06 Carbon Nanotubes concentrates were added to EL2 Epoxy neat resin as additives in order to enhance its mechanical properties for the study. 200g 2x2 Twill 3K Black Carbon Fibre cloth with EL2 Epoxy neat resin and EPOCYL 128-06 Carbon Nanotubes and then, 450g 2×2 Twill 12k Carbon Fibre cloth with EL2 Epoxy neat resin and EPOCYL 128-06 Carbon Nanotubes were used to manufacture two different composite materials with nanomaterial. Hand lay-out technique was used for all manufacturing process of composite materials with nanomaterials as well. Tensile testing and 3-point bending testing procedures were applied to both composite materials with Carbon Nanotubes. Elasticity Modulus of composites with Carbon Nanotubes were presented.

Material properties, tensile strength and flexural strength of all materials have been obtained. The experimental procedures were completed to determine the strengthening effect of Carbon Nanotubes. Comparison between composites with different Carbon Fibre weight as well as between composites with and without Carbon Nanotubes were discussed in detail. The level of increase in flexural and tensile properties in composite laminates were presented.

# #103 Mixed mode crack initiation from square holes

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*Square hole* *Finite Fracture Mechanics* *Mode mixity*

**Abstract** In this work, mixed mode crack initiation from square holed plates under uniform remote uniaxial tension is analysed. As the hole size decreases, the mode mixity increases: thus, both the modulus of the crack deflection (with respect to the V-notch bisector) and the failure load increase. This behaviour is caught experimentally by carrying out ad hoc tensile tests on PMMA notched samples. In order to get accurate theoretical predictions, the coupled Finite Fracture Mechanics (FFM) approach is employed numerically through a full finite element analysis (FEA) and analytically by an asymptotic matching (AM) expansion. The tensile strength and the fracture toughness i.e., the two material properties involved by FFM, are identified by testing circular holes with different sizes. The FFM results are in good agreement with recorded data, despite the great scatter observed for certain sizes, especially as regards the crack deflection angle, which may be imputable to the notch radius effect and damage during the machining procedure.

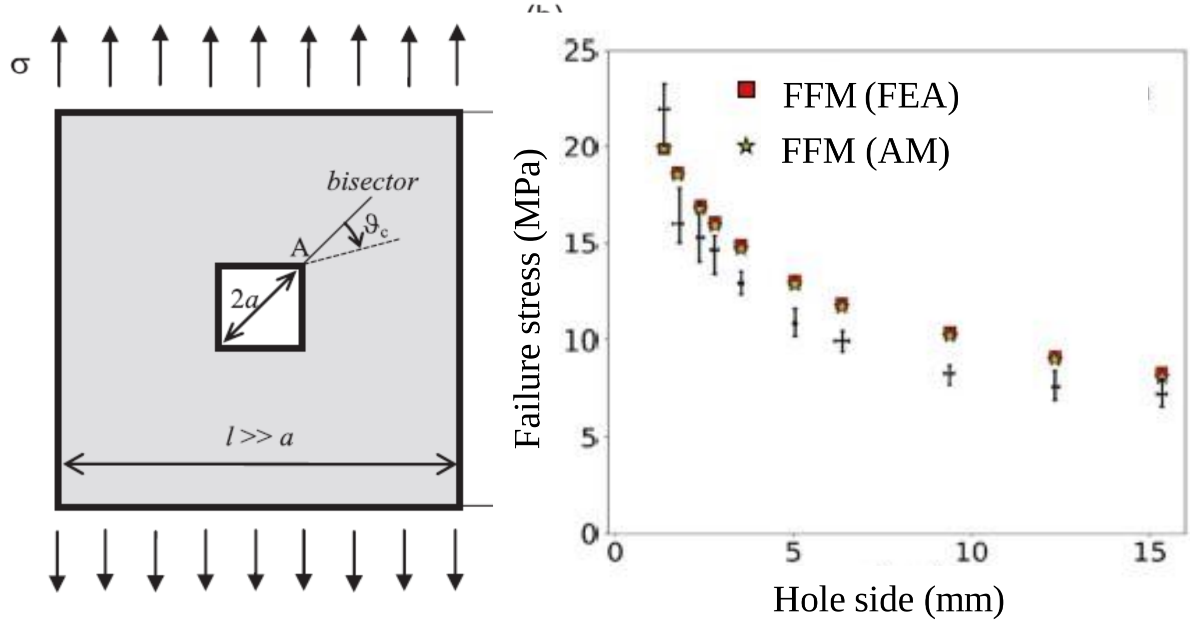


***Figure 1** - Square holed plates and comparison between experimental and FFM results.*

# #104 Experimental investigation of Dynamic strain localization in Additively manufactured Titanium alloys

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*High strain rate* *Additive manufacturing* *Digital image correlation*

*Titanium alloys*

**Abstract** Titanium alloys have been the prime choice in various applications such as aerospace, defense, automobile and medical engineering thanks to their specific strength and good corrosion resistance. Additive manufacturing (AM) has become a popular manufacturing method, as it is able to overcome the limitations presented by traditional manufacturing techniques. AM allows the generation of any complex shape while bypassing the time constrains and multiple steps required by traditional manufacturing processes. The present study investigates the high rate deformation behavior of SLM produced Ti6Al4V alloy using a split-Hopkinson tensile bar equipped with ultra-high speed imaging equipment. A detailed experimental campaign is conducted for three different layup directions and their influence on the dynamic strain localization and true stress-true strain response is analyzed. The post necking behavior is investigated and compared to traditional Ti64. Furthermore, a numerical model is established using the commercially available LSDYNA-Explicit solver for low and high strain rate loading conditions. A numerical study is conducted to analyse the stress-state in the necked section and its dependency on the directionality.

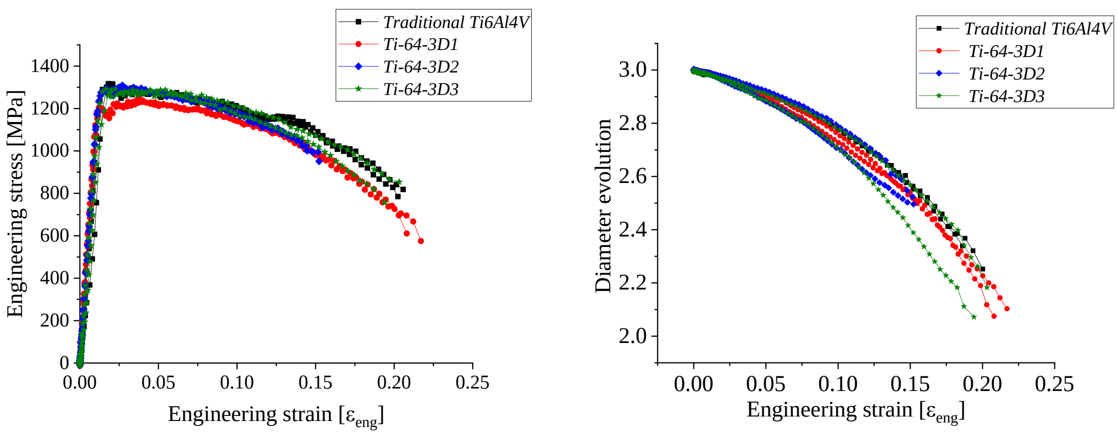


*Figure 1: Engineering stress -strain response and evolution of necking diameter for traditional and additively manufactured Ti6Al4V.*

# #105 Assessment of the influence of the process parameters selection on fatigue life of laser powder bed fusion-fabricated Ti-6Al-4V

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*Additive Manufacturing* *Defects* *Fatigue life prediction*

**Abstract** Laser Powder Bed Fusion – Additive Manufacturing (LPBF-AM) process has been utilized for the fabrication of structural parts with complex geometries which were very difficult to be fabricated with conventional manufacturing methods (Jiménez et al., 2019). One of the most common materials for the LPBF process is Ti-6Al-4V metal alloy that is characterized by its high strength and low density, high corrosion resistance, heat treatability and excellent biocompatibility (Becker and Dhansay, 2021). For this reason, the use of LPBF-AM process with Ti-6Al-4V is very attractive for aerospace, automotive and biomedical applications. However, the development of residual stresses, the formation of process-induced defects, the rough surface finish and the brittle microstructure affect the material's performance significantly and consequently the overall fatigue life and structural integrity of a LPBF component.

The process-induced defects detrimentally affect the fatigue strength of LPBF Ti-6Al-4V material. The main types of defects found in LPBF parts include lack-of-fusion, keyhole and gas pores. These defects may be formed either by improper selection of process parameters or by process instabilities (Snow et al., 2020). Lack-of-fusion and keyhole defects usually result from insufficient and excessive amount of input volumetric energy density, respectively (Gong et al., 2014). Although, process optimization may lead to a minimum porosity in LPBF parts, a certain amount of defects has been observed in literature works (Sanaei and Fatemi, 2020) and these defects serve as stress raisers and fatigue crack initiation sites.

In the present work, the influence of the process parameters on the fatigue life of LPBF Ti-6Al-4V is investigated through a predictive framework. First, the prediction of the areas susceptible for defect formation in coupons is performed through a simulation of the LPBF process with a finite element model for various process parameters combinations. Then, a fracture mechanics modelling approach for fatigue life prediction is implemented to assess the effect of defect on fatigue life of LPBF Ti-6Al-4V material. Literature available small fatigue crack growth rates of AM Ti-6Al-4V are used as an input to the defect-based model as the defects are treated as small cracks whose plastic zone is generally neglected (Zhai et al., 2016).

# #106 Efficient Thermomechanical Modelling and Simulation of Laser Powder Bed Fusion process for the Prediction of Residual Stresses of Parts

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*Simulation* *Additive Manufacturing* *Residual Stresses*

**Abstract** Laser Powder Bed Fusion Additive Manufacturing (LPBF-AM) process utilises a laser beam to selectively melt metal powder on a substrate to fabricate a layer-by-layer part with a desired shape. LPBF-AM technique offers superior design freedom, reproducibility and dimensional accuracy for part production [1]. For these reasons, LPBF process has attracted the interest of research and industrial communities. One the challenges to the wide adoption of the technology for the fabrication of reliable and safe critical parts are process-induced residual stress and distortion fields. Residual stresses are inherent to thermal manufacturing processes such as AM processes and LPBF parts are susceptible to build defects and failure associated with residual stresses during their fabrication [2]. Therefore, the prediction of residual stresses and distortions of an LPBF part is critical to ensure the quality and the performance of a part.

In the present work, the development of a numerical modelling technique for the prediction of residual stresses and distortions of LPBF fabricated parts is presented. A coupled thermo-mechanical analysis is utilized to simulate the building conditions of the LPBF process. Most of the process parameters that significantly affect the thermal conditions are used as input parameters in the modelling method. The well-known element birth and death technique is utilized to simulate the layer addition during the LPBF process [3]. To efficient simulate the process many layers are appropriately lumped to a larger one. Every lumped layer is gradually set to the melting temperature of the metal powder material to reproduce the temperature field during the LPBF process. Consequently, the estimated thermal fields are imported into the mechanical model as predefined fields. Temperatures are automatically mapped between thermal and structural analyses and the thermal expansion drives the deformation of the building part. The residual stresses and distortions of the building part are estimated at the end of the analysis on each lumped layer and on the substrate. Moreover, different meshing techniques are employed and their accuracy and efficiency is assessed.

To test the accuracy of the proposed LPBF numerical modelling methodology, comparisons with available experimental results was performed [4]. The comparison between numerical and experimental results successfully validated the numerical modelling method, making it a suitable and efficient modelling strategy for the simulation of LPBF parts, towards the estimation of the level of residual stresses and distortions.

# #107 Fatigue enhancement using lattice structures for geometrical tailoring

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*Additive Manufacturing* *Lattice Structures* *Notch Mechanics*

**Abstract** In the design of mechanical components and structures, the presence of geometrical discontinuities is unavoidable. These geometrical discontinuities are usually the weakest points of the structure and act as stress raisers and therefore prone to local failure under mechanical loading. Therefore, it is of great importance to control the stress level around these areas to prevent early failure of the structure. The present paper will focus on investigating case studies where the stress concentration around the notch has been minimized by incorporating lattice structures around the main geometrical discontinuities for achieving enhanced fatigue strength. For this aim, several cases of geometrically tailored notched specimens were studied by performing numerical and experimental analyses and the effect of geometrical tailoring on the fatigue behavior has been evaluated. The specimens were additively manufactured and tested under cyclic loading. According to the experimental analysis, controlling the stress condition in the notched specimens eventually led to better mechanical performance under cyclic loading condition.

# #108 Measurement of strain and temperature by fiber-optic sensors embedded in samples obtained using additive technology

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*Fiber-optic sensors* *Additive technologies* *Strain and temperature measurements*

**Abstract** Fiber-optic sensors (FOS) are widely used in various fields of technology, industry and medicine due to their high sensitivity and accuracy of measurements, the ability to provide measurements in difficult environmental conditions. Due to the small dimensions of FOS they can be embedded in the controlled material at the manufacturing stage, expanding the possibilities of registering the mechanical state during production and operation. At present, the direction of additive technologies is actively developing, which allows to significantly reduce the development and design time. One of the most common materials used in the manufacture of structures using additive technologies are thermoplastic materials, which are subjected to significant temperature changes, technological strains and shrinkage during the manufacturing process.

The paper demonstrates the possibility of using embedded fiber-optic sensors for registering the mechanical state data of structures (strain, temperature) made by fused deposition modeling (FDM) technology from thermoplastic material at the stages of manufacturing and loading the finished structure.

An experimental demonstration of strain and temperature measurement using embedded fiber-optic sensors was carried out on the example of samples in the form of equal strength beam. The process of creating a sample with embedded optical fiber lines with temperature and strain FOS is described. A change in strains was registered during the sample printing and after printing was completed. It is shown that the main process of formation of technological compression strains begins after the end of the printing process. Comparison of the results of numerical simulation and experiment under loading of the finished sample with embedded FOS is carried out.

# #109 Analysis of the notch effect of weld joint

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*Notch* *Weld joint* *Fatigue*

**Abstract** In general, the welded joints are multifactorial notches. The article summarizes preview results of the published experimental methodology of separation of two main components of total notch effect of weld: geometrical notch factor (when the weld can be seen on the surface) and technological notch factor (internal defects of the weld joint, structural changes of the material and residual stress). Experimental results are analyzed to create a numerical FEM model. Methodology of FEM model creation will be presented. Results of numerical simulations of geometric notch of weld will be confronted with experimental results. The result of the numerical simulation can be an expression of the influence of the external weld geometry on the weld joint fatigue lifetime. The effect of removing this geometry on outside surface to the fatigue lifetime of the weld joint will be discussed.

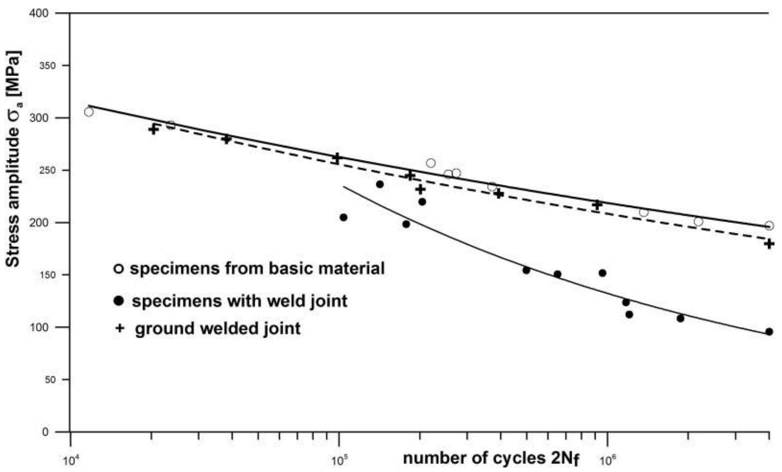


***Figure 1*** Fatigue lifetime curves of those three specimen groups mentioned above (with the weld, without weld and with removed weld geometry) will be the basic for separation of the overall notch effect of the weld joint.

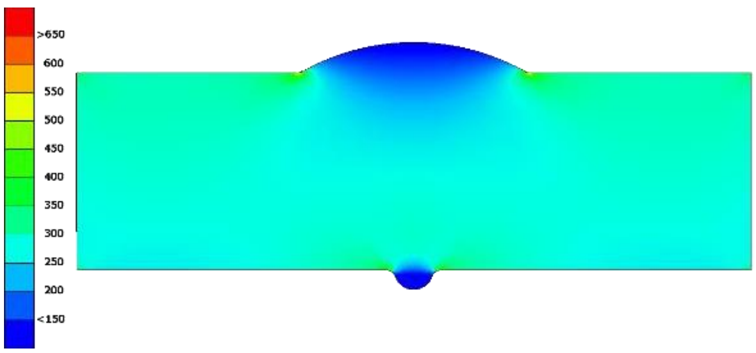


***Figure 2*** FEM simulation of the V-weld of two pipes.

# #110 Influence of additional factors on the integrity of pipelines with small corrosion defects

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Pipeline *Corrosion defects* *Integrity*

**Abstract** The ASME and DNV criteria mainly assess large area defects on pressure pipelines. For small corrosion defects, the use of these approaches leads to unduly conservative results for the assessment of pipeline integrity. In the operation of piping systems, the most common cause of accidents is the synergy of multiple effects on the piping. This paper will analyze the cases of small corrosion defects when additional bending acts together on a pressure pipeline. Through experimentally validated simulations, diagrams can be produced to assess the safety of pipeline operation: e.g. for nominal stress from internal pressure, corrosion defect size and length of the deflected pipeline, an increase in stress with increasing deflection size from the original pipeline centerline can be seen (Fig.1).

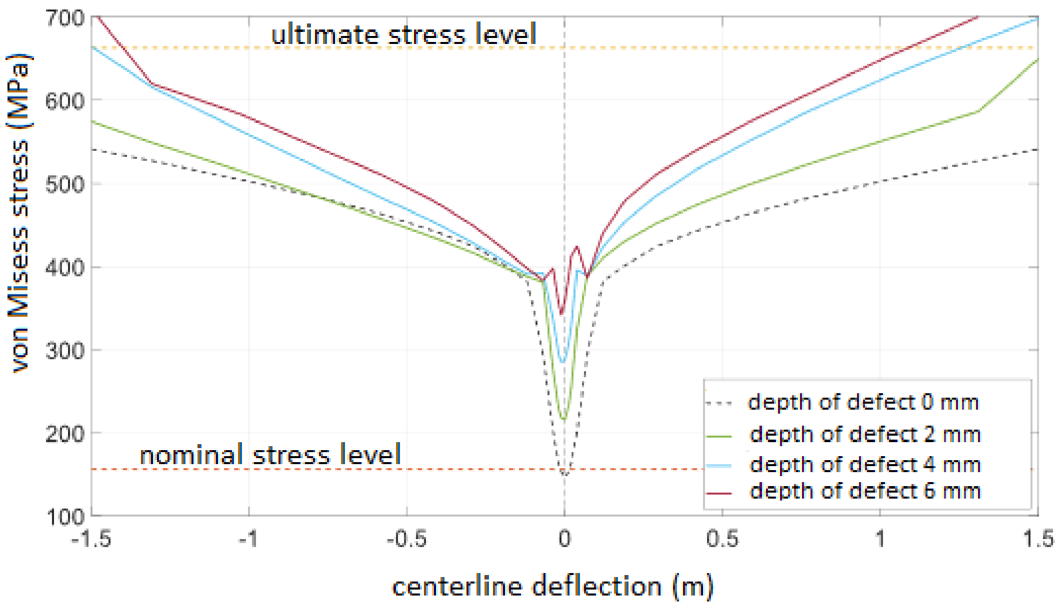


***Figure 1** Effect of additional bending (centerline deflection) on the magnitude of stresses in a corrosion defect.*

# #111 The Beneficial Effect of Autofrettage on the Combined 3-D Stress Intensity Factors for Inner Radial Crack Arrays in a Spherical Pressure Vessel

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**Abstract** The distributions of the combined 3-D Stress Intensity Factor (SIF), $K_{IN}=K_{IP}+K_{IA}$, due to internal pressure and to autofrettage along the front of radial crack arrays emanating from the bore of an overstrained spherical pressure vessel are evaluated. The 3-D analysis is performed using the finite element (FE) method employing singular elements along the crack front. A novel realistic autofrettage residual stress field incorporating the Bauschinger effect is applied to the vessel. The residual stress field is simulated using an equivalent temperature field in the FE analysis. Numerous radial crack array configurations are analyzed. SIF distributions are evaluated for arrays of radial cracks containing one to twenty cracks, $n$=1-20, of crack depth to wall thickness ratios of **a/t**=0.01-0.8, and ellipticities (crack depth to crack length) of $a/c$=0.2-1.0 prevailing in fully or partially autofrettaged spherical vessels of outer to inner radii $R_0/R_i$=1.1, 1.2, and 1.7, bearing three levels of autofrettage ($\varepsilon$ =50%, 75%, and 100%). A detailed study of the influence of the above parameters on the prevailing SIF is conducted. A few general conclusions regarding radial crack arrays emanating from the inner surface of an autofrettaged spherical vessel can be drawn from the above analysis:

a. As the number of cracks in the array increases, the combined SIF decreases along the entire crack front as a result of crack interaction. This interaction starts in arrays containing $n \geq 10$ cracks, of depths $a/t \geq 0.2$, for moderately thick vessels, $R_0/R_i$=1.2, and for cracks deeper than $a/t \geq 0.1$ in thick vessels $R_0/R_i$=1.7.
b. The beneficial effect of autofrettage decreases as the number of cracks in the array increases. However, in the most critical part of the vessel's fatigue life when the cracks are very small, the number of cracks in the array has almost no influence on the combined SIF.
c. In the case of thick vessels, $R_0/R_i$=1.7, the critical crack configuration consists of n=4 cracks. For a thinner vessel such as $R_0/R_i$=1.2, the results for arrays of n=1-8 are practically identical. Therefore, n=1 can be considered as the critical crack configuration.
d. The influence of the number of cracks in the array intensifies with crack depth and with the vessel's wall thickness. Therefore, the presence of multiple cracks will mainly affect the fatigue life of relatively thick spherical pressure vessels that attain rather deep cracks before reaching catastrophic fracture. The total fatigue life in all other cases can be estimated based on a single crack.
e. The results emphasize the importance of properly accounting for the Bauschinger effect including re-yielding, as well as the significance of the three-dimensional analysis herein performed.

[1] Aaron Fish Professor Emeritus of Mechanical Engineering-Fracture Mechanics and Graduate student respectively.
[2] Presently, PhD student, Faculty of Aerospace Engineering, Technion Israel Institute of Technology, Haifa, Israel.

# #113 Evaluation of Static Fatigue Life of Ultra-High-Strength Steel under Stress Corrosion Environment

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*Static fatigue* *Corrosion environment* *Hydrogen-assisted cracking*

**Abstract** Ultra-high-strength steel (UHSS) structures are exposed to corrosive environments during service, and hydrogen-assisted cracking (HAC) may occur owing to stress corrosion cracking and hydrogen embrittlement. In this study, the HAC threshold stress intensity factor and fatigue life of UHSS steel are evaluated by applying stress in a corrosive environment to prevent structural fracture. On the surface of cracks, grain boundaries are embrittled by corrosion, and grains are clearly observed. Meanwhile, cracks in the surface direction propagate slightly, unlike cracks in the depth direction. The HAC threshold stress intensity factor of the depth is determined to be 1.96 $MMMMMM\sqrt{mm}$. The static fatigue limit of UHSS (SKD11:HV670) is determined to be 400 MPa, and the fatigue limit of the crack specimen can be evaluated using Equations (2) and (3). The experimental results agree well with the evaluation results.

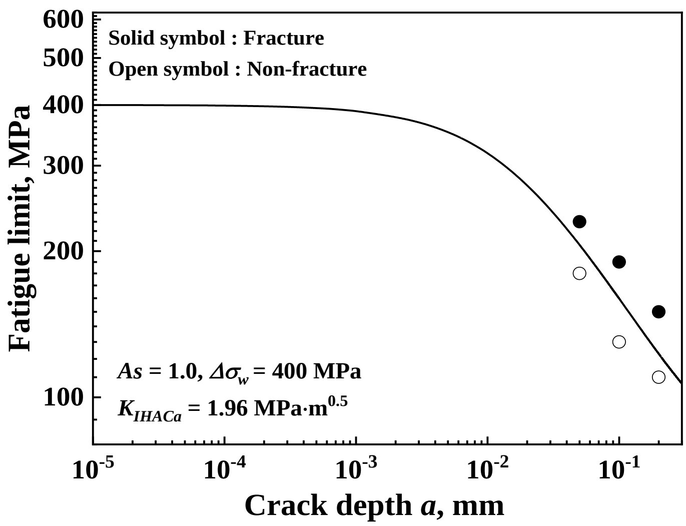


*Figure 1 Relationship between fatigue limit and crack depth.*

# #114 Mechanical and Corrosion Properties of Friction Stir Welded A6061 Aluminum Alloy

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*Friction stir weld* *Mechanical property* *Immersion test*

**Abstract** The mechanical properties and corrosion behavior of Friction Stir Welding (FSW) A6061 aluminum alloy were investigated. In the advanced side (As), the boundary between the base metal (BM) and the nugget zone (NZ) is clear, but the retreating side (Rs) is faint. The grain sizes of the nugget zone (NZ), heat-affected zone (HAZ), and base material (BM) were different from each other. As a result of the hardness test, the minimum and maximum hardness values were obtained in NZ and BM, respectively. As a result of the tensile test, fracture was obliquely along the HAZ in AS of the welding progress direction. It was shown that fracture occurred in the relatively brittle region between NZ and HAZ. Immersion test was conducted at 5wt% NaCl and NaOH solutions. In NaCl, a lot of pitting occurred with the increase of time, but less pitting was observed after a certain time. This is because the corrosion product covered the pitting hole. The size of pitting was in the order HAZ>TMAZ>BM>NZ. However, after the oxide film on the surface was peeled off in NaOH, and then there was little change over time.

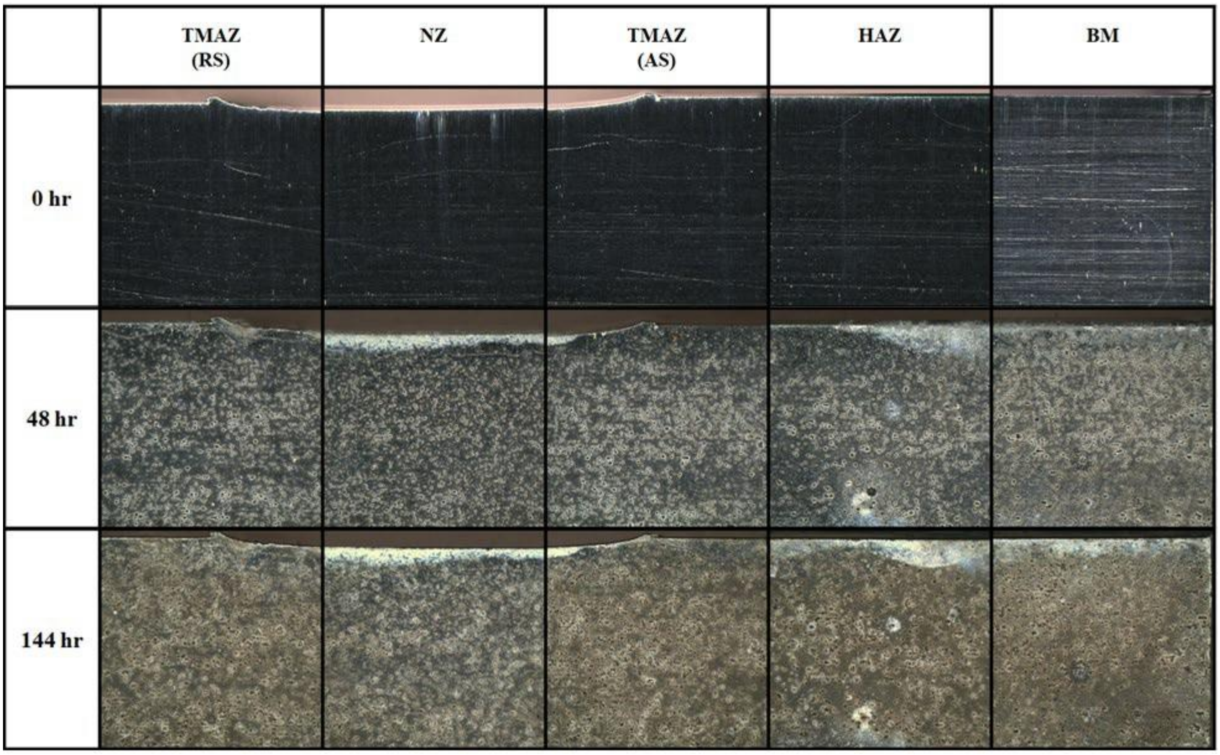


*Figure 1 Appearance in NaCl solution*

# #115 ProCrackPlast: A software for 3D fatigue crack growth simulations under large scale yielding conditions

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*fatigue crack growth* *finite element simulation* *plastic deformations*

**Abstract** If structural components are exposed to intensive cyclic thermal and mechanical loading in their service phase (Low Cycle Fatigue, LCF), the fatigue crack growth is accompanied by large plastic deformations and creep in an extended region around the crack tip. In this case, large scale yielding and loading history of plastic deformation have to be taken into account during crack growth, that's why suitable simulation tools are rare. In order to predict and evaluate such crack behavior, a pragmatic finite element software, ProCrackPlast, is developed for automated simulation of fatigue crack growth in arbitrarily loaded three-dimensional components under large scale inelastic deformations. A special FEM-algorithm is implemented as Python script to conduct the incremental crack growth by successive adaptive remeshing, whereby the deformation fields and internal state variables are mapped from the old mesh onto the new one for each crack growth step. For the pre-processing, the FEM analysis, and the post-processing the commercial software ABAQUS is used, so that any available or user-defined plastic material law can be incorporated. The cyclic crack tip opening displacement (ΔCTOD) is considered as an appropriate fracture mechanical parameter for LCF crack growth and calculated for finite plastic crack tip deformations. Efficient methods are implemented to capture crack tip blunting and to determine ΔCTOD. Finally, some application examples are presented for a typical cast iron, Ni-Resist, to show the capabilities and the performance of ProCrackPlast.

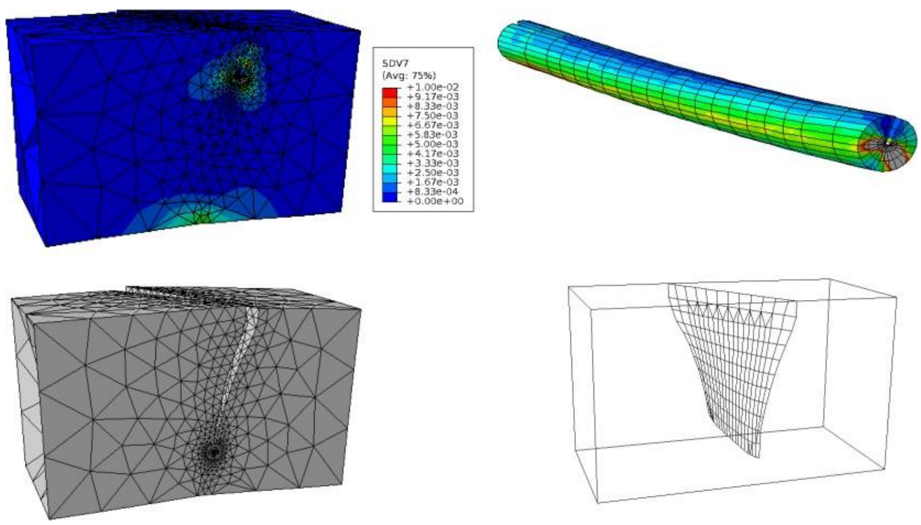


***Figure 1** – Mixed-mode crack growth in a 3PB specimen under LCF (region of crack growth is shown in the Figure); Equivalent inelastic strain in an intermediate crack growth step, the focused mesh around the crack showing the opening; Mesh details of the final crack shape; Final crack surface after the simulation.*

# #116 Biaxial testing of EPDM rubbers for use in the automotive field: development of a fixture for uniaxial testing machines

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*Hyperelastic behavior* *Biaxial static test* *EPDM rubber*

**Abstract** The experimental characterization of hyperelastic mechanical behavior of rubber-like materials is one of the essential preliminaries for the structural design of components made of such materials. The hyperelastic behavior of isotropic rubber-like materials is defined by a strain energy density parameter depending on the right Cauchy-Green invariants [1]. The use of only uniaxial tensile test for the characterization of such strain energy density is insufficient as highlighted in previous researches [1]. A further experimental test, which uses several directions of stretching, is required. Among the various mechanical tests available, the pure shear and the biaxial tensile tests are the most widely employed [2]. In this context, a new fixture (Fig. 1a) has been developed to perform biaxial static tests using a uniaxial testing machine. Finally, the developed fixture has been validated by performing experimental biaxial tensile tests on cruciform specimens (Fig. 1b) made of Ethylene-Propylene-Diene Monomer (EPDM), which is typically employed to manufacture automotive seals.

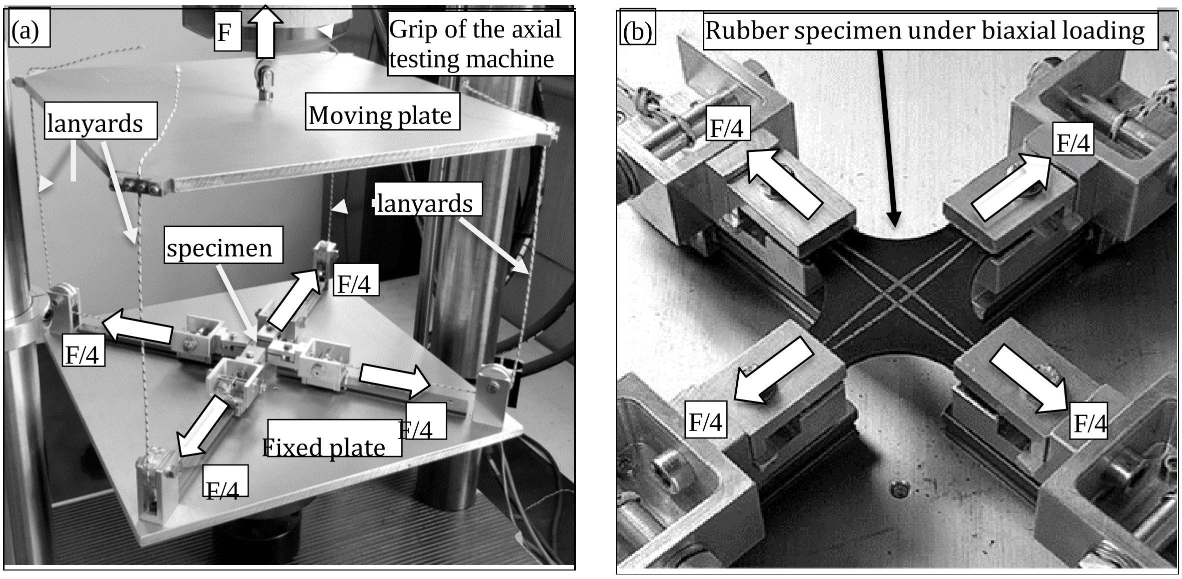


***Figure 1*** *– (a) Developed fixture to perform biaxial testing of rubbers using uniaxial testing machines. (b) Example of EPDM rubber cruciform specimen under biaxial loading.*

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# #117 Qualification of uniform fatigue damage tolerance law for additively manufactured and cast Al-Si alloys


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*High cycle fatigue (HCF)* *Damage tolerance* *Elastic-plastic fracture mechanics*



**Abstract** The demand on light-weight structures and materials are steadily growing in automotive and aerospace industries. Hypo-eutectic Al-Si alloys are promising candidates due to its high specific material strength and corrosion resistance. Near net shape manufacturing by additive manufacturing (AM) and castings e.g. die (DC) or sand casting (SC) allow a high resource efficiency. The complex geometries lead to a high range of structural features due to process-induced variations in local cooling rate. Therefore, the relationships between structural features (e.g. dendrites, grain, eutectic, porosity, lack of fusion) and fatigue behavior have to be understood to enable a light-weight and reliable design of Al-Si alloys. In this study, the effect of process and process-induced structural features on stress-strain behavior (quasi-static, cyclic) and high cycle fatigue behavior at different stress ratios (R = -2, -1, -0.5, 0.1, 0,5) were characterized. The specimens were processed by powder bed fusion with laser beam (PBF-LB, short: AM), die casting (DC) with porosity variation and sand casting (SC) with variation in dendrite arm spacing. Hereby, the age-hardenable Al-Si alloys AlSi10Mg (AM10, SC10) and AlSi7Mg (DC7, SC7) were investigated. AM batches were tested in as-built condition. All casting batches got a T6 heat treatment and selected castings got no HIP-densification (DC7p).

The quasi-static (QSS) and cyclic stress-strain (CSS) curves in **Fig. 1a** show a strong cyclic hardening of the DC and SC batches while the AM batches differences between QSS and CSS behavior is negligible. The fatigue results were analyzed based on nominal stresses according to Woehler (S-N curve, **Fig. 1b**) and effective J-Integral of Heitmann [1] at local fracture-initiating defects using elastic-plastic fracture mechanics (EPFM) transformed to cyclic stress intensity factor according to Shiozawa [2] (K-N curve, **Fig. 1c**). S-N diagram shows the highest scatter independent of process, stress ratio and defects. EPFM-based K-N diagram enables a uniform fatigue damage tolerance (FDT) prediction by one curve or lifetime law independent of process and chemical composition related changes in microstructure and stress-strain behavior. This uniform FDT law for additively manufactured and cast Al-Si alloys allow a safe design based on the local stresses, stress ratio, defects and plasticity behavior.


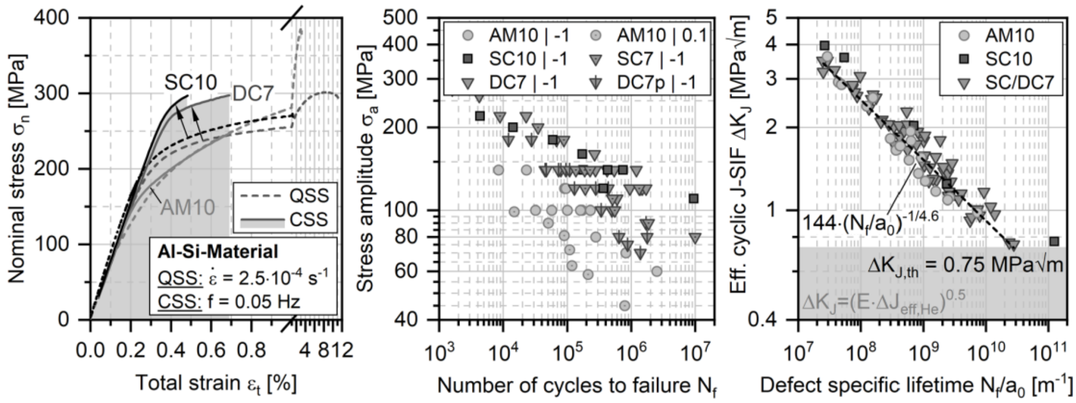


***Figure 1*** *– Uniform fatigue damage tolerance law based on batch-specific (a) CSS curves in comparison to QSS curves, (b) S-N diagram according to Woehler including defect-, plasticity and R-related scatter and (c) K-N diagram according to Shiozawa using the effective cyclic J-Integral at local fracture-initiating defect.*


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# #119 High temperature isothermal fatigue of AM produced hot work steels

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*High temperature fatigue* *Additive manufacturing* *Hot work tool steels*

**Abstract** Additive manufacturing is becoming more common as a manufacturing technique, especially in tooling. Except the design freedom, laser powder bed fusion technology allows improved cooling conditions in hot working tools by minimizing hot spots and getting more efficient uniform cooling. AM produced tool steels are presently under strong development and becoming commercially available at a strong rate with one of their main fields of application being die casting. Since the die is one of the most expensive parts in several hot forming applications it is important to investigate the suitability of AM steels in such operations by studying their high temperature fatigue behavior. This work examines new hot work die steels produced by AM technology using elevated temperature isothermal fatigue testing. The materials examined are two new AM hot work die steel grades, one PM plus HIPed steel and two conventionally cast and forged, premium grades that will be compared. The results provide crucial information such as fatigue life and softening behavior of the steels during their fatigue life (Figure 1).

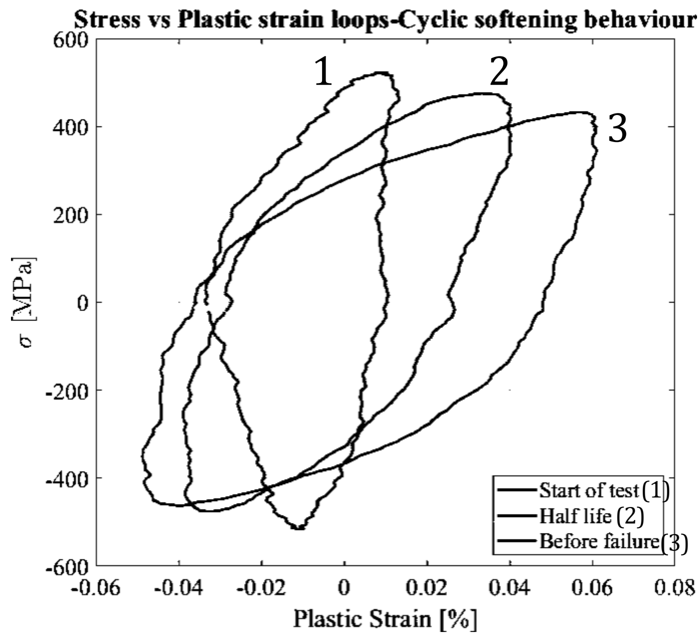


***Figure 1*** *– Plastic strain evolution during fatigue testing*

# #120 International Fracture Mechanics Summer Schools in ex-Yugoslavia and Serbia from 1980-2008 – in memory to Prof. Stojan Sedmak

Aleksandar Sedmak[1], Blagoj Petrovski[2], Simon Sedmak[3]

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*Fracture Mechanics* *Teaching* *Summer School*

**Abstract** International Fracture Mechanics Summer Schools (IFMASS), founded 40 years ago, have been organized for ten times, the last one (IFMASS 10) in 2008. Publishing the monographs after each School enabled to form useful references for introduction of fracture mechanics as an effective tool for structural integrity assessment, but also supporting its theoretical, experimental and numerical development. The first IFMASS, "Introduction to Fracture Mechanics and Fracture-Safe Design", held in 1980 in ex-Yugoslavia, was initiated by Prof. Michael Wnuk, who was at his sabbatical leave in Belgrade, to work together with Prof. Stojan Sedmak. As it turned out to be a great success, including strong support from the industry, it was only natural to organize the next Summer School (IFMASS 2) "Modern Aspects of Design and Construction of Pressure Vessels and Penstocks". It was clear at that time that IFMASS served not only to educate, but also as a forum to exchange the experience and ideas among the participants and lecturers. Next very important event was the joint Yugoslav - USA project "Fracture Mechanics of Weldments", performed by six institutions from all 6 ex-Yu republics and the National Institute of Standards and Technology (NIST), Boulder, Colorado, which started in 1982 and ended in 1992. Following already established pattern, IFMASS 3 "Fracture Mechanics of Weldments" was organized 1984, again for education and as a forum. The success of IFMASS was continued through the fourth School "Prospective of Fracture Mechanics Development and Application" in 1986, leading to the most successful, the fifth one, held under the title "The Application of Fracture Mechanics to Life Estimation of Power Plant Components" in Dubrovnik, 1989. The IFMASS 5 was supported by the "Electricity of Serbia", with impressive number of 145 participants, and the monograph under the same title was published for the first time in English by EMAS Publisher from England in 1990. With IFMASS 5, the flourishing period in fracture mechanics and structural integrity development in was stopped due to unfortunate chain of events in ex-Yugoslavia. It happened that during IFMASS 6 "Service Cracks in Pressure Vessels and Storage Tanks" in June 1991 these unfortunate events started, but still IFMASS 6 was a successful one. Unfortunate circumstances prevented the organization of the next School up to 1997, when again with a strong support of the Industry "GOŠA", IFMASS 7 was held under the title "Experimental and Numerical Methods of Fracture Mechanics in Structural Integrity Assessment", attracting 137 participants and 8 foreign contributions out of 25 lectures. The unfortunate events culminated in 1999 with NATO bombardment, which delayed for 3 years the next one (IFMASS 8), held under the title "From Fracture Mechanics to Structural Integrity Assessment" in Belgrade, in 2003, after the Society for Structural Integrity and Life (DIVK) has been established in 2001 and took over IFMASS. Later on, final two Summer Schools were organized in Varna Golden Sand, Varna, Bulgaria (IFMASS 9 "The Challenge of Materials and Weldments") and Zlatibor, Serbia (IFMASS 10 „Fracture Mechanics Fundamentals and Structural Integrity Assessment Procedures"). The last 3 editions of IFMASS monographs are published by in English, available on ESIS website (www.structuralintegrity.eu) for free. After 2008, IFMASS driving force, Prof. Stojan Sedmak has retired at age of 80 and we are still waiting for somebody of his energy to carry on. Anyhow, in 2018, 5th ESIS Fracture Mechanics Summer School was held in Belgrade, in the scope of ECF22, including the special lecture delivered by Prof. James Rice on the occasion of the 50th Anniversary of J integral, with 90 participants. Coincidently it was also 50th Anniversary of the first important scientific contribution on Fracture Mechanics in ex-Yu, Stojan Sedmak's Magisterium thesis

# #121 The Theory of Critical Distances to perform the static assessment of of 3D-printed concrete weakened by manufacturing defects and cracks

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**Abstract** The present paper deals with the use of the Theory of Critical Distances to model the detrimental effect of cracks and manufacturing defects in 3D-printed concrete subjected to static loading. The validity and robustness of the proposed approach was assessed against a number of experimental results that were generated by testing, under three-point bending, 3Dprinted rectangular section specimens weakened by saw-cut crack-like sharp notches, surface roughness (due to the extrusion filaments) and manufacturing defects. The sound agreement between experiments and predictive model (Fig. 1) allowed us to demonstrate that the Theory of Critical Distances is not only a reliable design approach, but also a powerful tool suitable for guiding and informing effectively the additive manufacturing process.

3D-Printed Concrete

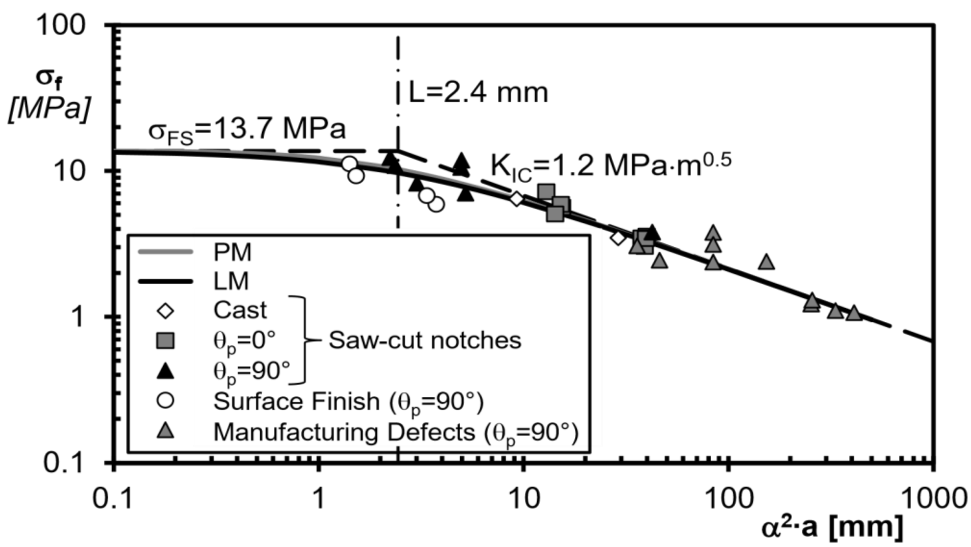


**Figure 1.** Accuracy of the TCD in modelling the detrimental effect of cracks and defects in 3D-printed concrete loaded in three-point bending.

# #122 How should we define compression after impact fatigue growth in CFRP ?

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*Composites* *BVID* *Fatigue*

**Abstract** Using a ‘slow-growth’ procedure in damage tolerant design could potentially reduce the weight of composite structures. To adopt this procedure however, damage growth needs to be slow, stable and predictable. The scenario of fatigue with barely visible impact damage (BVID) has been tested by previous researchers. These experiments showed almost no damage growth for the major part of the fatigue life, followed by a fast and unstable growth close to final failure. Due to this observation, the ‘no-growth’ design approach has always been adopted for composite aircraft structures. Until now, ‘damage growth’ has implicitly been defined as delamination propagation outside of the impact damage envelope. However, evidence from the present work suggests that this may actually not be a good descriptor of fatigue propagation of BVID.

In this work, quasi static and fatigue compression after impact (CAI) tests were conducted on a quasi-isotropic layup of CFRP. Impact tests showed the presence of a non-delaminated cone below the impact contact point caused by the out of plane compressive stress. Acoustic emission monitoring during the quasi-static CAI test clearly showed the activation of fiber failure at relatively low stress (70 % of CAI strength), and thus fiber failure can also be expected to occur at an early stage in the fatigue life. Periodic ultrasonic scanning during the fatigue test showed that delamination growth occurred inside the non-delaminated impact cone before the onset of external delamination growth. The conclusion from this series of test is that a more refined description of fatigue growth of BVID is needed, which should include damage modes other than pure delamination. Furthermore, the tests show that the delamination propagation inside the impact cone plays a role in fatigue degradation.

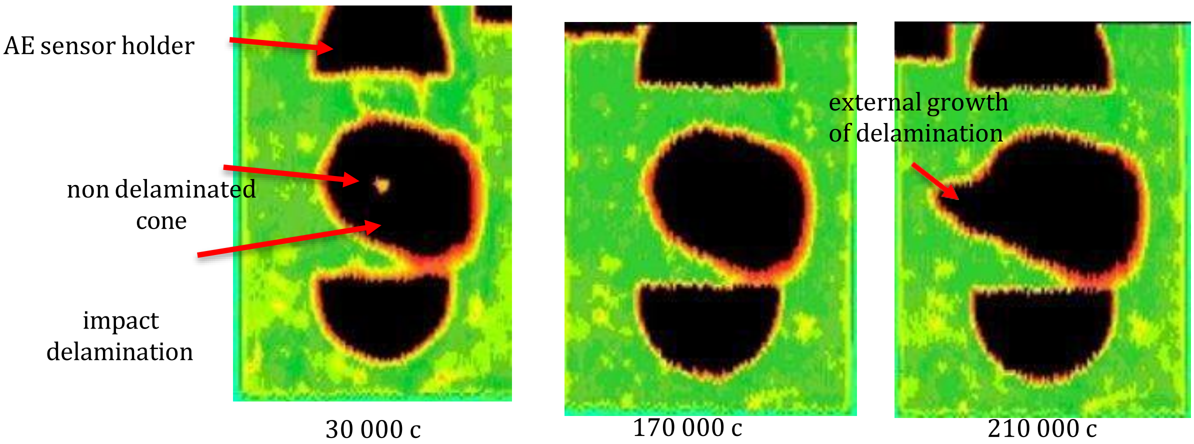


***Figure 1*** *– C-scan image of delamination at different stages during the fatigue test, showing growth into the non-delaminated cone*

# #124 Risk based assessment of structural integrity of corroded oil drilling pipe

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*Remining life* *Corrosion* *Oil drilling rig*

**Abstract**: Risk based assessment of remaining life of a corroded oil drilling pipe is presented and applied on the prototype (welded pressure vessel made of pipe) with artificial defects, Fig. 1, which was previously examined under service (10 MPa) and testing (22 MPa) pressure. The new concept based on application of probability and consequence of failure was used. Probability of failure is defined according to the relation between the spent working hours and the remaining life, estimated by using the basic linear elastic fracture mechanics concept, i.e. Paris law for fatigue crack growth. Taking into account probability and consequence, the risk matrix, Table 1, was made for the pipe, with a round defect 1.75 (depth) x 28 (length) mm, in the case of service and testing pressure, as well as new and old material. Detrimental effect of testing pressure is clearly shown, table 1. The results are useful for managers to make decision about further use of damaged pipes, based on data provided by engineers. Presented procedure for risk assessment of remaining life is a general one, applicable to any component with known geometry, including crack, material properties and loading data.

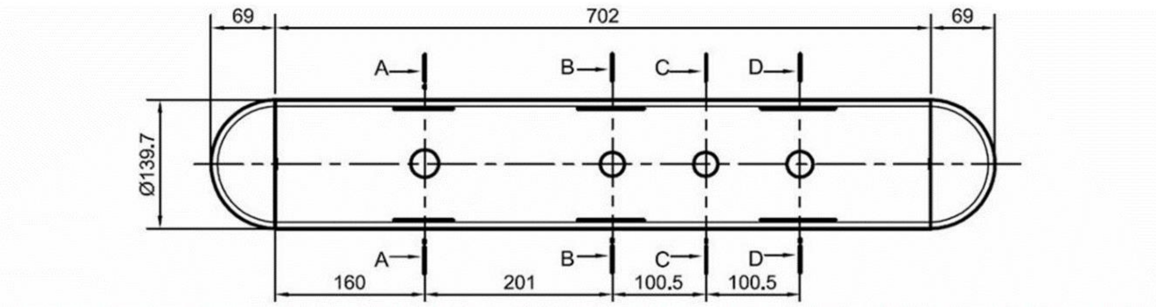


***Figure 1 - Prototype with artificial defects***

Main technical characteristics of the oil rigs:

- working pressure: maximum=10.01 [MPa], minimum=7.89 [MPa].
- number of strokes of pump rod: n=9.6 [min$^{-1}$]

Table 1. Position of assessment points in the risk matrix

| | **Consequence category** | | | | | |
|---|---|---|---|---|---|---|
| **Probability category** | 1 – very low | 2 - low | 3 - medium | 4 - high | 5 - very high | **Risk legend** |
| ≤0.2 very low | | | | | | **Very low** |
| 0.2-0.4 low | | | ***p*=10, MPa new 0.33** | | | **Low** |
| 0.4-0.6 medium | | | ***p*=10, MPa old 0.42** | | | **Medium** |
| 0.6-0.8 high | | | ***p*=22, MPa new 0.73** | | | **High** |
| 0.8-1.0 very high | | | ***p*=22, MPa old 0.92** | | | **Very High** |

# #125 Effects of Over-Loading of Pipeline made of HSLA steel

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*Finite Element Method*  *Pipeline structural integrity*  *HSLA steel*

**Abstract** The effect of proof over-pressure on pipeline structural integrity is analysed in the case of pipeline in Reversed Hydro Power Plant, made of High Strength Low Alloyed steel with 800 MPa tensile strength due to special design requirements. To assess its structural integrity, extensive testing of the full-scale prototype had been performed, including hydro static pressurizing, as well as application of fracture mechanics parameters. Since plastic strain was recorded during proof over-pressurizing, the special attention was given to the fact that this is actually a mechanism for ductile crack initiation and propagation. The Finite Element Method was applied to simulate the full-scale prototype behaviour during loading and unloading, confirming that the combined effect of over-pressure, welding mismatching and stress concentration can indeed produce plastic strain. Based on this experience, one can assume that the recorded or calculated plastic strain in the case of over-pressurized pipeline is high enough to initiate a crack, as adopted in this paper. This in turn means that testing of pressure vessels with significant over-pressure can cause much more problems than it has benefits, because it acts more like the first step in eventual failure, than it proves anything.

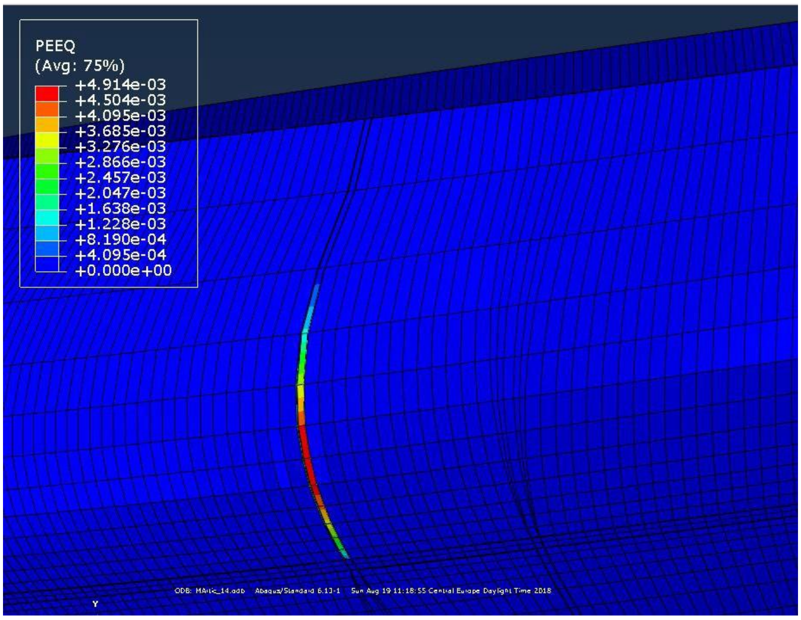


*Figure 1 - FEM analysis – stress distribution*

# #126 Some problems of XFEM application for turbine shaft life prediction

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*turbine shaft* *fatigue crack growth* *xFEM*

**Abstract** One of the major problems in numerical simulation of fatigue loading represents the generation of a finite element mesh, since the model with crack cannot use combinations of different types of mesh elements (such as HEX or TET). This paper presents the problem of the generated finite element method mesh during fatigue simulation of the Kaplan Turbine Shaft model in ABAQUS and Morfeo Crack software packages (xFEM approach). The model contains an initial crack of 37 mm. Simulation was performed in order of assessing the integrity of shaft with crack. During the first attempt, a denser mesh in the vicinity of the crack was used, which did not prove to be effective in obtaining satisfactory results. Finite elements whose size was similar or the same as the finite elements around the fatigue crack growth domain were used in the second attempt. After remeshing, the numerical simulation proved to be successful and gave more realistic results.

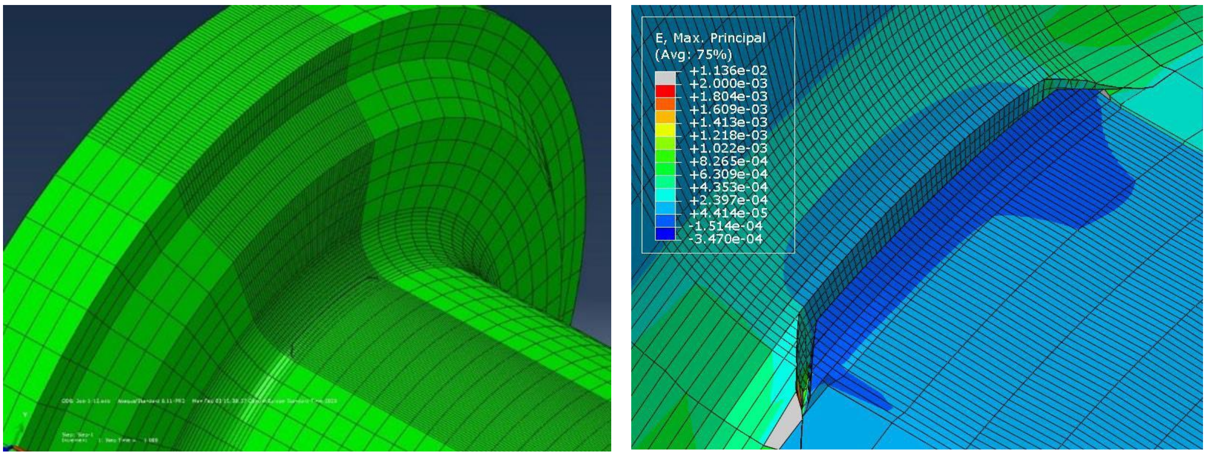


***Figure 1*** *- Position of the initial fatigue crack on one of the iterations during simulation*

# #128 Non-destructive direct current potential drop assessment of forming-induced pre-damage of AISI 5115 steel

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*Non-destructive damage characterization* *DCPD* *AISI 5115*

**Abstract** Due to efficient material utilization and reproducible high-quality level, metal forming processes, such as forward extrusion, meet the requirements of economical and resource-saving production. However, the performance of the workpieces is considerably affected among other things by the occurrence of forming process-induced damage. So far, there are only few investigations available on the influence of process-induced damage on fatigue properties. With the knowledge of damage influence on the component durability, components can be designed specifically and enable optimization of loading capability and lightweight construction. Also, the degree of process-induced damage after forming is currently measured by time-consuming, cost-intensive and destructive examinations in SEM. Electrical resistance measurement (DCPD) could offer the opportunity for a time-efficient and nondestructive assessment of ductile damage.

The aim was to develop a method for damage characterization that allows conclusions to be drawn about the expected lifetime of components. Therefore, a highly accurate resistance-based sensor system for the assessment of forming process-induced damage and loading-induced cyclic damage, and for the analysis of their interaction has been developed and validated. The measurement technology required for damage detection was integrated into a test setup and adapted to specimens. The goal was to achieve the highest possible reproducibility. The measurement parameters, such as applied current and duration of the current pulse, were optimized with the aid of statistical experimental design. The new sensor system was tested on round specimens of case-hardened steel AISI 5115 (16MnCrS5, 1.7139) with different processinduced damage states.

The signal acquisition could be optimized by the measurement parameter variation by a factor of more than 100 compared to initial measurements. By using the delta mode, the thermoelectric effects could be eliminated during the measurement. A significant influence of deformationinduced damage on the electrical resistance measurement was validated. Specimens with less forming-induced damage showed lower electrical resistance and vice versa. The results were validated with recordings by destructive testing in scanning electron microscopy. Thus, a rapid, cost-effective and non-destructive method for forming-induced damage analysis was developed, providing the capability for process monitoring in the future.

**Acknowledgements** The authors gratefully acknowledge the funding by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) for the subproject B01 within the Collaborative Research Center CRC/Transregio 188 "Damage Controlled Forming Processes" (Project number: 278868966).

# #131 Locale approach to fracture of titanium alloys: new insights into the mechanisms of hydrogen embrittlement

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*Hydrogen embrittlement Titanium alloys hydrides*

**Abstract** Hydrogen embrittlement (HE) is a phenomenon that is increasingly mentioned during premature fracture of industrial components constituted by the assembly of several materials including titanium alloys. These alloys have been chosen for their good corrosion resistance in seawater. However, to protect the other components, a cathodic protection (CP) is used. While this process is very effective and prevents corrosion, it remains a probable source of hydrogen ingress within the material, which can induce an embrittlement of the structure. The latter is characterized by a loss of mechanical properties and a change of the damage mechanism from ductile to brittle. The main evoked hydrogen-assisted damage mechanism in titanium alloys is the formation of hydrides even though lattice hydrogen has a clear impact on the plasticity of these alloys. Consequently, this does not exclude that other mechanisms may also play a role in the embrittlement. In present work, we investigate the influence of $\alpha$-phase crystallographic texture, and the fraction of $\beta$-phase of two phases alloys on hydrogen ingress and its consequence on damage processes in cathodic charging conditions in artificial seawater. A large variety of techniques was used to characterize the hydrogen state (SDL, TDS, XRD) and the micro-structural evolution depending on the cathodic polarization time (TEM, SEM-EBSD, FIB, AFM, indentation). The evolution of the apparent H solubility as a function of time highlights four stages for each alloys studied (T40, Ta6V), which illustrates clearly the implication of $\alpha$-grain boundaries, $\alpha$-grain orientation, $\alpha$ and $\beta$ phases and $\alpha/\beta$ interphase on hydrogen solubility, trapping and mobility processes. In a second step, we clarified the contribution of hydrogen states, hydrostatic stress and plasticity onto the fracture process. Tensile tests with axisymmetric specimens with several notch shapes were performed in pre-charging conditions and without hydrogen charging. Based on a local approach to fracture (Finite Element Method (FEM) calculation of the local mechanical state) the observed damage modes (initiation and fracture conditions) were formalized in terms of hydrostatic stress-equivalent plastic strain ($\sigma_m$, $\varepsilon_{peq}$) maps which allows to demonstrate at macroscopic scale the contribution of plastic deformation and hydrogen on damage. Irrespective of hydrostatic stress, void nucleation is observed mainly at twin interface, grain boundaries, $\alpha/\beta$ and $\alpha/\alpha$ interfaces and on the hydrides. Plastic strain accommodation of hydride is questioned in relation with the phase type ($\gamma$ and $\delta$) and orientation relationships (OR, and epitaxy between each phases). Using Beremin's analysis, a linear relation between hydrostatic stress and equivalent plastic strain was identified. Based on our experimental data, a critical stress of interfacial decohesion $\sigma_c$ and a plastic modulus $d\sigma_{eq}/d\varepsilon_{peq}$ depend on the hydrogen content. For single and two phases alloys, hydrogen content decreases $\sigma_c$ and increases $d\sigma_{eq}/d\varepsilon_{peq}$ (hardening process) which allows to promote void nucleation. Irrespective of void location the alloys present hexagonal cavities in relation with prismatic slip activity in the vicinity of these cavities. Fracture surfaces of each specimen present tubular dimples corresponding to the longest dimension of the hexagonal cavities along the crystallographic <c> axis. A linear relation is observed between the void diameter and the longest dimension. Despite this morphology, the Rice and Tracey model is efficient enough to describe the fracture condition in terms of triaxiality versus equivalent plastic strain ($\chi$, $\varepsilon_{peq}$). The growth rate coefficient identified depends on the alloy considered, the crystallographic texture and on the hydrogen content

# #132 Numerical model of corrosion influence on mechanical behavior of steel AH36

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*steel AH36* *material degradation* *numerical analysis*

**Abstract** Mechanical behavior of butt-welded joints made of AH36 shipbuilding steel exposed to corrosive environments is analyzed experimentally and numerically in this paper. Testing specimens have been cut out of butt-welded sheets in a way that they incorporate base metal, heat-affected zone and weld metal (BM, HAZ, WM). The specimens were exposed to real marine environment (water, sea water, sea tide) for prolonged periods (6, 12, 24 and 36 months) in order to determine the influence of the environment. In the experimental part of the research, after the specimens were extracted from experiment site, they have been tested to determine the change of the mechanical properties of the metal. Standardized tensile tests have been performed along with the Charpy impact tests. Moreover, the corroded surface was examined using optical and scanning electron microscopy. Results show deterioration of the mechanical properties of steel exposed to the sea environment. The most significant deterioration is noticed on the specimens exposed to continuous influence of the sea waves. As for the numerical analysis, the experimental results were base for development of the numerical model of the corroded surfaces. The corrosion pits for each zone (BM, HAZ, WM) were modeled using spatial Poisson process and Gamma process for the pit depth progress. The finite element model of the butt-welded steel specimen was developed in order to perform simulated tensile test using SMCS ductile fracture criterion with different $\alpha\alpha$ parameters and hardening models for each zone. Because of the huge number of the finite elements, the submodeling was necessary to perform for each environment and the period of exposure. It is shown that with the increase of the stress triaxiality, i.e. average triaxiality, which depends of the pit size and distribution, critical plastic strain decreases. Consequently this leads to the earlier ductile fracture initiation and degradation of the mechanical properties. The numerically assessed results show good agreement with the experimental results. Additionally, since the numerical procedure is based on the real corrosive conditions (not laboratory accelerated), it can be used for further assessment of other types of welded steel exposed to the sea environment, particularly for EH and DH steels which are used for the naval and offshore structures.

# #133 Fracture Toughness of a 9Cr ODS steel determined on tube specimens

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*Toughness* *Fuel cladding* *ODS steel*

**Abstract** The ASTM E1820 standard provides guidelines to conduct tests on cracked specimens. It is based on several numerical parameters to obtain the $JJ - \Delta aa$ curve from the CMOD-force curve. When using the unloading compliance technique, the procedure allows determining the entire $JJ - \Delta aa$ curve using a single specimen. The ASTM E1820 standard can be applied to CT, DCT, and SENB specimens but is not suited for thin-walled parts such as tubular claddings. This study aims to develop a procedure similar to ASTM E1820 but can be applied to tubes. It uses the Pin Loading Tension test (PLT) proposed in the literature [1], [2] (see fig 1a). Finite element simulations of the test are carried out to establish the procedure. The mesh is shown in figure 1b. The effects of the following parameters are studied: (i) friction between the pin and the tube, (ii) gap between the pin and the tube, (ii) crack length. Parameter $\eta\eta$ linking the plastic part of the $JJ$ integral to the plastic work, the function allowing the evaluation of crack length from the compliance, and the function providing the stress intensity factor are the principal outcomes of the numerical study. The proposed methodology is then applied to the study of crack growth resistance of a nuclear fuel cladding made of a high-strength ODS (Oxide Dispersion Strengthened) steel [3] which is a potential candidate for the fabrication of the fuel assembly in fast-neutron reactors.

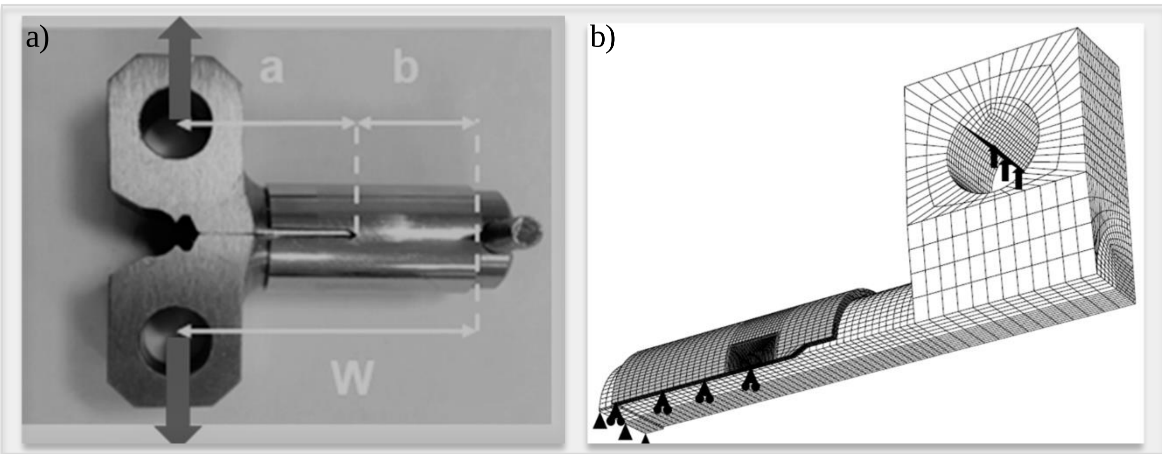


***Figure 1** – a) Pin Loading Tension test, b) experimental JJ-R curves*

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# #134 Hydrogen embrittlement of a martensitic carbon steel at high hydrogen pressure

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*Hydrogen embrittlement* *Fracture surface* *High pressure hydrogen*

**Abstract** Underground storage and the use of hydrogen are becoming increasingly important in the context of green energy. Hydrogen will play an enormous role in the transportation sector and also the oil and gas industry is increasingly focused on generating renewable energy seriously considers. However hydrogen embrittlement can occur in steels. To evaluate hydrogen embrittlement susceptibility high pressure autoclave tests were carried out, to simulate conditions close to underground gas storage and natural gas transportation. The aim of this work was to determine how much hydrogen is absorbed in a carbon steel under certain conditions and how this affects cracking behavior of the steel. A martensitic carbon steel has been investigated in two conditions, quenched (Q) and quenched and tempered (Q & T). Testing conditions were various gases with and without addition of $CO_2$ and $H_2S$ at room temperature and 120 °C. Results shows brittle fractures of the Q material at room temperature. There cracking is independent of the pressure of $H_2S$ and $CO_2$. At higher temperature cracking appeared with addition of $CO_2$ and $H_2S$. The fracture surfaces are evaluated and hydrogen content is discussed. Q & T, conditions did not result in any cracking representing an L80 quality.

# #135 Finer-scale residual stress characterisation in laser-welded Eurofer97 steel for fusion plant

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*Residual stress* *Neutron Bragg edge imaging* *PFIB-DIC*

**Abstract** Residual stresses almost always remain in an object after manufacturing, e.g., welding processing, additive manufacturing and synthesis of composite, ceramics and bioinspired materials. They can be detrimental or beneficial to the manufacture and performance of engineering components. Inspection of residual stresses is necessary for complex industrial material systems, as undesirable residual stresses can cause premature catastrophic failure of critical components. The Reduced Activation Ferritic Martensitic Steel Eurofer97 is the main material considered for the in-vessel components (e.g. breeding blanket structure) of the demonstration fusion plant DEMO. The laser welding, one of fast and reliable methods, has been used for remote manufacturing and maintenance of the component. It is understood that the mechanical properties can be degraded by the heterogenous residual stresses and crystallographic structures in the weldment, leading to in-service creep stress relaxation cracking and lifespan reduction. The multi-scale residual stress evaluation could provide valuable insights into keeping the structural integrity of the fusion plant components. In this work, the as-welded Eurofer97 sample was butt-welded by the single laser welding technique, and the residual strain is evaluated by three technologies at multi-scale, including neutron diffraction, neutron Bragg edge imaging and Xe+ plasma focused ion beam and digital image correlation (PFIB-DIC) techniques. Significant residual strain was observed across the fusion zone (FZ), heat affected zone (HAZ) and base material (BM) in multi-scale. The sharp residual strain gradients quantified by high-resolution characterisations are beneficial to the development of micromechanical rationale for failure mechanisms such as creep cracking initiation. The multi-scale residual strain distribution is correlated with microstructure characterisation and mechanical property using electron microscopy, micro-hardness and nano-indentation methods. Such correlation will contribute to a predictive model to help optimise the mechanical properties and lifetime of components.

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2. Bin Zhu, Nathanael Leung, Winfried Kockelmann, Saurabh Kabra, Andrew J London, Michael Gorley, Mark J Whiting, Yiqiang Wang*, Tan Sui*, Revealing the residual stress distribution in laser welded Eurofer97 steel by neutron diffraction and Bragg edge imaging, *Journal of Materials Science & Technology*, 114, 249-260, 2022.

# #136 Simulation of slant and cup-cone fracture using a nonlocal GTN model integrating two internal lengths

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*Cup-Cone fracture* *Nonlocal GTN model* *FE simulation*

**Abstract** Ductile failure prediction is essential to avoid structural integrity loss or control crack propagation during the forming process. One of the main difficulties is the prediction of complex crack paths. This study proposes a nonlocal extension of a local Gurson-Tvergaard-Needleman (GTN) ductile damage model [1] at finite strains that captures cup-cone or slant fracture. The proposed model is based on an implicit gradient formulation, which solves the problem of spurious strain and damage localization [2,3]. The model integrates two different material characteristic lengths used to separately regularize damage by void growth and damage by void nucleation. Void growth is assumed to be initiated at coarse particles such as MnS in steels, whereas nucleation corresponds to secondary nucleation on secondary particles such as iron carbides. Each material length is associated with one damage mechanism. After parameter fitting using data for a line pipe steel, conditions to obtain converged solutions are studied, which can be used to select the mesh size in the localization band. With the appropriate mesh design, it was possible to study the effect of the characteristic lengths on the formation of cup-cone fracture and slant fracture. It is observed that large characteristic lengths favor flat crack advance for a given specimen size. Similarly, size effects can be predicted for given material lengths, with small specimens more prone to flat fracture. This paves the way to a more direct determination of material lengths by using homothetic specimens to obtain different crack paths.

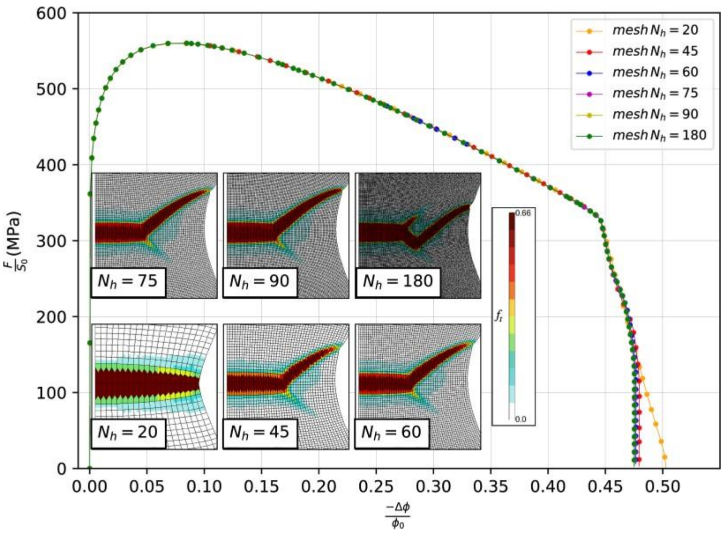


***Figure 1** – Nominal stress vs. diameter reduction for a notched round bar. Mesh size independence.*

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# #137 Size effect and finite fracture mechanics. Application to the study of microcracks initiation in particle reinforced composites

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*Finite fracture mechanics* *Size effect* *Composites*

**Abstract** Size effect is a well-known phenomenon in fracture mechanics. The size of structural elements and specimens can affect both qualitatively and quantitatively their failure. In fact, most of the classical criteria in fracture mechanics are size-dependent and some of them only are valid for certain scales.

This work analyzes the size effect in the context of the coupled criterion of the finite fracture mechanics. This criterion, relatively recent in the history of fracture mechanics, is particularly useful to predict crack initiation in the absence of an initial crack. Several previous works reported that this criterion predicts a strong size effect in the loads leading to crack initiation in certain problems.

The problem of crack initiation in particle-reinforced composites is studied in order to illustrate the size effect. Thus, an experimental campaign is designed to evaluate the size effect in the crack initiation at the particle-matrix interface. The comparison of these experimental results and the predictions by the coupled criterion shows a good agreement and extends the validity of this criterion to a wide range of scales.

# #138 Effect of chemical heterogeneities (segregations) on fracture toughness of low alloy ferritic steel used for large forged components in the nuclear industry

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Segregations Fracture mechanisms Fracture toughness

**Abstract** Low alloy ferritic steels used for large forged components in nuclear power plants might contain chemical heterogeneities called segregations. Segregations are formed during the solidification process of the metal cast into large ingots. They remain in the material despite forging and numerous heat treatments, thus leading to microstructural heterogeneities in the final component at different scales. This study aims at evaluating the effect of chemical and microstructural heterogeneities at the mesoscopic scale on the fracture toughness and at identifying their impact on the fracture mechanisms at low temperatures (close to the expected $T_0$ value of the Master Curves).

Characterizations of segregations using image analysis, micro-hardness testing, and electron probe microanalysis (EPMA) showed that meso-segregated regions appeared diskshaped with an average thickness of 250 µm.

Using reduced-size compact tension specimens (mini-CT), fatigue pre-cracks were located both randomly and intentionally inside meso-segregated regions to help crack initiation happening inside the heterogeneities. The fracture toughness was then correlated to the local fracture mechanisms.

It was shown that the predominant fracture mechanism in segregated zones, even at the crack initiation site, was transgranular cleavage and not intergranular cracking, resulting in a wide range of fracture toughness values. Small intergranular cracks (< 20 µm in size) were systematically found near crack initiation sites (distance < 100 µm) but were not at the origin of the specimens fracture.

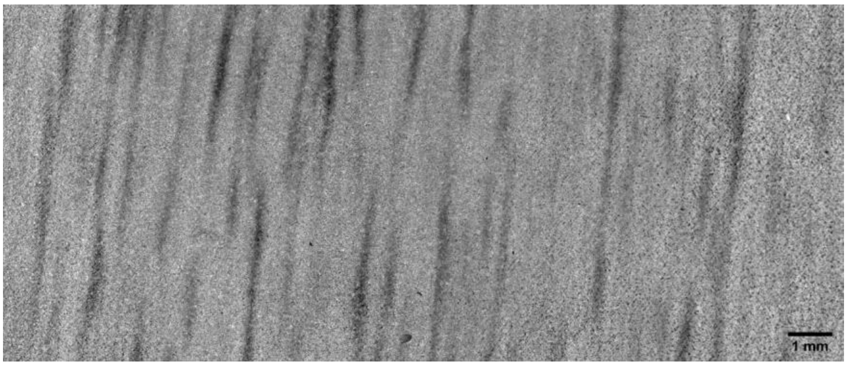


Figure 1 – overview of a segregated specimen etched using an iron chloride solution ($FeCl_3$) that reveals the presence of meso-segregated regions (darker regions)

# #139 On the localizability of voids in adhesive joints loaded in mode I

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*Optical measurement techniques*    *hyperelastic adhesive joints*    *double cantilever beam*

**Abstract** During the manufacturing process of adhesive bonds in industrial applications, voids and kissing bonds can occur, leading to a loss of structural integrity of the entire structure. This requires a thorough study of connection behavior in the presence of faults and requires identification of such faults.

There are currently only a few publications in connection with adhesive joints obtaining voids, cavities or improper adhesion. The work found in literature [1,2] focusses on thin adhesive layers of rather large stiffness. In contrast, the aim of our study is to experimentally determine the limits of the void's localizability in thick layered hyperelastic adhesive joints with stiff adherends and, hence, at finite deformations.

For this purpose, Double Cantilever Beam (DCB) specimens with predefined faults have been manufactured and tested. The experimental investigations include several measurement methods to identify the deflection of the adherent beams and to calculate J-integral in-situ during testing. Optical measurement techniques as Digital image correlation or shearography are compared to touching strain measurement by optical glass fibers.

In addition to a quantification of the effects of certain faults on the mode I fracture behavior, a discussion of the applicability of the selected test methods and their individual limitations is given.

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# #140 Effect of a single overload on the cyclic R-curve behaviour of a γ-titanium aluminide

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*Titanium aluminide* *R-curve* *overload*

**Abstract** The effect of a single overload on the threshold of stress intensity range of a semi-brittle material, an intermetallic γ-titanium aluminide, was analysed. This type of material exhibits a pronounced R-curve behaviour of the fracture toughness and the threshold of stress intensity range, which is mainly caused by crack bridging, formation of shear ligaments, crack deflection and branching.

Specimens with short cracks on deep sharp notches were subjected to overloads of 60 and 80 % of the fracture toughness. Contrary to ductile materials, the experiments revealed no significant increase in the long crack threshold, however a pronounced increase in the slope of the R-curve for the threshold of stress intensity range. These results can be explained by the facts that the fracture toughness and the long crack threshold of stress intensity range are dominated by the above-mentioned crack tip shielding mechanisms. The crack tip shielding generated in the overload cycle is only partly destroyed during cyclic loading below the long crack threshold of stress intensity range and contributes therefore beneficially to the cyclic crack growth resistance.

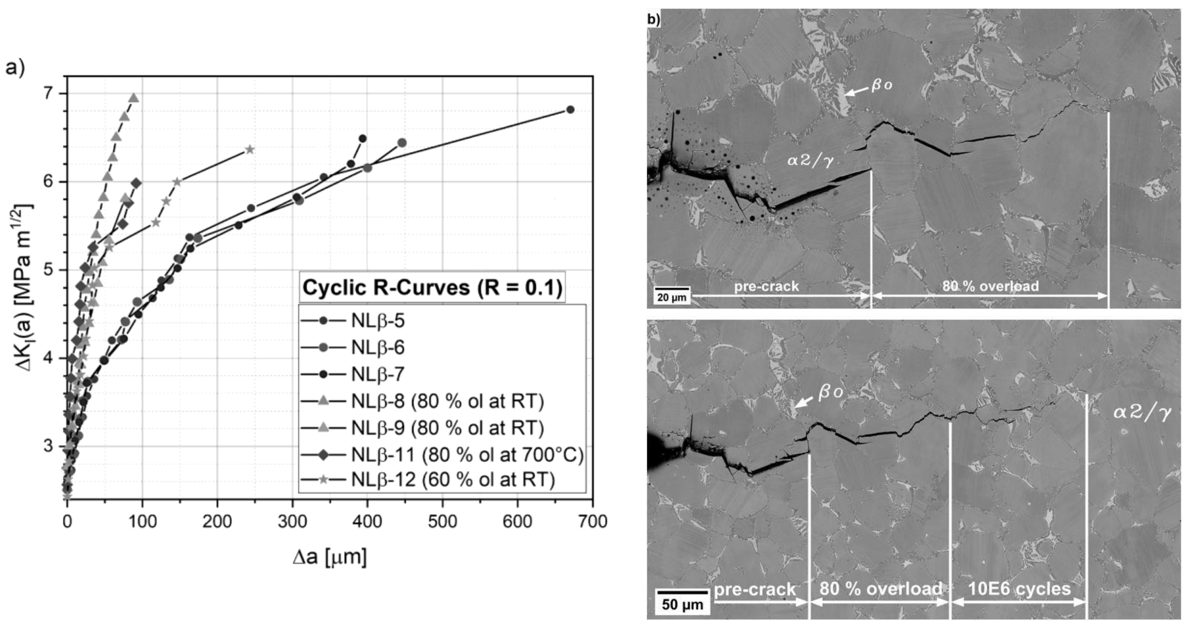


***Figure 1** – a) Cyclic crack resistance curves (R-curves) of the threshold $\Delta K_{th}$ at a load ratio of R = 0.1, b) SEM crack path analysis of an overload experiment*

# #141 Hydrogen increased ductility due to martensitic transformation versus hydrogen embrittlement in 304L stainless steel: the role of the deformation rate

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*304L stainless steel* *Martensitic transformation* *Hydrogen embrittlement*

**Abstract** In the present work, hydrogen embrittlement of 304L austenitic stainless steel is examined. Austenitic stainless steels are considered as one of the more hydrogen-resistant steel types due to their intrinsically low hydrogen diffusivity. However, they are not insensitive to hydrogen embrittlement, especially when the austenitic microstructure is metastable under deformation, i.e. transforms to α'-martensite, exhibiting a higher hydrogen diffusivity and intrinsically prone to brittle failure. In-situ tensile testing of electrochemically hydrogen charged 304L and 10% pre-strained 304L austenitic stainless steel at different deformation rates results in a largely reduced elongation at fracture compared to the corresponding test in air. Prestrained 304L austenitic stainless steel shows a higher embrittlement for every tested deformation rate due to the presence of pre-existing α'-martensite, influencing the apparent hydrogen diffusivity. The hydrogen diffusivity and diffusion depth is, therefore, analyzed through thermal desorption spectroscopy as a function of the α'-martensite fraction. Moreover, hydrogen embrittlement increases with decreasing deformation rate due to the increased time that is given for hydrogen to accumulate at vulnerable locations in the microstructure. Finally, as hydrogen triggers intense (additional) martensitic transformations at the surface, both to α'martensite and to ε-martensite, the strain hardening of the alloy improves and necking and crack propagation are postponed by the action of hydrogen as opposed to the negative hydrogen embrittlement effect. Additionally, ε-martensite does not have disadvantageous hydrogen properties as compared to α'-martensite when formed out of an austenitic matrix. This opens possibilities for the creation of more hydrogen-resistant materials where the balance between HE and hydrogen-enhanced martensitic transformation can be optimized for the required application.

# #142 Analysis of Compressive Behaviour of Pristine and Cracked 5- Stringer Butt-Joint Panels Made from Carbon Fibre Reinforced Thermoplastic Polymer

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*CFRTP* *Panel* *Post-buckling*

**Abstract** The FE analysis of 5-Stringer Butt-Joint Panel made from carbon fibre reinforced thermoplastic polymer (CFRTP) loaded in compression is introduced. The panel is intended to rotorcraft tail and demonstrates the alternative to CFRP panels made from fabrics by common laminate process. The pristine and cracked (initially delaminated) panels were investigated. Multi-layered detail FE models were generated by ABAQUS plug-in PbPModGen so that each composite layer was represented by a layer of finite elements (see Figure 1a). Cohesive elements (CZM) were utilized between skin and stringers. Buckling mode shapes and eigenvalues were determined by linear (eigenvalue) analysis and gradual buckling development was analysed by explicit solver. The panel with initial delamination between central stringer and the skin was analysed analogically. Local skin buckling in the delaminated area was found in addition. The post-buckling behavior was evaluated by explicit solver. Compared to the test results, the explicit analysis predicted failure conservatively with the difference of 3% of pristine and 9% of cracked panel (see Figure 1b). The failure occurred after local debonding of stringers from the skin. The work carried out introduces post-buckling behaviour assessment and studies the effect of a crack on the compression strength. The explicit solution together with CZM seems as adequate method for post-buckling analysis of parts made of thermoplastic composites. Especially, in combination with ply-by-ply model, when indispensable portion of the panel volume is formed by a filler and the common shell model requires more simplifications.

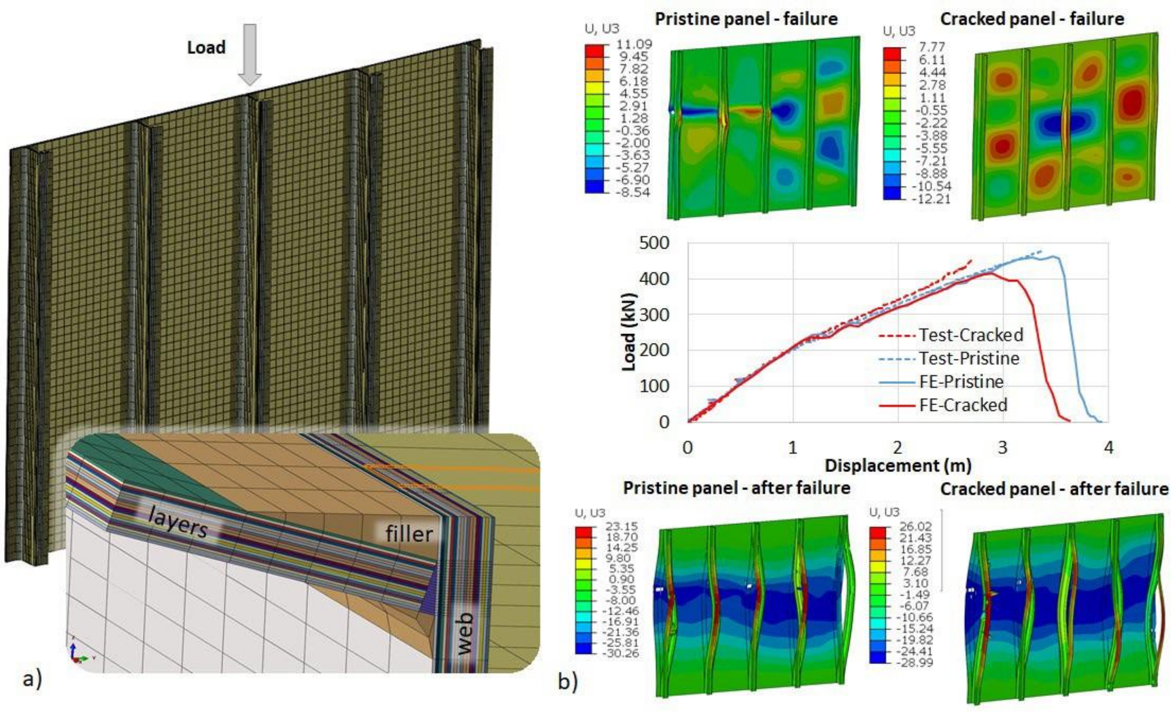


***Figure 1** – a) FE model, b) Analysis results in comparison with the test*

# #143 Experimental and numerical study of fracture behaviour of bioinspired alumina-based dental crown composites

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***Keywords:*** *Bioinspired, alumina-based composites, fracture toughness*
**Abstract** Human dental tissue is hierarchically structured from stiff, high-strength, brittle enamel at the surface to damage-resistant, low-strength dentine near the centre. When these tissues are damaged and lose the capability of replicating the anatomy, restoring their function is a challenge. The clinical failure mode of current commercial dental crown ceramics is radial cracking at the interface (i.e., ceramic/cement) driven by surface tension from flexure of the ceramic layer on the subsurface. Therefore, it is important to research a competent combination of materials to reduce stress concentration in dental crown materials. It has become well known that the anisotropic complex structure of natural materials, such as nacre, can help to develop strong, tough and damage-resistant bioinspired materials. By mimicking the natural structural optimisation and mechanical functionality, the disadvantages of dental ceramics can be overcome. In this study, four types of freeze-casted, bioinspired, multi-layer alumina-based composites infiltrated with polymethyl methacrylate (PMMA), epoxy, polyurethane, and urethane dimethacrylate/triethylene glycol dimethacrylate were tested by *in situ* mechanical microscopy to determine the fracture toughness and *R*-curve behaviour. This study focused on 60% (with 11 $\mu$m ceramic wall thickness) alumina-based composites as they exhibited promising results for fracture toughness whilst preserving their strength [1]. Finite element micromechanical modelling was established to validate the fracture process observed in the experiment. The bioinspired composites displayed *R*-curve behaviour and a fracture toughness higher than monolithic alumina, with PMMA composites having higher toughness. The increase in toughness was the result of multiple toughening mechanisms including crack deflection, crack bridging, branching and microcracking. Preliminary results of multi-layer fracture modelling for the same four composites were also achieved, which demonstrated different fracture processes. This work is important for the development of new generation, dental crown composites as it provides insight into potential strong and tough material combinations.

**Acknowledgements**
The EPSRC project (EP/S022813/1) “Understanding and enhancing the mechanical performance of bioinspired zirconia-based dental materials” is acknowledged for the funding support.

**Reference**

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# #144 Investigation of the Influence of Osteoporosis and Aging on Periprosthetic Femoral Fractures using Finite Element Analyses

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*Periprosthetic Fractures* *Subject Specific FEA* *Osteoporosis*

**Abstract** Total hip replacement with an artificial hip stem is one of the most successful orthopedic procedures conducted in clinics today [1]. However, the average time a patient is in need of an endoprosthesis is rising with an increasing life expectancy [2]. In order to reduce the stress of multiple revision and correction surgeries on patients, these need to be reduced and avoided as long as possible. However, changes of the bone tissue due to the advancing age of the patient effect the stability and load bearing capacity of a femur implanted with an endoprosthesis, which often results in periprosthetic femoral fractures (PFF) [3]. Especially osteoporotic periprosthetic fractures in the femur show complex fracture patterns and are difficult to treat [4]. Because of the increased risk for a revision surgery with elderly patients, who show signs of osteoporosis, the prevention of PFF is essential. One way to prevent PFF is to optimize the treatment of individual patients, who are potentially at risk of osteoporotic fractures, by choosing the most suitable implant design for their subject specific circumstances. Thereby, revision surgeries due to PFF can be avoided. But for that, appropriate models are necessary to predict these fractures for aging bone, which in turn allows an optimization of the initial treatment. In a previous study [5], a subject specific finite element (FE) model was developed and validated. The geometry of a femur was created from quantitative computed tomography (QCT) scans and virtually implanted with a hip stem endoprosthesis. Also, the density values from the QCT scans were mapped onto the finite element mesh of the model. For each element the material parameters were calculated based on the assigned density value, creating a heterogeneous material definition. To simulate PFF, element deletion was implemented and triggered with a stain based damage criterion. In the current work, statistical studies on the changes of bone quality with increasing patient age and developing osteoporosis were incorporated in the model. The WHO classifies the severity of osteoporosis with values for a T-score and Z-score that compare the bone mineral density (BMD) of a patient to a statistical reference population [6]. On the basis of statistical data, the BMD values measured in the QCT scans of the modelled femur were varied, while the individual heterogeneous density distribution was preserved. The new density values were mapped onto the FE mesh of the femur model. Thereby, the femur was modelled to mirror the bone in different age groups and with different severity levels of osteoporosis in high age. The final models incorporate the subject specific geometry and density distribution of a patient's femur as well as the statistical density values resulting from aging and osteoporosis. The FE analyses revealed that a statistical change of bone density with aging at constant Z-Score leads to relative small decrease in fracture load for periprosthetic fractures of a femur implanted with a cementless endoprosthesis. However, for osteoporosis, the fracture load can differ by up to 30% with a cementless endoprosthesis, depending on the severity level of the disease.

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# #145 Developing Stress Corrosion Cracking with Corrosion Small Punch Test


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*Stress Corrosion Cracking* *Small Punch Test* *Spent AGR Fuel Cladding*



**Abstract** Spent AGR fuel is stored in cooling ponds, and the fuel cladding may suffer from stress corrosion cracking (SCC) due to neutron irradiation during operation. Therefore, it is vital to understand the process of cracking and to know the mechanical properties of the cracked cladding material. Because the small punch test (SPT) is commonly used in nuclear industry due to its versatility and the small size of the sample, it was chosen and modified to allow the initiation of SCC and further monitoring crack progression. The new SPT setup (Fig.1a) includes a loop system that circulates a heated corrosive solution to accelerate the initiation of SCC. A mirror is also placed below the specimen to allow further implementation of DIC (digital image correlation) to monitor the cracks. In order to initiate SCC in a short period of time, the combination of environment and loading has been studied, and a 395 ppm sodium thiosulphate solution at 60 °C and a 1.5 kN constant load (Fig.1b) were selected. In a preliminary experiment, the sample was loaded under the stated condition for 7 hours and a crack was observed under the microscope (Fig.1c), however, it was only deformation was found under the SEM (Fig.1d). The experiment therefore will be extended to a longer period of 70 hours. Stress corrosion cracks are expected to develop, and they will be observed under microscopes. In further studies, the DIC will be added to the system that can track the progression of the cracks.


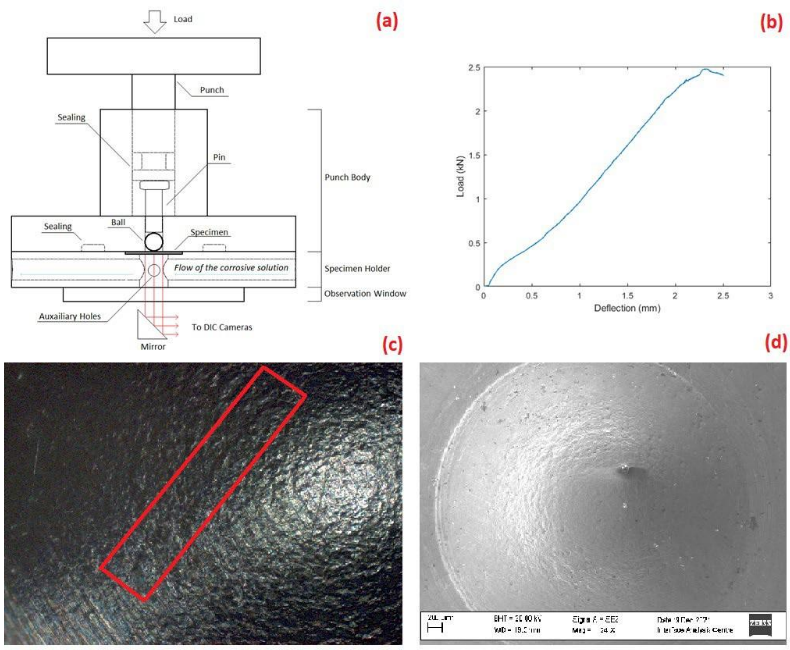


*Figure 1 – (a) corrosion SPT setup; (b) load and displacement curve of a SPT sample; (c) optical microscope image and (d) SEM image of the preliminary test sample*

# #146 Multiphysics FE-analysis and measurements for thermo-mechanical fatigue crack growth rate testing applications

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*TMF* *FEM* *Multiphysics*

**Abstract** Thermo-mechanical fatigue (TMF) data is critical for the generation of appropriate lifing methodologies for a range of in-service applications where non-isothermal conditions are prevalent. To this end the presented methodology is addressed to in-phase (IP) and out-of-phase (OOP) loading cycles in stationary and transient thermo-mechanical fields. The subject of the numerical and experimental study is a single edge notch (SEN) specimen produced from a high-temperature nickel-based alloy XH73M with a rectangular cross- section in the gauge.

The test setup included a Zwick/Roell HA100 servo-hydraulic test frame with a Zwick CUBAS control system. A Trueheat 10-kW induction heating system is utilised to deliver rapid heating rates through a non-uniform multi-turn longitudinal field helical or rectangular coils. Rapid cooling rates were enabled through forced air cooling using pneumatic air amplifier with three nozzles. The TMF tests were performed at uniaxial loading with a load ratio R = 0.1 at a temperature range of 400 - 650°C in the cycle including 30 seconds of loading(heating)/unloading(cooling) periods.

In order to determination a local thermo-mechanical stress-strain rate and displacement fields a new algorithm for the multi-physics numerical calculations developed and implemented incorporates Maxwell 3D, Fluent and Transient Structural modules of ANSYS 2021R1. The algorithm builds upon a coupled heat losses from eddy currents of magnetic induction and force convective cooling accounting for by k-omega SST turbulence model response, which cause gradients of mechanical elastic-plastic deformations.

In the present study, the displacement and strain fields ahead of the notch tip in the SEN specimen was measured using digital image correlation (DIC). The images were captured using a Isi-sys 3D-Micro-DIC stereo sensor system. Infra-red thermography camera, allowing for accurate non-invasive area-based measurements, was employed for temperature distributions control in the SEN specimen under thermo-mechanical loading conditions.

In order to represent the cyclic history associated with the TMF conditions in the experiments, multi-physics finite element (FE) modelling of the stress, strain and displacement fields in the SEN specimen was performed. Moreover, time dependent non- uniform temperature fields were applied with the same cyclic variations and magnitudes as in the experimental OOP and IP cycling. A sensitivity analysis was carried out to explore the effects of the finite element meshing, the turbulence model and the boundary conditions. As a complement to the FEM computations, the DIC displacement field around the notch tip and the infra-red thermography temperature distribution measurements was implemented for the TMF state in the experiments in the SEN specimen. The comparison multiphysics FE-analysis and direct measurements shown in the present study is intended to contribute to a better understanding of the different mechanisms driving TMF crack growth and the address the outstanding questions associated with basic methodology.

# #147 Effects of Liquid Metal Environment on Slip Band Morphology of 316L Austenitic Stainless Steel

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*Liquid metal environment* *Slip band* *316L*

**Abstract** In the development of Generation IV nuclear reactor, it is essential to understand the interaction between corrosive coolant such as molten salts or lead alloys with structural materials[1]. As one of the candidate materials for Generation IV reactor, 316L so far does not show any evidences on susceptibility to liquid metal embrittlement in contact with liquid lead-bismuth eutectic (LBE), one of the coolant candidates. However, there are evidences that LBE might influence plastic deformation of austenitic stainless steels even not being the embrittling factor. Understanding of the mechanisms of the interaction between liquid lead alloys and steels are necessary for the justification of the assessments on potential materials degradation effects.

In one of the mechanisms proposed to explain liquid metal embrittlement (LME), adsorption of liquid metal atoms eases the nucleation of dislocations [2].This interaction may manifest as changes in the surface morphology of the sample since surface is where the interaction between environment and material starts to happen.

In this study, we investigated the effect of LBE on the slip morphology and near-surface deformation of 316L. We use uniaxial loading in slow strain rate tests (SSRT) to obtain materials with a specified deformation state. The surface morphology were investigated with scanning electron microscopy (SEM). In addition to that, in this work we tried to assess the use of quantitative SEM image analysis in assessing slip morphology such as slip band spacing. The assessment was carried out by comparing the results with a more advanced technique such as atom force microscopy (AFM).

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# #148 Structural-temporal peculiarities of dynamic deformation of rock

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*Fracture toughness* *Incubation time* *Fracture energy*

**Abstract** The dynamic fracture of rocks is considered from the point of view of force and energy limiting criteria formulated on the basis of the concepts of the structural-temporal approach. For each limiting criterion set at a different point in fracture time, the incubation time is calculated as a key constant characteristic of the material of the proposed approach, depending on the scale and being the main measure of the reaction of materials. Water saturation effect on the strain rate dependencies of the fracture toughness or and fracture energy of rocks is considered. Using the dynamic destruction of coal and granite as an example, it is shown that the incubation time determined by the force criterion does not depend on the length of the sample cut.

# #149 Numerical modeling of energy dissipation during fatigue crack propagation in metals

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*Energy dissipation* *Plastic work* *Fatigue*

**Abstract** As it has been shown by Taylor and Quinney the process of plastic deformation of metals is accompanied not only by extensive heat dissipation but also by energy storage [1]. According to the classic approach, fraction of energy converted to heat is estimated by constant Taylor-Quinney coefficient. However, experimental investigations show that this value depends on such parameters as material structure, strain, strain rate and loading history [2]. Therefore, precise calculation of the dissipated energy value should take into account the portion of energy which is accumulated in the material.

Approaches based on thermodynamic of irreversible deformation are widely used for the development of models for energy balance calculation in the process of plastic deformation [3]. The main idea is to introduce some internal variable to describe energy accumulation induced by structural changes in the material. In this work, we applied standard thermodynamic formalism to obtain constitutive equation for structural parameter under assumption of small strain induced by initiation and growth of the defects. Thus, total strain is the sum of elastic and plastic strains. Isotropic Hook's law is applied to relate stress tensor and elastic strain tensor. Plastic strain is related to the dissipated processes induced by movement and annihilation of dislocations. Combined kinematic hardening is used for plastic strain calculation. It is assumed that free energy is function of elastic strain and structural parameter in isothermal case. Evolution equation for structural parameter is derived from phenomenological form of free energy function and is used for stored energy calculation. Value of dissipated energy is calculated as difference between plastic work and stored energy.

We have applied this model to calculate dependence of dissipated energy per cycle on crack length for three different titanium alloys in the process of cyclic loading. In all considered cases geometry of the specimens was the same. All samples had an initial crack equal to 3 mm. Stress ratio was equal to 0.1. Simulation was carried out in finite-element package Comsol Multiphysics in plane stress formulation. A stationary crack approach was used for energy balance calculation at the crack tip. Results of the simulation were compared with experimental data on heat dissipation obtained in the Institute of Continuous Media Mechanics UB RAS.

The research was carried out within the state assignment of Ministry of Science and Higher Education of the Russian Federation (theme No. 122012400263-7)

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# #150 Determination of cracks using multiple DC potential drop measurements – FEM Analysis and Experimental Verification of an advanced model

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*Fatigue* *Crack detection* *Potential drop measurement*

**Abstract** The early detection of cracks in fatigue experiments on specimens with round cross-sections is often difficult to perform. Investigations by Hartweg and Bär [1] have shown that cracks can be detected early with a multiple potential probe measurement and even the location of the crack can be localized with the help of a simple geometric model. They used three potential probes attached in a distance of 120° on the circumference of the sample and calculated the normal vector of a plane spanned by the 3 potentials. The opposite direction of the normal vector is the direction were the crack initiation site is located as illustrated in figure 1.

In this work, a further development of the model is presented, with the help of which, in addition to the position of the incipient crack, statements can also be made about the size and geometry of the crack. For this purpose, the resulting potentials for different crack positions, sizes and geometries were first calculated in FEM analyses. The analysis shows, that the crack length can be determined from the length of the normal vector when the geometry of the crack is considered. For different length to depth-ratios of the cracks, however, there are also differences in the relationship between the length of the normal vector and the crack length.

The model is experimental verified by fatigue experiments on a high alloyed steel. Crack initiation was forced by introducing notches with an engraving laser. The experiments show a good agreement with the FEM-Simulations.

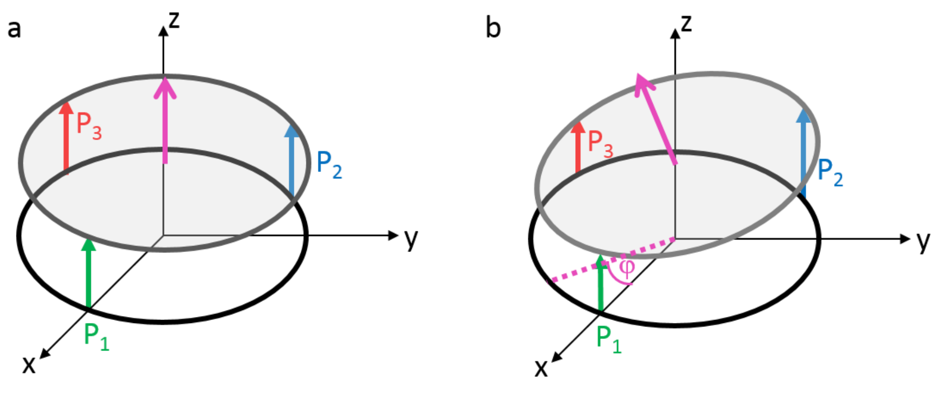


***Figure 1** – Model for determining the position of an initiated crack [1]*

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# #151 Hydrogen effects on micro-damage arrest in an FCC-HCP transformation-induced plasticity steel

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*hydrogen embrittlement* *multiphase steel* *damage evolution*

**Abstract** A special focus of this talk is hydrogen-assisted damage evolution behaviors of multiphase steels. In general, multi-phase steels such as ferrite/martensite dual-phase steel shows hydrogen-assisted failure after significant plastic deformation [1]. During the plastic deformation prior to the failure, damages (e.g., crack or void) are initiated in an early deformation stage, then, they once stop growing via tip blunting neighboring grains that have a different crystallographic structure. When the damages restart to grow or coalesce each other, final failure occur. Therefore, when considering hydrogen effects on failure of multiphase steels, we must note two factors: damage initiation resistance and damage arrestability.

In this talk, we present an example of hydrogen-assisted damage evolution behavior during tensile deformation: a case of ε-transformation-induced plasticity (TRIP) steel that shows deformation-induced martensitic transformation from face-centered cubic (fcc) to hexagonal close-packed (hcp) phases. The steel showed significant hydrogen embrittlement [2]. Specifically, the TRIP steel pre-charged with hydrogen showed ε-martensite-related damage initiation. The damages were significantly arrested at austenite region. According to damage quantification results [3], the average damage size after initiation did not increase until a certain strain, then start to increase, which resulted in final failure [2]. This fact indicates that all of the small damages were fully arrested until the critical strain for restarting damage growth. Furthermore, lowering strain rate accelerated the ε-martensite-related damage growth [4]. Correspondingly, the area fractions of intergranular fracture and quasi-cleavage fracture on the fracture surface increased with decreasing strain rate. In the presentation, we will show details of microstructure-related mechanisms and comparisons with other multiphase steels. In addition, we will discuss microstructure design strategy for hydrogen-resistant high-strength steels, in terms of a use of multiphase microstructures.

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# #152 Fatigue limit estimation of welded joints under constant amplitude uniaxial loading adopting the cyclic R-curve analysis

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*Welded Joints* *Fatigue Limit* *Cyclic R-curve*

**Abstract** Most of the in-service failures of welded structures are due to fatigue damage occurring in the joints. Damage tolerant approaches based on the principles of Fracture Mechanics have been shown to play a key role in this framework, as the fatigue limit is defined by the non-propagating condition of multiple defects at the weld toe [1]. The fatigue limit assessment can be performed using the cyclic R-curve analysis [1–4] which consists in comparing the driving force of a crack propagating into a component, which depends on the geometry, material and external loads, with its resistance curve, i.e. the cyclic R-curve. The crack propagation occurs whenever the crack driving force is higher than the resistance to fatigue crack propagation, while the crack is arrested in the opposite case. Consequently, this suggests that the fatigue limit of a component is defined as that stress level at which the crack driving force curve is tangent to the crack resistance curve. In the present work, the cyclic R-curve analysis has been adopted for determining the fatigue limit of stress-relieved transverse non-load-carrying (nlc) joints made of S355 structural steel and subjected to fatigue axial loadings. Experimental tests have been performed to evaluate the fatigue limit of the joints. The driving force, identified by the applied Stress Intensity Factor (SIF), has been evaluated by means of linear elastic finite element analysis taking advantage of the Peak Stress Method for its rapid estimation. Based on the experimental observations that the crack initiation and early crack growth phases in welded joints occur within the Heat Affected Zone (HAZ) the cyclic R-curve has been experimentally derived for both the base metal and HAZ material.

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# #153 Structural Integrity Assessment of Plates Containing Semi-elliptical Surface Cracks: Finite Element Fracture Analyses

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*Fracture assessment* *Limit load solutions* *Semi-elliptical cracks*

**Abstract** This paper summarizes results of limit load solutions for plates containing semi-elliptical surface cracks subject to complex loadings, to include biaxial tension and positive cross- thickness bending (crack opening moment). The elastic-plastic J-integral data have been determined from a series of cracked body finite element analyses (FEA) incorporating various plate and crack geometries, loading combinations, and elastic and elastic-plastic material models.

The FEA results are validated by Lei and Budden limit load solutions [1], principally via production of R6 Option 3 failure assessment curves (FACs) and comparison with Option 1 and Option 2 FACs. Comparison with other available limit load solutions in the literature has also been carried out. The paper aims to provide some improved guidelines for the safe life assessment margins regarding structural integrity of aged components for energy industries.

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#154 Multiaxial fatigue behavior of a Low nickel/High nitrogen austenitic steel with superimposed static compression and torsional loads

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*Multi axial fatigue* *Low-nickel austenitic steel* *Cyclic softening/hardening*

**Abstract** Austenitic stainless steel P558 with a low nickel content and high nitrogen content was subjected to multiaxial fatigue testing at room temperature in static compression/cyclic torsion modes. 5°, 10°, 15° and 20° cyclic torsional angles and 250 MPa and 350 MPa axial static compression loads were employed. Experimental test results indicate that for the low angle rotation experiment, a cyclic hardening in the negative direction and a cyclic softening in the positive direction and asymmetry in the shear stress magnitudes for positive and negative directions was noted. On the other hand, for the high angle rotation experiments, initial cyclic hardening is followed by continuously gradual softening for most of the fatigue life of most the samples, more rapid softening followed until fracture. A symmetric shear stress nature was also observed. Electron microscopy observations revealed that dislocation gliding is the main deformation mechanism in the 5° rotation experiment. Furthermore, annealing twin boundaries tend to lose their integrity due to accumulation of dislocations while deformation twins start to form in the high angle experiments. The mechanical response and microstructural changes are different from those of 316L an austenitic steel with similar chemical composition but with higher nickel content. It is believed that the minimum Ni and/or high nitrogen contents imposes a sensitivity of the stacking fault energy on the FCC crystal structure.

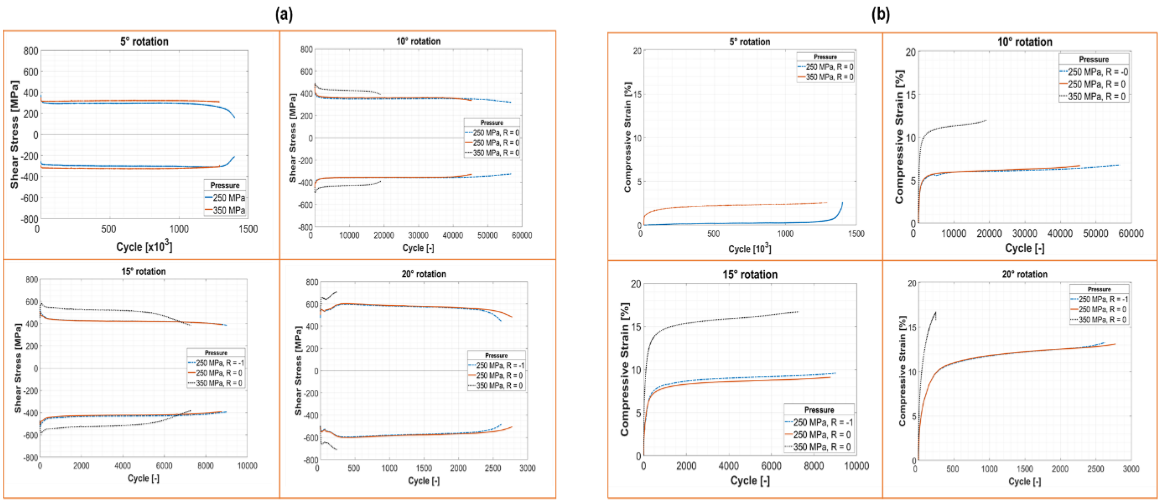


***Figure 1*** *- (a) Plots of shear stresses against cycles to failure for 5 degrees, 10 degrees, 15 degrees and 20 degrees angle range and (b) Plots of axial strains against cycles to failure for 5 degrees, 10 degrees, 15 degrees and 20 degrees angle range.*

# #155 Fatigue delamination growth: is UD testing enough?

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*Fatigue delamination growth    Multidirectional interface    CFRP*

**Abstract** Over the past decades, the research community has adopted standard specimen geometries for the study of fatigue driven delamination growth in fibre reinforced polymer composite materials. Examples include the double cantilever beam (DCB) and end notched flexure (ENF) specimens. In these specimens, the studied delaminations are always between two plies with identical fibre orientations. However, operational structures usually consist of multidirectional laminates. Furthermore, it is well known that in case of out-of-plane loading, delaminations preferentially occur at interfaces with different fibre orientations. This raises the question of how the fatigue delamination growth behaviour is affected if the adjacent plies have different fibre orientations. Although studies have been performed into the effect of multidirectional interfaces on delamination growth under quasi-static loading, the fatigue problem has so far received almost no attention.

This work presents a first study into the effect of fibre orientation on fatigue delamination growth. We conducted delamination growth tests on DCB specimens with a number of different delaminating interfaces, namely: 0//0, 0//45, 0//90, 45//45, 90//90 +45//-45, and 30//-60. As shown in Figure 1, the crack growth rate at a given maximum SERR is strongly affected by the fibre orientation. In case of a dissimilar interface, the crack growth curve moves to the right compared to the unidirectional interface. However, this relationship is not monotonic; for instance, the crack growth curves for the 0//90 interface are between those for the 0//0 and 0//45 interfaces. The change in crack growth rate was associated with observable changes in the nature of the crack growth process. For example, for the 0//90 interface oscillatory crack migration was observed. The results of this work show the importance of further investigating the effect of fibre orientation on delamination growth, if we want to understand delamination growth in practical applications.

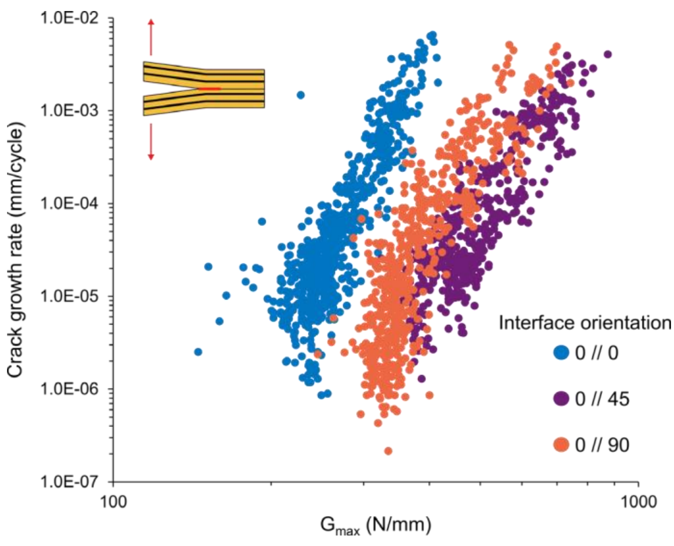


***Figure 1** – Crack growth rate curves for three of the tested interfaces. Combined results shown for 2 specimens per interface.*

# #158 Fatigue damage analysis on 42CrMo4+QT via critical volume approach

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*Notches* *Size effect* *High cycle fatigue*

**Abstract** Notches have influence on the fatigue strength of components. Two major approaches are often encountered when assessing this effect – the theory of critical distances and the stress gradient approach. The assessment of the size-effect, quantified for example by the volume of the region where fatigue crack initiation is most probable, should be used in these solutions, but is often omitted.

The size effect can be interpreted as the result of the weakest-link principle in fatigue – the larger the volume of the loaded material, the larger the probability of an occurrence of a large defect, detrimental to the service life of the component. An analysis of this effect is important to properly assess the influence of notches on fatigue strength of components. The topic is important in other areas, e.g., using experimental results obtained on laboratory-type specimens for predicting the fatigue properties of real components (which are generally much larger).

Several S-N curves have been obtained experimentally, two on notched (V-type) and four on unnotched specimens, all manufactured from 42CrMo4+QT high-strength steel. The unnotched specimens have been designed in such a way to have a widely varying critical volume – see Figure 1. Experiments were carried out in the high-cycle fatigue region (roughly $10^4$ to $10^7$ cycles) in fully reversed push-pull mode.

Obtained experimental data has been used in a numerical solution. This involves the postprocessing of FEM results through an optimization routine in order to find a dependency of the critical volumes of individual samples and the experimentally obtained fatigue lives. The goal is to apply the same model for predicting the fatigue strengths of both notched and unnotched specimens. This can lead to fatigue notch sensitivity assessment using data obtained on unnotched specimens only.

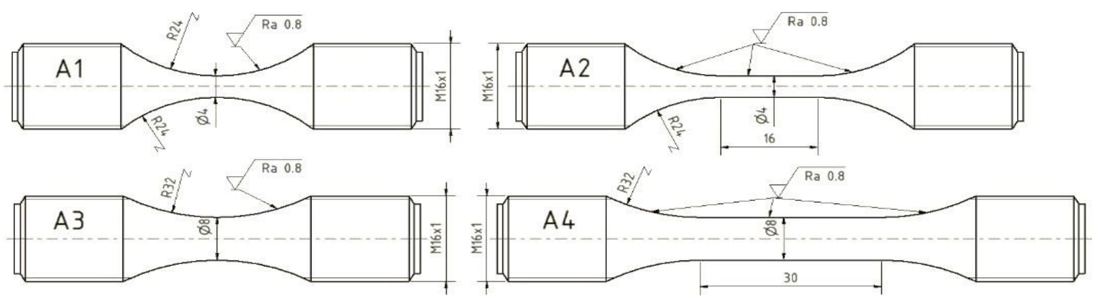


***Figure 1** – unnotched specimens used in the experiments*

# #159 Numerical modelling of cleavage in high strength steels with parametric study on microstructures

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*Cleavage fracture* *Multi-barrier modelling* *Microstructures*

**Abstract** The need for more accurate cleavage modelling is particularly acute for a new generation of high-strength steels because they obtain their favorable properties through complex, multi- phase microstructures. One of the challenges in cleavage modelling is the strong sensitivity to material characteristics at the micro level.

A numerical method is proposed that represents the cleavage fracture toughness of steels incorporating the statistical information of microstructures and tensile properties. The method is a multi-barrier model and is coupled with Finite Element Analysis that accounts for microcrack nucleation by hard inclusions and microcrack propagation based on the weakest link mechanism. The method accounts for several microstructural features (grain size, hard particle size, and hard particle geometries) simultaneously, and incrementally considers the deactivation of crack initiators. This model is based on prior multi-barrier models [1] and has been demonstrated on fracture data from a S690 QT plate that was fractured at -100 ° C [1] based on previously published data [2]. In this article, isoparametric variations on microstructural parameters, such as grain size, second particle distribution, second phase, etc. are performed in order to find the correlations with macroscopic fracture parameters.

By comparing the simulations, the trade-off between various microstructural parameters for controlling toughness is quantitively estimated.

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# #160 Hydrogen trapping and embrittlement revealed in martensitic Fe-xAl-yC steels

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*Martensite* *Thermal desorption spectroscopy* *In-situ bending*

**Abstract** Designing lightweight materials is nowadays one of the biggest challenges for materials science engineers. Recently, a new design concept for bearing steels was suggested based on a martensitic Fe-Al-C system which offers a lot of opportunities: it is cost effective, high strength levels are reached and it has a lower density and better general corrosion resistance compared to the traditional bearing steels such as 100Cr6. However, steels are exposed to hydrogen (H) containing environments both during production and in-use. Therefore, this study investigates the susceptibility to hydrogen embrittlement (HE) of various Fe-xAl-yC steels. In order to do so, a systematic approach is used. In a first step, the effect of C additions on the interaction between H and generic Fe-C martensitic steels is investigated. Thermal desorption spectroscopy (TDS) analysis shows that the main H trapping sites are dislocations and high angle grain boundaries (HAGBs). The amount of H detrapping from dislocations increases with increasing C content while H trapping at the HAGBs is mainly dominated by the prior austenitic grain (PAG) size. In-situ hydrogen bending tests show that H causes a transition from a microvoid (Fe-0.2C), intergranular (Fe-1.1C) or mixed (Fe-0.4C) fracture type for the reference air-tested samples to a hydrogen induced cleavage fracture appearance. This transition is paired with a significant ductility loss which can be explained by the hydrogen enehanced decohesion (HEDE) mechanism, indicating that hydrogen trapped at the HAGBs plays an important role. Due to the limited amount of ductility (the samples break already in the elastic region when tested in a H rich environment), H trapped at the dislocation plays an insignificant role in the HE mechanism for these type of materials. In a next step, Al is gradually added to several Fe-yC steels so a well-founded study on the effect of both alloying elements and their interaction with hydrogen is established. For an optimal Al/C ratio, a very thin ferritic film on the PAGBs is formed which increases the ductility in air to a high extent. When mechanical tests are performed in a H rich environment, the ferritic microfilm causes a delay in hydrogen induced fracture, when compared to samples with a similar hardness that do not contain such a microfilm, since fracture propagation is redirected along the ferrite/martensite interface resulting in an intergranular fracture surface. The underlying mechanism is an interplay between the HEDE and hydrogen enhanced localized plasticity (HELP) mechanism. These results indicate that an optimal ratio between C and Al in martensitic Fe-xAl-yC steels offers the opportunity to increase the resistance to HE by innovative grain boundary engineering.

# #161 Effect of specimen size and thickness on ductile crack growth of a high toughness 316L steel

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*Fracture toughness* *Ductile fracture* *Size effect*

**Abstract** Crack growth resistance is a key mechanical property to assess structural integrity. ASTM E1820 and ISO 12135 are the two testing standards used to determine $JJ - \Delta aa$ curves. There are minor differences between these two standards, but they both require the specimens to be large enough to consider the resulting toughness as valid. Determining the valid plane strain crack growth resistance of very tough materials requires large specimens. In practice, smaller specimens must often be used because the material is scarce (e.g., irradiated materials) or only available with a specific shape (e.g., plates). The question then arises of obtaining valid $JJ - \Delta aa$ curves from tests on small or miniaturized specimens.

This study investigates the ductile fracture behaviour of an austenitic stainless steel 316L(N). Its elastoplastic behavior at high strains is determined using various axisymmetric specimens (see fig. 1a). Edge tracking is used to monitor diameter variations. Homothetic compact tension specimens (CT50 to CT4) and CT specimens with various thicknesses (CT12.5 with thickness=12.5,10,7.5,5 mm) were tested using the elastic unloading compliance method to determine the J-R curves. Metallographic and fractographic observations were systematically carried out. These experimental data were used toparametrize a Gurson-Tvergaard-Needleman damage model for ductile failure. Tests on CT specimens, including the unloading steps, are simulated (fig.1b), to check the testing procedure. $JJ$ values can then be derived from the simulation results applying the procedure of the standards (see fig. 1c). Using the parametrized GTN model, very large specimens satisfying the validity criterion of the standards can be simulated to derive valid $JJ - \Delta aa$ resistance curves.

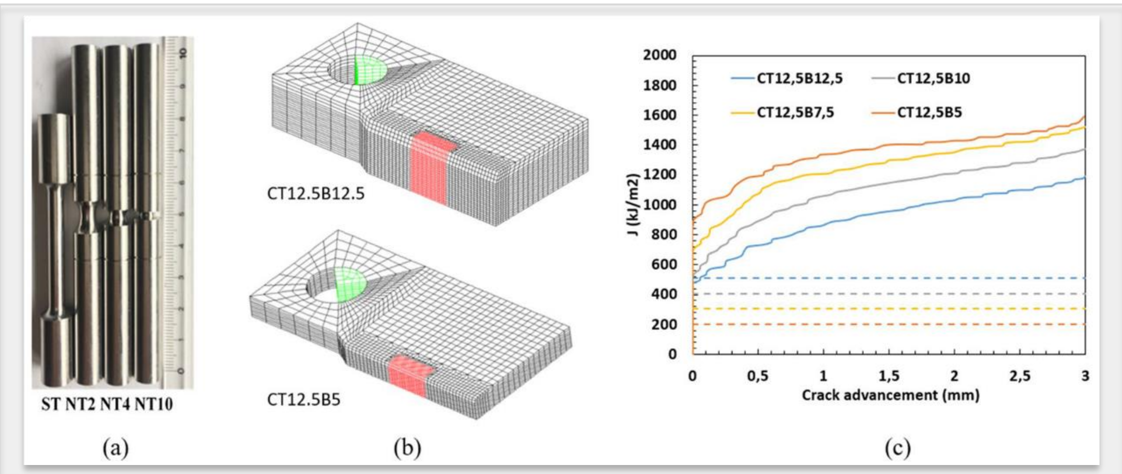


***Figure 1** – (a) Tension specimens; (b) Models de CT (c) J-R curves for CT12.5 with different thickness*

# #162 Investigation on the fatigue resistance of transverse attachments and design of VA fatigue tests

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*Welded joint* *Variable amplitude loading* *Load Measurements*

**Abstract** The fatigue strength of structural steel components subjected to cyclic loading is often characterized in terms of S-N curves derived under constant amplitude (CA) loading. However, these are often subjected to load histories of variable amplitude and mean stress, i.e. variable amplitude (VA) loading. To take into account this loading condition for the design or the verification of structural components, damage accumulation models and modification of S-N curves have been proposed in the literature. However, these models require experimental characterization to verify or eventually calibrate some model parameters, e.g. the critical value of the Palmgren-Miner damage, among others.

This paper investigates the CA fatigue behavior of transverse welded steel attachments by reporting on an experimental characterization. Fatigue cracks have been monitored to obtain information about nucleation sites and growth rates. Moreover, the paper reports on the experimental design of VA fatigue tests using a load history obtained from traffic measurements from a Swiss road bridge. As a design tool, the preliminary study using advanced probabilistic fatigue prediction models calibrated on similar welded details is presented. This model can also be used to define other load spectra to be applied in future VA experimental studies.

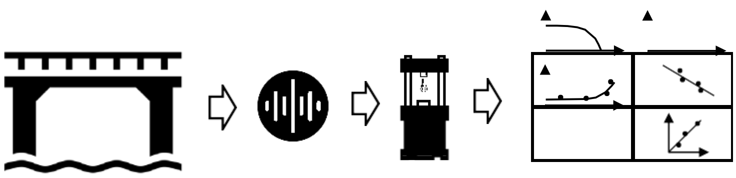

*Figure 1. Overview of procedure*

# #163 A novel FFT-based homogenization scheme for cohesive zones

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*Computational Homogenization* *Cohesive Zone Modeling* *Multi-layer material*

**Abstract** Cohesive zone models with finite thickness are widely used for the fracture mechanical modeling of adhesive joints. Within this approach, the whole adhesive layer is modeled as a cohesive zone, which usually leads to a significant thickness dependence of the related traction separation law and the energy release rate. The traction separation laws can be measured directly in experiments, e.g., by means of a double cantilever beam (DCB) test. Nevertheless, a full experimental characterization requires many experiments at different load rates, thicknesses, and mixed-mode fracture (if it should be considered in the model). Moreover, materials that are used in engineering applications are usually heterogeneous and its mechanical behavior is determined by the constituents. If the constituents, their mechanical behavior, and the characteristics of the microstructure of the material are known, computational homogenization can be applied to reduce the necessary experimental effort. Besides the classical Finite Element Method (FEM), solvers, which are based on the Fast Fourier Transform (FFT), are also used for homogenization. Those are computationally more efficient for many types of materials. A homogenization scheme for cohesive zones is already available in the literature using FEM, however an FFT-based method could reduce the computational cost. Based on that existing method, such an FFT-based homogenization scheme for cohesive zone models is presented. For this purpose, the intrinsic periodic boundary conditions in the FFT solver are not appropriate in through thickness direction of the cohesive zone. Instead, the separation and consequently the displacements at those boundaries are prescribed which is approximated by small, stiff layers that constrain the periodic fluctuation displacements. The separations are imposed by means of a specific volumetric average strain tensor and the tractions can be obtained as the volumetric average of the stress field multiplied by the normal vector to the middle plane of the cohesive zone. Our implementation of an FFT solver, which uses the displacement-based Lippmann-Schwinger equation and Anderson extrapolation, is presented as well. Finally, two practical examples are given including the generation of virtual Representative Volume Elements (RVEs): An adhesive with fillers and pores and the fiber matrix core material of a metal sandwich plate, Hybrix™. Furthermore, an implicit gradient damage model is implemented to describe the ductile failure behavior of the base materials. It is demonstrated that the boundary conditions are well approximated in both examples. In addition, it is shown that the homogenized traction separation law is independent of the RVE size, which is the case if standard continuum mechanical homogenization techniques are applied to damage mechanics.

# #164 Numerical Investigation on the Effect of Fillers on the Fracture Behavior of Adhesives

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*Computational Mechanics* *Micromechanics of Fracture* *Machine Learning*

**Abstract** Adhesive bonds play an important role in industry, not least because they perform various tasks in the field of lightweight construction. An important example is the analysis of released energy during crash tests in the automotive industry. This results in the demand for a calculation model that is suitable for representing the fracture behavior. In order to research in a resource-saving way the non-destructive methods for determining the constitutive law are increasing. One approach is the homogenization of microstructures using solvers, based on Fast Fourier Transform (FFT). Further approaches in the field of machine learning become relevant in the research.

The microstructure of adhesives is investigated in order to determine the effects of different fillers and volume fractions on the cohesive constitutive law in a sustainable way. For this purpose, a program is developed, which automatically generates representative volume elements (RVE's) with different volume fractions of various fillers, as well as different pore fractions. These are used for homogenization with the aid of a preprogrammed FFT solver.

In the further process, the results of the homogenization are used to train a preprogrammed neural network, in order to generate predictions for the cohesive zone model in dependence of the volume fractions. Afterwards this neural network is implemented as user material (UMAT) in the commercial finite element (FE) program Abaqus.

Therefore, simulations of double cantilever beam (DCB) tests as an example are used, as data analysis. This is a necessary step to validate the developed non-destructive method in terms of its preciseness and the resulting practical usability, with focus on computation times, convergence, etc.

# #166 Finite element modeling of the mesoscale fracture of Ti–6Al–4V lattice structures using microtomography

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*Mesofracture* *Lattice structures* *Microtomography*

**Abstract** This work concerns modeling of the deformation process, taking into account the local fracture of additive manufactured lattice structures obtained by laser power bed fusion. The study uses diamond structures of Ti–6Al–4V titanium alloy with nominal relative density of 18.5%, 27%, 50%, and 66%. To model the process of tensile deformation of the materials, geometric models were used, recreating the real shape of the investigated lattice structures. The realistic shape of the lattice mesostructure of the material was obtained by means of x-ray computed microtomography. The work presents the numerical modeling investigation and the results of the calculations. For numerical modeling of the deformation and fracture process the true stress-strain curve was used in order to determine the nonlinearity of the material in range of plastic strain, and the ductile fracture criterion was implemented. The influence of the material relative density and structure shape on mesoscale fracture process is also discussed. The numerical nominal stress–strain curves are compared with the results of experimental testing. The analysis of stress and strain distributions and their variability caused by local mesofracture in the studied additive manufactured material is also described.

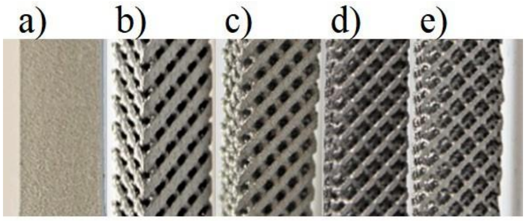


***Figure 1 -*** *Tested additive manufactured specimens with various relative density values a) near to 1 (solid material), b) 66%, c) 50%, d) 27% and e) 18.5%.*

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# #167 Numerical study on the effect of defects in additive manufactured titanium lattice struts on its fracture initiation

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*Fracture* *Lattice struts* *Finite element method*

**Abstract** The works described numerical study on the effect of defects in additive manufactured titanium lattice struts on its fracture initiation during deformation. In the investigation were use struts separated form diamond lattice structures of Ti–6Al–4V titanium alloy with nominal strut thicknesses of 0.49 and 0.6 mm. To carry out numerical calculations, the finite element method was used. In order to take into account the real shape of the mesostructure in numerical calculations, microtomographic measurements of the examined struts were used. Due to the use of the tomographic technique in numerical calculations, the shape of defects resulting from the laser power bed fusion method was included. These were, among others, micropores and micronotches on the surface of the tested struts, formed mainly as a result of the production of subsequent layers of the material the characteristics of the production method. As a result of the numerical tests, the distributions of stress and strain in the deformed lattice struts were obtained. On the basis of the results, the deformation process of the material was analyzed and the places where the fracture of the material could initiate were indicated. The influence of the struts thickness and their defects on the fracture initiation were also analyzed.

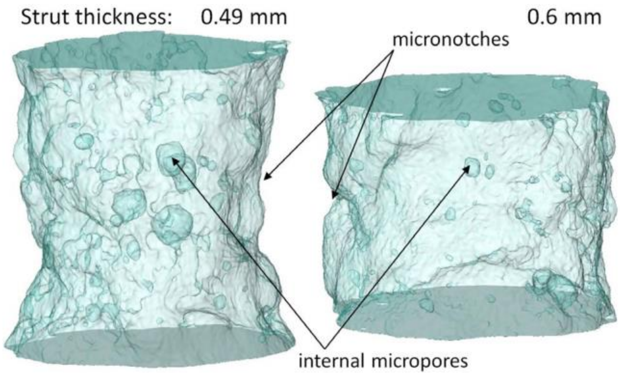


***Figure 1** – Concerned additive manufactured Ti–6Al–4V lattice struts*

The paper was accomplished under grant no. UMO-2016/23/N/ST8/03519 at the Bialystok University of Technology and financed by the National Science Centre (Poland). Participation in the conference was funded by the program of the Ministry of Science and Higher Education (Poland) under the name “Regional Initiative of Excellence” in the years 2019–2022, project number 011/RID/2018/19, with an amount of financing equal to 12,000,000PLN.

# #168 A numerical method for obtaining plasticity-induced crack closure

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*Crack closure* *Finite Element Method* *Contact pressure*

**Abstract** The vertical displacements of the nodes behind the crack front have been extensively used to obtain numerically the crack opening loads ($P_{op}/P_{max}$) and, therefore, the plasticity-induced crack closure. Although this procedure has been demonstrated to be adequate for positive stress ratios (Figure 1*a*), it has been found an uncertainty of using the vertical crack tip opening displacements (CTOD) of the first node behind the crack tip under negative stress ratios (Figure 1*b*). For this reason, the main objective of this paper is to develop a numerical methodology for obtaining accurate results of crack opening loads for the whole range of stress ratios. Furthermore, the paper is focused on analyzing the distribution of the plasticity induced crack closure through-thickness, going further than the simple plane stress or plane strain assumptions. The purposed method consists of evaluating the element contact pressures of all nodes behind the crack tip from the first to the last released row of elements (Figure 2) included on a crack propagation finite element model. Moreover, this method is tested at positive stress ratios and results show a good agreement with the CTOD method (Figure 1*b*).

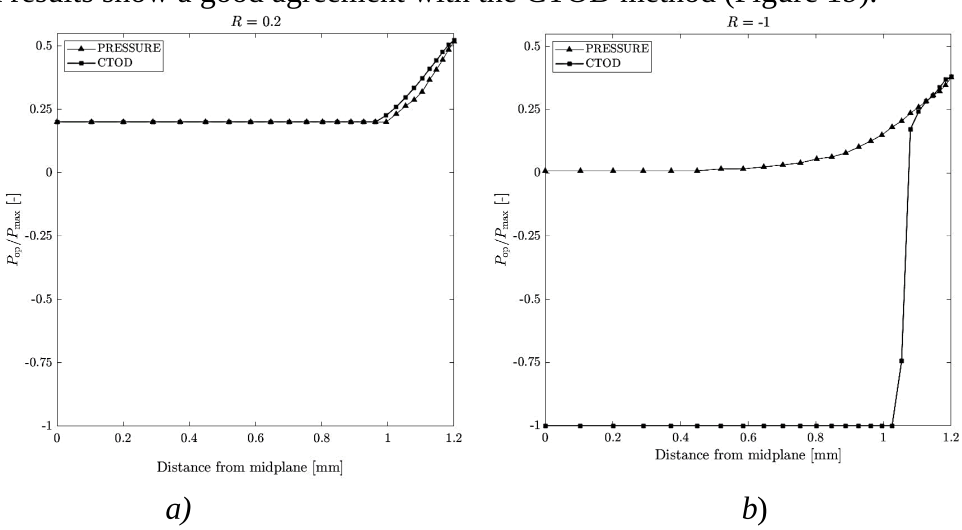


***Figure 1** – Comparative of two method for processing numerical results*

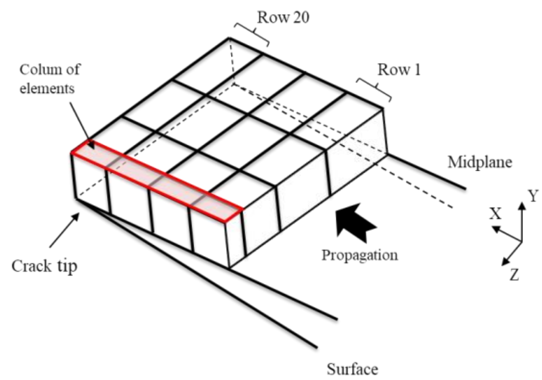


***Figure 2** – Numerical purposed method*

# #169 A Machine Learning Approach to Finite Fatigue Life Prediction in Additively Manufactured Metals

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*Fatigue* *Machine Learning* *Additive Manufacturing*

**Abstract** The advent of modern manufacturing techniques such as Additive Manufacturing has allowed today's engineers to unleash their creativity in creating topology optimised components. Nevertheless, this comes to a price, at least in the current state of development of the technique. The price to pay is related to the presence of inhomogeneities within the manufactured material that may affect its mechanical performance. For instance, but not limited to, additively manufactured materials may show distributions of both sub-millimetre defects and multi-scale residual stress. Accounting for the presence of these features turned out to be of utmost importance when designing these materials against failure; fatigue failure particularly.

Especially when dealing with the evaluation of the material defect populations, modern experimental techniques, such as Computed Tomography (CT), can give an important input towards a more and more accurate fatigue failure assessment. In fact, this non-destructive technique enables researchers, or engineers, to retrieve a large amount of significant information about defects, e.g. dimensions, aspect ratio, location, morphology etc. This data is not completely employable in conventional solid mechanics theory, although it is known that some of them may play a non-negligible role. To attempt accounting for these "extra" data, to predict the mechanical behaviour of this class of materials, Machine Learning can be the most suitable approach.

In the present work, a Machine Learning approach based on Neural Network (NN), is employed to forecast the finite fatigue life of a Ti-6Al-4 V alloy manufactured via the Selective Laser Melting (SLM) technique. Upon accurate training of the structured NN using experimental data, independent fatigue tests are used to validate the proposed method. The robustness of the proposed method and comparison with the Linear Elastic Fracture Mechanics (LEFM) approach is carried out to highlight benefits and limitations.

# #170 A probabilistic FEM approach for the design of glass components

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*Glass* *Structural Integrity* *XFEM*

**Abstract** Stress-based failure criteria are commonly used in the design of glass components [1], even though they rely on a parameter, glass strength, that is not a true material property because it depends on the fracture toughness, the flaws size distribution, the test setup, as well as the specimen size and geometry [2]. As a result, large safety factors are introduced to ensure a safe design. In addition, the interaction between cracks, the effect of stress concentrations, and the influence of the edge flaws condition on the glass strength are usually neglected. To get around the drawbacks of such approaches, a new computational methodology is herein proposed for a more reliable and sustainable design of load-bearing glass elements. The methodology, that adopts a stress intensity factors-based fracture criterion, can be applied to predict the edge strength of glass elements with arbitrary geometry and edge flaws scenario.

The novel developed methodology consists in: (i) modelling the structural element through the finite element method, (ii) randomly applying to the FE model a population of surface flaws extracted from a pre-defined statistical distribution function, (iii) computing the related stress-intensity factors, (iv) evaluating the load carrying capacity by equating the maximum stress-intensity factor to the fracture toughness. Because of the stochastic nature of the problem, where the size of the edge flaws is the random variable, the Monte Carlo method is used to obtain the probability density function of the failure load. Finally, the critical load referred to a chosen probability of failure is derived.

The eXtended Finite Element method is used because of its inherent capability to deal with multiple cracks of any position and length without adapting the mesh topology [3], and the enrichment functions proposed by Liu et al. [4] are implemented since they enable a direct computation of the stress-intensity factors at the tip of the cracks without any post-processing. The current version of the numerical methodology is limited to plane stress/strain models, although its extension to 3D problems is quite straightforward.

Several case studies are shown to demonstrate the accuracy and reliability of the method in assessing the structural integrity of glass components.

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# #172 Effect of the impact pulse on the dynamic fracture toughness behavior of high-strength steel and nodular cast iron

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*Fracture Toughness* *Impact Test Machine* *Metallic Materials*

**Abstract** The effect of the impact pulse in an instrumented pendulum impact testing machine on the energy conversion was investigated. To this end, the impact velocity, the stiffness, strength and toughness behaviors of the specimens were varied. The impact velocity was varied in the range of 0.22 to 0.84 m/s (corresponds with 0.5 to 7.0 J impact energy $E_0$),

i.e. low-blow tests were performed. Furthermore, two different materials, i.e. quenched and tempered steel 42CrMo4+QT and nodular cast iron EN-GJS-400-18, were examined. Specimens with different notch/crack geometries ($0 \leq a/W \leq 0.5$) were used.

The force was measured by the instrumented tup. The displacements and velocities of the specimen and the components of the testing machine were identified by displacement and velocity measurements using two laser interferometers. Furthermore, the crack opening displacement was determined using an optical extensometer. The development of the damage was then examined on the fracture surfaces.

The results showed an incomplete conversion of energy on the samples during impact tests. Furthermore, a non-linear relationship between force and displacement was observed during linear-elastic tests. This leads to an overestimation of the stress that is experienced by the specimen. A part of the applied energy is absorbed by components of the test machine. Using the displacement measurement, the dissipated amounts of energy could be quantified. By measuring the velocity and displacement at several points in test machine, it was also possible to identify the contribution of individual components over time. Furthermore, the crack length could be estimated from the resonance frequency of the specimens.

Based on the results, the dynamic fracture toughness calculation could be adjusted. This was done by subtracting the displacements of the (oscillating) support and other components from the total displacement of the specimen. Furthermore, it was shown that the evolution of the crack opening displacement could be used to determine the onset of crack growth.

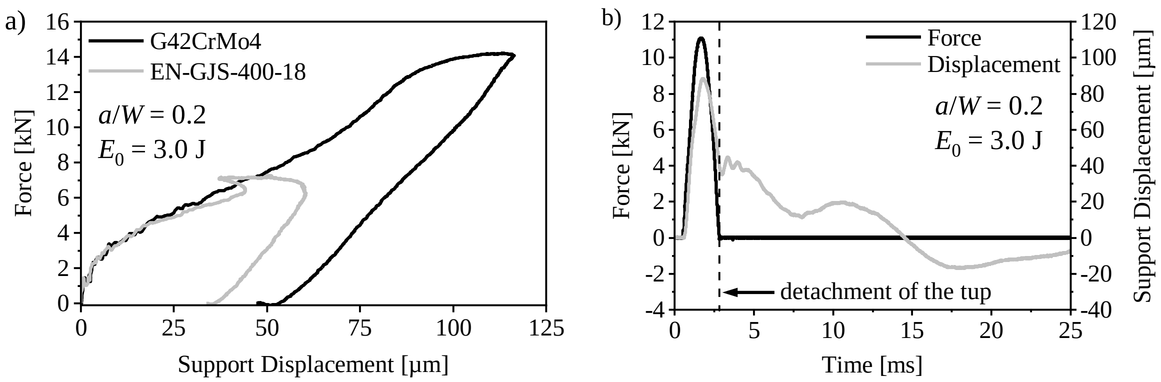


***Figure 1** – a) Force-displacement curves of the support in elastic tests for different materials, b) Force- and displacement-time curves after testing 42CrMo4*

# #173 Microstructural Investigation of Ti-6Al-4V after High Pressure Torsion Fatigue (HPTF) Experiments by Scanning Electron Microscopy (EBSD)

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*Ti6Al4V* *Multiaxial stresses* *Monotonous pressure by cyclic tostion*

**Abstract** During the last century, use of implanting endoprosthesis in the human body has increased. In addition to the absolutely necessary biocompatibility, materials must have wear and corrosion resistance as well as a corresponding fatigue behaviour. As a result of the stresses that occur in the implanted state of the material, fatigue has a significant influence on long-term use of an endoprosthesis. However, very little empirical research has been carried out to determine the material fatigue behaviour after multiaxial stress tests.

In order to be able to examine the entire fatigue, high-pressure torsion (HPT) procedure are required, which is based on monotonous multiaxial tension. Since fatigue by definition occur as a result of temporarily alternating loads, HPT approaches are to be provided with a cyclical stress component in the context of fatigue tests. The HPT principle is to be expand; corresponding to that a monotonous pressure and a cyclic torsional stress should be applied. This approach is known as high pressure torsion fatigue (HPTF).

The aim of this study was therefore to investigate the mechanical behaviour of the titanium alloy Ti6Al4V, which is a common biomedical material and often come to use in surgical intervention, after HPTF by scanning electron microscopy to determine which microstructural changes occur in the context of multiaxial cyclic stresses.

The selection of the test material Ti6Al4V is based on the different crystal lattice structures: the β-phase is body cubic centered (b.c.c) and the α-phase has a close-packed hexagonal crystal structure (c.p.h.). Aluminum is added in order to achieve an increase in strength through solid solution hardening and also stabilizes the hexagonal α-phase. As a β-isomorphic element, vanadium stabilizes the β-phase up to room temperature and gives the alloy improved ductility properties. The HPTF process were carried out on double-cone samples. The test parameters include the same compressive strength by different torsional angles to achieve grain refinement.

Results of the HPTF test showed that the change in the microstructure increases with higher torsional angle, so significant differences between sample with high torsional and less torsional angle were observed. In contrast to sample with lower torsional angle, sample, which were stressed with higher torsional angle, show a higher change in the grain structure; precipitations, grain reorientation and grain-clustering take place in the microstructure of high stressed sample. Furthermore, crack initiation can be found as well. In return sample with minimum torsional angle show no significant change in the microstructure even at the extreme radius of the specimen.

This suggests that with HPTF tests grain refinement is under certain circumstances is possible until crack initiation starts.

# #174 Role of softening in reduced ductility of hydrogen-affected pipeline steel

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*Hydrogen softening* *Pipeline steel* *Fracture*

**Abstract** The development of macroscopic localizations due to diffuse necking, localized necking, and shear banding is highly influential to the engineering fracture strain. These effects are well known to depend on material hardening/softening, so there is competition between the macroscopic true stress/strain curve and fracture behaviour when explaining loss of ductility. Hydrogen is known to both soften and embrittle steel. It is also known to be drawn to areas of high plastic strain and high stress triaxiality, which are both characteristic of a neck or other localization. Therefore, some loss of ductility in hydrogen-affected steels might be explained by an interaction by which hydrogen is attracted to a macroscopic localization, thus softening the material and accelerating the localization process.

Among many others, Boot et al. [1] have reported that pipeline steel will have a decreased engineering strain to fracture when exposed to gaseous hydrogen at pressures representative of pipeline operating temperatures. The results of [1] are relatively invariant of hydrogen exposure up to the point of necking, then subsequently show an increased softening and then lower engineering failure strain. While fractographic inspection has clearly shown a change of mechanism from pure void nucleation, growth and coalescence to a mix including transgranular fracture, it is unclear from the macro-level results what the separate roles of localization and fracture are.

In this paper, we will re-examine the experimental results of [1] by inverse engineering the plasticity properties that are necessary to obtain the measured engineering stress-strain curves for a pipeline steel that was tested with pressurized hydrogen. This will be done with a coupled hydrogen diffusion model that was proposed by Krom and Bakker [2] and implemented by [3]. In order to isolate the role of strain hardening, softening, and localization on the results, damage and fracture mechanics will be ignored in the model.

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# #175 Cement Paste and Cement-Steel Interface Cohesive Parameters Estimates: Supervised Learning on Numerical Simulations Results

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*Cohesive Zone Model* *Identification* *Interface*

**Abstract** Numerical simulations of a three-point bending test are carried out on both pure cement paste sample and cement-steel composite one at the cement-steel interface scale. In these simulations, damage behavior is modeled by cohesive zones localized on the boundaries of a planar Delaunay mesh elements – Cohesive-Volumetric Finite Element approach – allowing a progressive separation between adjacent elements. Simulations are performed up to the samples total failure.

Practical formulas are derived from a supervised learning comparing the results of simulations associated to distinct cohesive parameters values of both cement paste and cement-steel interface. Knowing the force at breaking point and an average value of the crack speed, these formulas estimate the normal mode cohesive parameters which have been considered in numerical simulations.

The three-point bending tests which have been considered in the numerical simulations are then carried out on CEM I cement paste and cement-steel composite samples. Using the practical formulas and the experimental measurements, normal mode cohesive parameters of both cement paste and cement-steel interface are estimated at the scale of the interface between cement paste and steel aggregates in concrete.

# #176 Anisotropy of hydrogen embrittlement in ferrite-pearlitic steel considering operational degradation

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*Pipeline steel* *Hydrogen* *In-service degradation*

**Abstract** The green hydrogen currently plays an important role as a decarbonized energy carrier. It can be transported cost-effectively over long distances by pipelines. It is potentially possible to use existing gas transmission networks for this purpose. However, a significant part of gas transit pipelines is near the end of their design life, that is in-service degradation of gas pipeline steels [1, 2] should be taken into account at assessment of possibility of usage of existing gas pipelines for hydrogen transport. Long-term operated pipeline steels can be more susceptible to hydrogen embrittlement. The research is aimed to the assessing a susceptibility of operated pipeline steels to hydrogen embrittlement. The low-carbon pipeline steels with different strength grade from the point of view of their sensitivity to hydrogen embrittlement in the as-delivered state and after long-term operation were investigated. The main objective of this study was to determine whether degraded pipeline steels became more susceptible to hydrogen embrittlement than the as-delivered one and whether long-term operation influenced on susceptibility of pipeline steels to hydrogen embrittlement. The properties and fracture mechanism of operated steels tested under mutual action of hydrogenation and static loading were compared with that for steels in the as-delivered state (from reserved pipes), which enabled evaluating the effect of operation on hydrogen embrittlement sensitivity of pipeline steels.

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# #177 A study on defect-induced fatigue failures in SLM Ti6Al4V Alloy

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*Additive Manufacturing* *Fatigue* *Defects*

**Abstract** Additive Manufacturing (AM) facilitates design freedom with near-net complex shape structures. Despite several advantages, AM components are associated with lots of inherent defects such as lack of fusion, unmelted powder particles, porosities, etc. These types of inherent defects are known to deteriorate the mechanical properties of the component. The aim of this research is to investigate the effect of defects on the fatigue behavior of selectively laser melted (SLM) Ti6Al4V alloy at room and elevated temperatures.

Specimens for tensile test, fatigue test and microstructural analysis of Ti6Al4V alloy were fabricated in vertical orientation using Selective laser melting (SLM) process. A layer thickness of 60 µm and optimized process parameters were selected for manufacturing to understand the subsequent effect on fatigue properties. These as-fabricated samples were heat-treated (HT) at an annealing temperature of 800°C with a dwell period of 2 hrs in a controlled environment. Microstructural and texture characterization was carried out using FE-Scanning Electron Microscope (SEM) and optical microscope. Tensile tests were performed on the specimen with an application of load parallel to the build direction. Furthermore, the tension-compression fatigue testing with stress ratio of -1 and at a cycle frequency of 20 Hz was carried out using MTS servo-hydraulic fatigue testing machine. The tests were continued till $10^7$ cycles or till the complete failure, whichever came first. The fracture surfaces of broken specimens were examined using SEM to investigate fatigue damage mechanism, crack initiating defects, their size parameter ($\sqrt{area}$) and location.

The as-fabricated Ti6Al4V alloy consists of acicular α' martensitic phase with needle-like microstructure because of high cooling rate during the SLM process. Coarsening of the α laths within the prior β grain boundary took place with annealing heat treatment. The Stress-life curve based on crack initiating defects was generated using experimental results and an endurance limit of 300 MPa was observed. The fatigue life of AM alloy was lower as compared to its conventional counterparts owing to the presence of defects, which acts as stress raisers. The extreme value statistics of crack initiating defects was plotted and a maximum possible defect size ($\sqrt{area}$ ) of 137 µm was estimated. Most of the observed defects were porosities and incomplete fusion, often located at surface and sub-surface regions. The fracture mechanics parameter was then evaluated using various defect models and found out to be in the limit. Tests are still going on at different ambient temperatures. The observed results with possible underlying mechanisms shall be discussed and presented.

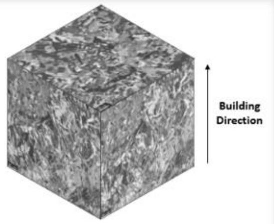


***Figure 1** – EBSD IPF Map of HT SLM Ti6Al4V alloy*

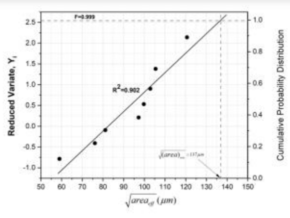


***Figure 2** – Extreme value statistics of defects*

***Table 1*** - Mechanical Properties of HT SLM Ti6Al4V alloy

| YS* (MPa) | UTS# (MPa) | Elongation (%) | Hardness (HV) |
|---|---|---|---|
| 808±5 | 872 ±12 | 14.4±2.1% | 389±8 |

*YS- Yield Strength #UTS – Ultimate Tensile Strength

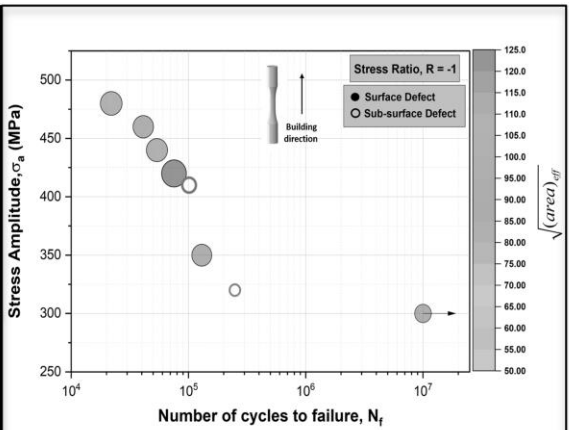


***Figure 3** – Defects based SN Curve*

# #178 Constants and parameters of the low cycle damage accumulation model with isotropic and kinematic hardening for 25Cr1Mo1V steel

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*Damage accumulation* *Isotropic hardening* *Kinematic hardening*

**Abstract** The aim of the work is to verify the method of identifying the parameters used in the generalized model, which includes the exponential isotropic hardening laws (1) and the Armstrong-Frederick kinematic hardening (2). Damage accumulation is produced according to Lemaitre's model (3). Parameter identification is performed for 25Cr1Mo1V steel based on two standard uniaxial tensile and low-cycle fatigue tests.

$$(1)\ \sigma_y(R_n) = \sigma_0 + R_{\inf} \cdot \left[1 - \exp(-\gamma \cdot \varepsilon^e_{pl})\right], \qquad (2)\ \dot{\boldsymbol{\beta}} = a \cdot \dot{\boldsymbol{\varepsilon}}_{pl} - b \cdot \boldsymbol{\beta} \cdot \dot{\varepsilon}^e_{pl}, \qquad (3)\ \dot{\omega} = \dot{\gamma} \frac{1}{1-\omega} \cdot \left(\frac{-Y}{r}\right)^s$$

To verify the required constants and parameters ($R_{\inf}$ and $\gamma$, $a$ and $b$, $r$ and $s$), the model representations (1)-(3) were implemented as a dynamically pluggable library of user material for the software of calculations using the finite element method.

***Table 1*** **-** Properties and parameters of 25Cr1Mo1V steel at room temperature

| E, MPa | $\sigma_0$, MPa | $r$, MPa | s | $R_{\inf}$, MPa | $\Upsilon$ | $a$, MPa | $b$ | $\omega_c$ |
|---|---|---|---|---|---|---|---|---|
| 211220 | 353.26 | 1.3 | 1.5 | 850 | 6.46 | 82877 | 428.81 | 0.299 |

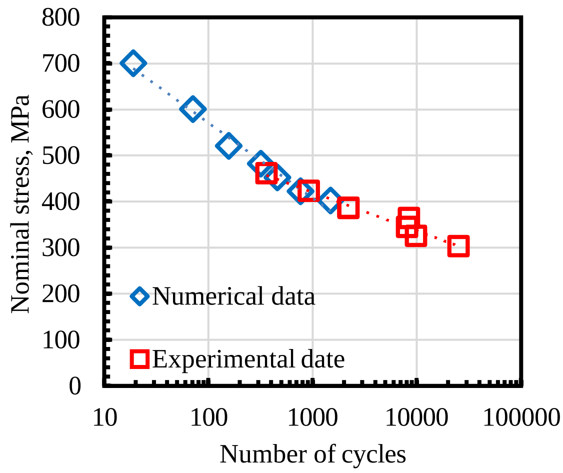


***Figure 1*** **-** Comparison of numerical and experimental data when modeling the fatigue life of smooth cylindrical 25Cr1Mo1V steel specimens at room temperature

Based on the found constants and parameters (Table 1), the cyclic loading of cylindrical specimens was simulated using the finite element method. Numerical tests were fully repeated experimental low-cycle fatigue tests. The fatigue life curve for 25Cr1Mo1V steel was obtained (Figure 1). The specimen was considered failed when the critical damage parameter $\omega_c$, which is a material characteristic at a given temperature, was reached. A high degree of correlation between predicted durability and experiment was achieved.

# #179 Complex stress state analysis for aluminum alloy accounting for damage accumulation

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*Damage* *multiaxiality* *Isotropic hardening*

**Abstract** In this work, a complex study of the limit state of the 2024 aluminum alloy under multiaxial stress state was carried out. Various types of combined loading by tension, compression, torsion and internal pressure are considered. Damage at the microscopic scale level in the form of microvoids and cracks leads to loss of failure resistance of the material. The purpose of the study is to determine the effect of damage evolution in a material under a complex stress state on the characteristics of the material's fracture resistance.

In the field of engineering, the understanding of damage mechanisms in solids is crucial to the safe operation of structures and vehicles. In order to accurately predict such mechanisms during the design stage of a product, appropriate models for the simulation of damage are required. The use of such models based on the finite element method can be a useful tool for the design and operation of structural elements. The proposed model used combination the isotropic hardening law and the damage accumulation law. The model is implemented in the form of a dynamic load library for user material in the ANSYS software package.

In the study presents the results of tests under static loading. The object of numerical and experimental study is a hollow cylindrical specimen with a working length of 60 mm, an inner diameter of 10 mm and an outer diameter of the working part of 12 mm. The tests were carried out on a servo-hydraulic machine, on which it is possible to implement axial forces, torque, internal pressure, as well as their various combinations. A special device was used to measure the angle of rotation of a hollow cylinder during torsion, and a transversal extensometer was used to measure circumferential strains during internal pressure tests. The experimental program included various combinations of axial forces (-17.62 – 17.42 kN), torque (0-5.32 N*m) and internal pressure applied to a cylindrical sample (0 – 75MPa). In the numerical study, the linear-power law was used for isotropic hardening. The Lemaitre damage model was employed for determine the parameters of damage field.

Stress-strain state fields, damage fields, as well as the values of limiting stresses under various types of loading are obtained. Comparison study of different limiting stress state theories were numerically performed with take into account the damage accumulation under complex stress state.

# #180 Influence of non-singular stresses upon instability of coplanar crack propagation in mixed-mode I+III

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*Non-singular stresses* *Instability* *Mixed-mode I+III*

**Abstract** In an earlier paper (Leblond et al., 2011), we presented a linear stability analysis of the coplanar propagation of a crack loaded in mixed-mode I+III loading conditions; this analysis basically relied on a "double" propagation criterion which combined Griffith's (1920) energetic condition and Goldstein and Salganik (1974)'s principle of local symmetry. A theoretical threshold was derived for the onset of instability: instability modes were shown to emerge when the ratio $K_{III}^0/K_I^0$ of the unperturbed mode III to mode I stress intensity factors exceeded some "threshold" value $[K_{III}^0/K_I^0]_{cr}$ depending only on Poisson's ratio. Unfortunately, the predicted threshold was considerably larger than that observed in the majority of materials.

Subsequently, numerical simulations of crack propagation in mode I+III (Chen et al., 2015), based on some phase-field model, evidenced an important role of the specimen dimensions upon the non-coplanar instability. Here, we investigate the influence of possible existence of some finite characteristic length(s) (due to the loading in the case considered), by taking into account the possible presence of non-singular stresses $T_{ij}^0$ in the unperturbed configuration of the crack. This is done by extending Leblond et al. (2011)'s theoretical stability analysis so as to account for such non-singular stresses.

The results obtained are as follows. A *negative* non-singular stress $T_{xx}^0$ (parallel to the direction of propagation) has no impact upon the out-of-plane instability, while a *negative* non-singular stress $T_{zz}^0$ (parallel to the crack front) strongly hinders it. On the other hand, *positive* non-singular stresses $T_{xx}^0$ and $T_{zz}^0$, or *non-zero* non-singular stresses $T_{xz}^0$ (antiplane shear) promote the instability; in some cases instability modes drift along the crack front as propagation proceeds. Large values of $T_{xx}^0$, $T_{zz}^0$ and $T_{xz}^0$ may all generate a significant lowering of the threshold value $[K_{III}^0/K_I^0]_{cr}$ for instability, even down to zero. This emphasizes the possibility of existence of the out-of-plane instability even under pure mode I loading conditions.

However these results fail to explain the often reported formation of non-coplanar fracture facets at *very low* values of the ratio $K_{III}^0/K_I^0$. Indeed the wavelength of the instability modes predicted under such conditions is of the order of the finite characteristic length(s) introduced into the analysis, of at least centimetric magnitude, while the formation of facets has been observed at scales as low as tens of microns.

# #181 Fatigue fracture analysis of notched and unnotched 7075-T6 after RRA heat treatment and plasma nitriding

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*fracture analysis* *fatigue* *7075-T6 aluminum alloy*

**Abstract** This work assessed the fracture behavior of the AA7075-T6 aluminum alloy subjected to fatigue loading. Both the notched and unnotched specimens underwent a retrogression heat treatment and re-aging (RRA) and plasma nitriding before the mechanical tests. Plasma nitriding, which has been a method chosen to increase the surface hardness and the fatigue, wear and corrosion resistances of various alloys was carried out with an active screen with a 20 Hz DC source and a 40 Hz duty cycle. The RRA treatment, which is used to increase the strength and hardness of AA7075 aluminum alloy and obtain improvements in the fatigue and corrosion behaviors, was performed at 200 °C for 20 minutes with water cooling (resolubilization), followed by 24 hours at 120 °C (re-aging). The axial fatigue tests of notched and unnotched specimens were carried out with R = 0.1, frequency of 14 Hz, and at different stress levels: 75, 100 and 150 MPa for notched specimens, and 400 and 500 MPa for unnotched specimens. The fatigue fracture was then performed via stereomicroscopy and scanning electron microscopy. For the unnotched specimens, AA7075-T6 and AA7075-RRA conditions presented similar fracture features, with good definition of the three stages of fatigue failure; the AA7075 nitrited condition presented no evidence of typical fatigue fracture. The notched specimens presented fractographies similar to the severe stress concentration condition, with surface marks convex to the nucleation region.

# #182 A study of fatigue in smooth and notched 7075-T6 aluminum specimens after RRA heat treatment and plasma nitriding

Maria Gabriela Galvão Camarinha[1], Leonardo Contri Campanelli[1], Miguel Justino Ribeiro Barboza[2], Luis Reis[3], Antônio Augusto Couto[4], Danieli Aparecida Pereira Reis[1]

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*Fatigue* *7075-T6 aluminum alloy* *RRA and nitriding*

**Abstract** The 7075-T6 aluminum alloy is widely used in structural parts in the aviation industry for its low density and high mechanical properties. It is also known, however, for its susceptibility to localized corrosion. In order to take a step forward towards expanding the use of the material, the AA7075-T6 alloy was subjected to the retrogression heat treatment and reaging (RRA), as well as to plasma nitriding, aiming at an improvement of the corrosion resistance without compromising the fatigue behavior. The fatigue tests were carried out under axial loading (R = 0.1) and in the atmosphere. The fatigue behavior of notched specimens was also investigated for a theoretical stress concentration factor of 5.7. With the help of the maximum likelyhood method, the S-N curves of the unnotched specimens were compared and the main difference was observed for the plasma nitriding condition, with a significant drop in the fatigue performance due to the post-processing softening of the microstructure and the substantial increase in surface roughness. All notched specimens regardless the surface condition showed dramatic reductions in their fatigue performances.

# #183 Implementation of an s-version finite element method for analyzing elastic-plastic problems

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Keywords:

*s-version finite element method* *Elastic-plastic mechanics* *Element subdivision*
*Stress concentration* *Crack*

**Abstract** For structures/components with complex geometry and/or discontinuities, accurate prediction of the stress/strain field with conventional finite element requires considerable efforts in domain discretization and numerical cost in numerical calculation. The superposed finite element method (s-version FE method), by overlaying a local mesh with fine element size representing irregular features, such as holes and cracks, on the global mesh which represents the entire domain with simple geometry and coarse element size, can greatly simplify the domain discretization with less degree of freedoms and keep high accuracy in numerical prediction. However, most applications of the s-version FE method were performed in elastic problems, leaving its applications in elastic-plastic problems almost blank. For this concern, in this work, the s-version FE method is developed and applied to 3-dimensional elastic-plastic problems with recursive element subdivision technique. A stress concentration problem and a stationary crack problem are analyzed and compared with those from conventional finite element method with very fine elements. Comparison results highlight the versatility of the s- version FE method in domain discretization and numerical accuracy, displaying high potential applications in structural integrity assessment with complex structures and/or geometric defects.

# #184 High-speed crack propagation analysis in transparent elastic solid based on s-method compared with experiments

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Keywords

*Brittle fracture* *S-method* *Crack arrest* *Crack propagation*

**Abstract** A strategy to simulate the high-speed crack propagation and to analyse the stress distribution around the crack front based on the s-version of the finite element method (s-method) is proposed. This strategy spuerimposes a local mesh over the area that include the propagating crack tip, which is made possilbe by flexible definition of the local mesh. The transparent elastic solid (PMMA) is used for experiments and the shape of crack front is captured by high-speed camera to model the local mesh. Based on the numerical models, the fracture conditions can be obtained by the generation phase analysis. Finally, the application phase analysis can be performed based on the fracture conditions to simulate the crack propagation.

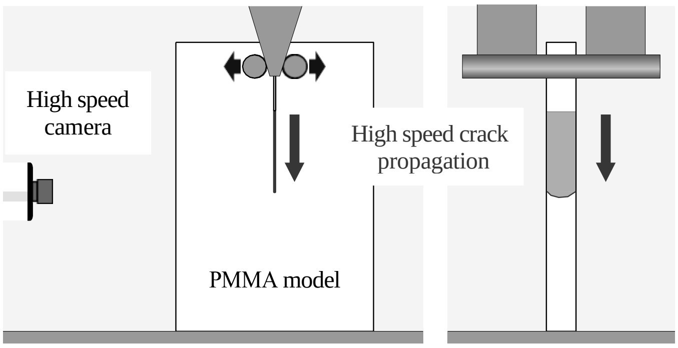


***Figure 1*** *– Experimental setup for crack arrest test using PMMA.*

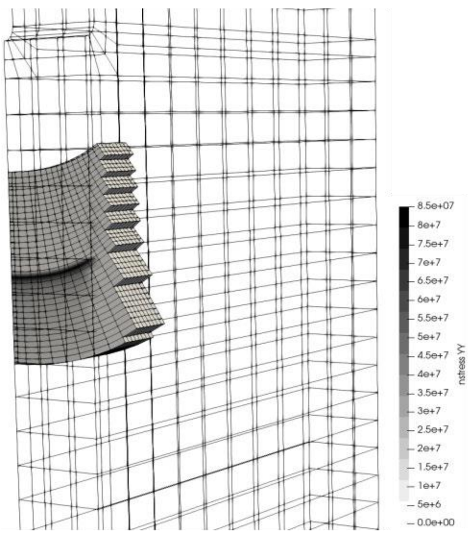

***Figure 2*** *– Numerical simulation based on the proposed s-method strategy.*

# #185 A novel method for studying crack initiation mechanism in materials in very high cycle regime

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*Very high cycle fatigue* *Method* *Crack initiation*

**Abstract** Very high cycle fatigue (VHCF) of metallic materials has become an important topic since structural integrity design and analysis of many engineering structures and components are related to fatigue in VHCF regime in recent decades. The research in the area is still a challenge in both fatigue crack initiation and fracture features comparing with traditional fatigue knowledge. In this study, a method using one single specimen progressive stepwise-load increasing test (PSLIT) was developed to study fatigue damage and crack initiation behavior in material in VHCF regime. The material used is an AISI 304 type of austenitic stainless steel. The start stress amplitude is 120MPa and then a progressive stepwise-load of 10 MPa. The number of cycles for each step is kept more than $10^8$ cycles. With this method, both VHCF fatigue strength and total fatigue life of this steel obtained are much higher than that of HCF. This is an un-expected result. Fracture surface and microstructure in the fatigue tested specimen were investigated using SEM/EBSD and SEM/ECCI. Although a total fatigue life up to $10^{10}$ cycles has been reached, surface fatigue crack initiation is still a dominant mechanism. Fine granular area, FGA, near the crack initiation was analyzed. Strain localization and grain fragmentation are the main processes for the formation of FGA. This method can also be used to predict the fatigue damage process, especially damage rate in individual specimen. This can correlate to the total fatigue life of the specimen.

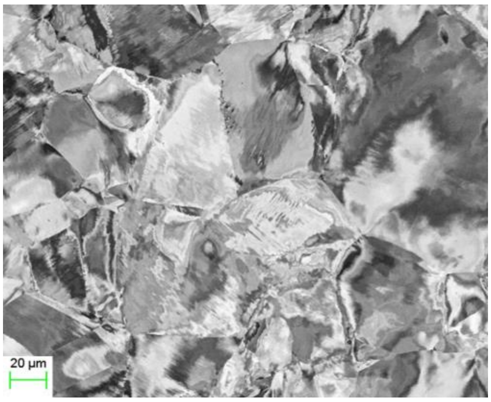


Fig. 1 Strain localization and grain fragmentation

# #186 Finite Fracture Mechanics from the macro- to the micro-scale. Comparison with the Phase Field model

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*Finite Fracture Mechanics* *Coupled Criterion* *Micro-scale*

**Abstract** Within the framework of Finite Fracture Mechanics (FFM), one of the fundamental ingredients of this methodology is that a crack is assumed to jump a given finite length at onset. This can be formulated through the invocation of the Coupled Criterion (CC) [1], stating that this length depends on the material toughness, the tensile strength but also the geometry. Complying with a different vision, according to the Phase Field (PF) model [2] there exists a length related to the size of the damaged region, called the phase field length scale. Both the PF length scale and the nucleation length obtained by the CC are proportional to the Irwin length defined from the material toughness and tensile strength. At the macro-scale, they are small compared to any dimension of the structure, whereas at the micro-scale both lengths are of the same order of magnitude or even larger and can interact with the dimensions of the structure.
The aim of this work is to analyze how the answer brought by the CC and the PF model evolves when descending the scales from the cm-scale to the µm- scale and even nm-scale. Based on previous results, it can be argued that both the CC and the PF model provide satisfactory predictions of cracking events in solids. However, this can be a controversial issue at smaller scales of analysis due to a lack of energy because of the smallness of the specimens. This is attributed to the fact that at such scales it is seen that the corresponding results are much sensitive to the toughness but less sensitive to the tensile strength.

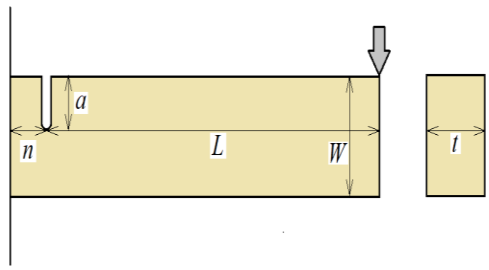


***Figure 1 -** notched micro- cantilever beams.*

Relying on the previous discussion, in this contribution, bending tests on notched micro-cantilever beams (Figure 1) made of a ceramic material 8Y-FSZ cubic zirconia are investigated. Particularly, we analyze how the fracture nucleation is affected considering different values of the toughness and the strength, according to the CC. A wider scattering in the determination of the tensile strength than in that of the fracture energy is observed. Furthermore, a comparison of the critical load calculated using the CC, to the ones obtained in experiments [3] is made.
Then, an optimization process is followed to estimate an average toughness, based on the minimization of the difference between numerical simulations and experiments. Finally, we replicate this analysis using the PF approach of fracture as modelling tool. In the latter, the influence of the phase field length scale in the crack nucleation at the micro-scale is examined, this parameter being considered a property of the material because of its relation to the strength [2].

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# #187 Tribological adaption of a failure hypothesis for fretting fatigue based on the local parameters slip amplitude and contact pressure.


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*Fretting fatigue* *Failure Hypothesis* *Safety analysis*



**Abstract** Fretting fatigue is a phenomenon that leads to catastrophic damage. The reason is that the strength under fretting fatigue is down to 20% or less of the intrinsic material strength depending on the tribological prarameters. Affected components, which were designed in the classical way in relation to these intrinsic material strengths, fail unexpectedly and prematurely. To solve this problem, a failure hypothesis is needed to assess the fretting fatigue in a realistic way and thus predict the risk to the components. For this target, the specific fretting fatigue strengths were determined for a permutation of the tribological parameters slip amplitude and contact pressure. Therefore, a double- actuated flat pad test bench was used. This test bench can keep the parameters slip amplitude and contact pressure constant over the entire test, independent of the cyclic tensile load on the tensile specimen. All experiments in this work were performed with the material pairing 34CrNiMo6+QT vs. 34CrNiMo6+QT. From these tests, an equation was developed which describes the fretting fatigue strength as a function of slip amplitude and contact pressure (Figure 1 left). Additional experimental tests were then carried out on connecting rods. The connecting rods failed due to fretting fatigue (Figure 1 right). The failure location and fatigue limits of the connecting rods were determined. By numerical analysis of the connecting rod, it was possible to determine the mechanical stress, slip amplitude and contact pressure locally. This was followed by a comparison of equivalent stress and fretting fatigue strength at the same parameter combination of slip amplitude and contact pressure for each point in the contact as shown in Figure 1. Whereby the equivalent stress was calculated with cutting plane methods that are able to consider the multiaxial stress state. The point with the highest degree of utilization is the calculated failure location. With this adapted failure hypothesis, the failure location could be determined with very good accuracy. However, the maximum error in determining the degree of utilization is about 20%.


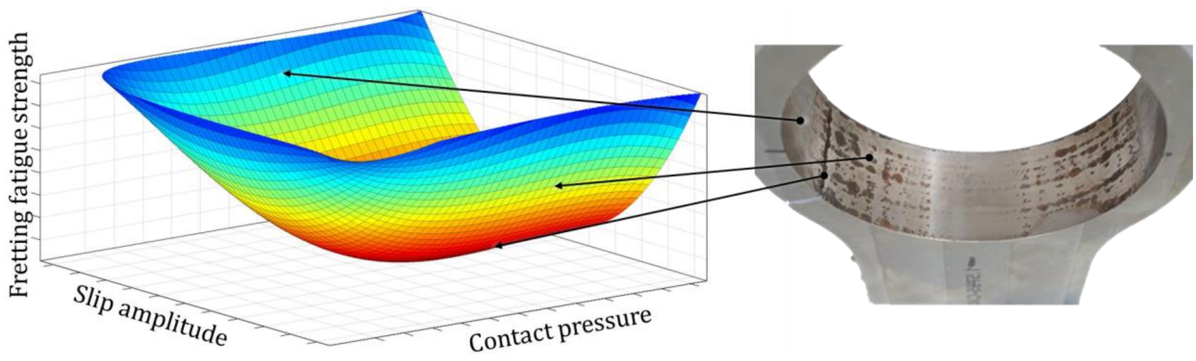


***Figure 1 -*** *Schematic representation of the local fretting fatigue strength of a connecting rod as a function of the local parameters slip amplitude and contact pressure*

# #188 Extending the finite fracture mechanics coupled criterion to quasi-brittle materials – Analytical derivation and experimental evidence

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*Plasticity* *Quasi-brittle materials* *Coupled criterion*

**Abstract** Structures made of steel alloys with V-notches may fracture at the V-notch tip at which a small plastic zone usually evolves. Failure criteria for predicting fracture loads for such quasi-brittle alloys, as a function of the V-notch opening angle are very scarce and have not been validated, to the best of our knowledge, by a set of experimental observations.

A set of experiments were performed on AISI 4340 steel alloy specimens with three different V-notch opening angles and three different tempering temperatures, loaded in mode I [1]. The finite fracture mechanics coupled criterion (FFMCC) for brittle materials [2] was shown to predict reasonably well the failure load for small opening angles ($30^o$) for which the plastic area is very small (~20% which is within the experimental error range). The under-prediction of the failure load constantly increases to ~50% as the V-notch angle increases to $90^o$ and plastic zone area increases to ~0.5 $mm^2$ (for a V-notch depth of 5 mm).

An attempt to extend the FFMCC to cases where a small-scale yielding plasticity is evident at the V-notch tips is presented, based on [3]. By measuring the plastic zone size by DIC and recording the failure load we use the Ramberg-Osgood law to model the plastic zone evolution and thus stresses still exhibit a singular behavior when approaching the notch root like the Rice and Rosengren model. When crack nucleates, an elastic unloading phase is assumed.

We shall present our analysis in an effort to enhance the FFMCC to cases where a small-scale yielding zone develops prior to crack initiation at the V-notch tip, and try to validate it by the experimental observations.

**Acknowledgements:** ZY gratefully acknowledges the support by the Israel Science Foundation (grant No. 964/18). The authors gratefully acknowledge the assistance of V. Mendelovich, I. Gilad and A. Bussiba (Tel Aviv University) for performing the experimental work and the partial support of the European Union's Horizon 2020 research and innovation programme under Marie Skłodowska-Curie grant agreement No. 861061- NEWFRAC.

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## #189 Numerical evaluation of damaged torque link fatigue life

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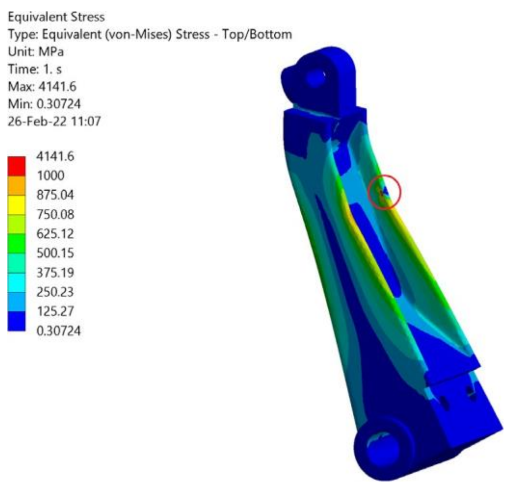
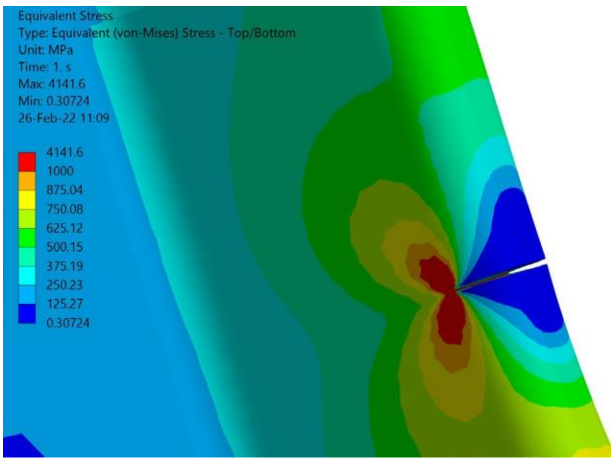
*Fatigue life* *Structural integrity* *FEM*

**Abstract** Torque link is the part of the light aircraft nose gear assembly that prevents the piston from rotating inside the cylinder and supports up and down motion during the neutralization of landing and taxiing shocks. It is one of the aircraft components whose structural integrity is crucial for overall aircraft safety. Due to complex shape and variable loading conditions during service, estimation of torque link fatigue life represents a real challenge. In this work, the fatigue life of two alternative designs of the torque link is evaluated by a numerical approach based on FEM. Firstly, the fatigue life of the actual damaged torque link was assessed for real loading conditions, and then a newly designed torque link with optimized shape was analyzed along with the evaluation of its fatigue life in the presence of assumed damage. The number of cycles for both designs is compared and discussed. Standard Paris growth law was used for the fatigue life estimation in both cases.



# #190 Crack arrest by curved interfaces: experimental and numerical analysis

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*Curved weak interface* *Crack arrest* *Finite fracture mechanics*

**Abstract** The phenomenon of arrest of an unstably growing crack due to a curved weak interface is analyzed. The weak interface can produce the deviation of the crack path, trapping the crack at the interface, leading to stable crack growth for certain interface geometries. This idea could be used as a technical solution for a new type of crack arrester, with a negligible impact on the global stiffness, strength, and weight of the structure. This work presents an analytical and computational study on the ability of curved weak interfaces to arrest crack propagation. In particular, the work focuses on the role of the interface radius to enhance this ability. The problem is analyzed using two different approaches commonly employed nowadays for these kinds of problems: i) Linear Elastic Fracture Mechanics, and ii) the Coupled Criterion of Finite Fracture Mechanics.

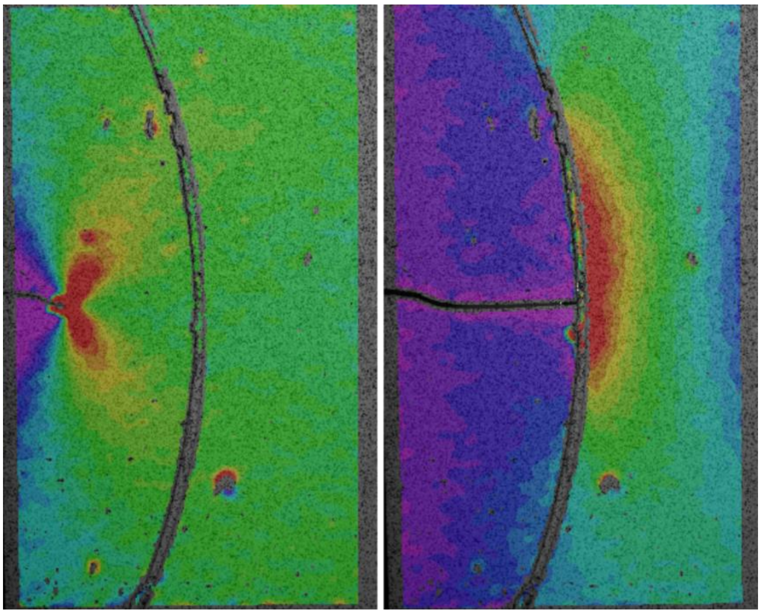

***Figure 1 -*** *3D digital image correlation representing vertical strain during crack propagation. The discontinuity of strain allows identifying the crack tip positions of the deflected cracks.*

# #191 A global-local approach for phase field fracture modeling of shell structures: Application to static and fatigue loading conditions with efficient quasi-Newton solution

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*Phase field fracture* *Solid shell element* *Quasi-Newton scheme*

**Abstract** To accurately predict the crack initiation and propagation in thin-walled structures, a reliable global-local approach for phase field modeling of solid shells considering the enhanced assumed strain (EAS) method and assumed natural strain (ANS) method for the alleviation of locking effects is proposed for the first time in this study. Aiming at tackling the poor convergence performance of standard Newton monolithic scheme, a quasi-Newton algorithm is adopted to solve the coupled phase field-displacement governing equations incorporating solid shell formulation in a monolithic manner. The excellent convergence performance of this quasi-Newton monolithic scheme for the solution of multi-field solid shell formulation is demonstrated through several paradigmatic boundary value examples, including single edge notched tension, fracture of cylindrical structure and fatigue induced crack propagation. Besides, compared with the popular alternating minimization (AM) or staggered solution scheme, it is also found that the quasi-Newton monolithic scheme to solve the highly nonlinear coupled equations in this framework is very computationally efficient, being at least 5 times faster than AM scheme to achieve the same accuracy in all the cases. In addition, a global-local approach for phase field fracture modeling in large-scale thin-walled structures is investigated in this work, and its effectiveness is verified by the modeling of a quarter of cylindrical plate subjected to both static and fatigue cyclic loading conditions, which can be appealing to industrial applications.

# #192 Experimental And Analytical Investigation of Tensile Behavior of P91 Steel Using Small Punch Testing

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*Small Punch Test*　　*P91 steel*　　*Gursson–Tvergaard–Needleman (GTN) damage model*

**Abstract** The Small Punch Test (SPT) is a useful technique for deriving location-dependent mechanical properties using small-sized specimens. P91 Ferritic-martensitic steel is a material of choice for structural components in Gen IV fission and advanced fusion nuclear reactors. An attempt is made to calculate the tensile and fracture behavior of P91 steel by the SPT technique in the temperature range of 300 – 550 ºC and under strain rates in the range of $1 \times 10^{-3}$ to $1 \times 10^{-1}$ $s^{-1}$. Firstly, the hot uniaxial and fracture behavior by SPT have been compared with the conventional tensile test. Further, the hot deformation material parameters in the exponential power-law, and hyperbolic sine constitutive equations have been evaluated for both deformation modes. Effect of temperature and strain rate variation on stress exponent in powerlaw and activation energy from hyperbolic sine equation have been correlated. Furthermore, an inverse finite element analysis (FEA) optimization process with Gursson–Tvergaard– Needleman (GTN) damage model has been implemented to describe the fracture behavior of P91steel. An inverse FEA has been proposed to calculate different material parameters for a fast-converging solution. The Gursson–Tvergaard–Needleman (GTN) damage model is based on the nucleation and growth of spherical voids within the material. In contrast to general plasticity models, changes in material volume are possible due to the nucleation, growth, and coalescence of voids during plastic deformation. The void volume fraction is described according to the GTN model during plastic deformation. These models have been validated with conventional tensile test and SPT test results for tensile and fracture behavior of P91 steel.

# #193 Automated FEA-assisted fatigue design of welded structures subjected to variable amplitude multiaxial loads according to the Peak Stress Method

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*Peak Stress Method (PSM)* *Variable amplitude* *Automated tool*

**Abstract** The Peak Stress Method (PSM) is a FE-oriented, local approach aimed at the fatigue strength assessment and fatigue lifetime estimation of welded structures and it is especially suitable when complex geometries and loading conditions are involved. Basically, the PSM allows a rapid estimation of the Notch Stress Intensity Factors (NSIFs) on the basis of the linear-elastic opening, in-plane shear and out-of-plane shear peak stresses calculated at the weld toe and the weld root by employing coarse FE meshes [1]. Then, by adopting the averaged Strain Energy Density (SED) as a fatigue strength criterion, a design stress, the so-called equivalent peak stress, can be defined [1]. At last, the equivalent peak stress can be combined with the PSM-based design curves to estimate the fatigue lifetime of welded structures under constant amplitude (CA) loadings. However, in service, real engineering welded structures are generally subjected to complex multiaxial variable amplitude (VA) loads. Accordingly, by adopting the Palmgren-Miner's Linear Damage Rule (LDR), the equivalent peak stress has been recently re-formulated in order to assess the fatigue strength of welded structures subjected to multiaxial VA loads [2]. In addition, an interactive analysis tool has recently been developed in Ansys® Mechanical to support the FE analyst in the fatigue design of complex welded structures [3,4]. The tool is designed to: (i) assess PSM applicability requirements, performing checks on the FE model under exam; (ii) identify all sharp notches of the structure and evaluate locally the notch opening angle; (iii) automate all implementation tasks required by the PSM. As an output, the automated tool generates fatigue life contour plots in Ansys® Mechanical, allowing the analyst to rapidly single out the most critical points of a welded structure among all competing crack initiation sites. Originally developed to treat CA load cases only [4], the automated tool has been improved here by implementing the newly developed multiaxial VA formulation of the PSM.

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# #194 Monitoring growing cracks in aircraft lugs by means of the electro-mechanical impedance method

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*electro-mechanical impedance method* *crack size estimation* *Structural Health Monitoring*

**Abstract** Lugs are common connecting elements in many fields of engineering, e.g. aircraft and automotive. High stress concentrations at the inner edge of the bolt hole lead to early crack initiation and rapid fatigue crack growth under cyclic loading. However, a complete failure of such components is in most cases not acceptable. This contribution presents a model-based methodology to monitor the crack propagation in aircraft lugs by means of the electro-mechanical impedance (EMI) method. For this purpose, piezoelectric sensors are permanently attached to the monitored structure. The evaluated structural components are necked, straight and tapered lugs. Crack propagation is analyzed numerically by coupled-field finite element models and experimentally using an impedance analyzer and a scanning laser Doppler vibrometer. Simulated and measured frequency spectra of pristine (no crack present) and damaged (a crack of various lengths is present) structures show significant deviations in resonance frequencies which are considered as clear indicators of the present crack. Furthermore, the length of artificially introduced cracks are determined by specific resonance frequency shifts for each lug shape. Crack size estimation based on resonance frequency shifts has already been shown in a recent study for necked double shear lugs, which will now be extended for straight and tapered lug shapes. Concludingly, a discussion on the applicability of the presented crack analysis methodology for structural health monitoring (SHM) of aircraft lugs under fatigue loading is presented

# #195 Friction stir welds with enhanced fatigue strength and life via laser peening

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*Laser peening* *Friction stir welding* *Fatigue life*

**Abstract** Friction Stir Welding (FSW) is being studied as a viable solid-state joining process for aircraft fuselage structures. As with any other high-temperature joining process, FSW will form an integrated structure with variably distributed residual stress fields and a microstructural gradation. This will adversely affect the structural performance of a joint. The FSW process may also introduce defects that would act as sites for fatigue crack initiation during service. Laser Peening (LP) has been demonstrated as an effective tool to improve overall fatigue life [1,2] by improving both fatigue crack initiation and propagation behaviour in aerospace aluminium alloys due to the introduction of a through-thickness compressive residual stress. This would also act as a deterrent for crack initiation from a pre-existing defect and potentially recover the fatigue life of a joint.

This study aims to quantify the influence of lack of penetration (LoP) defect depth on the fatigue life of peened and unpeened FSW joints. Fatigue tests with different stress amplitudes were performed for peened and unpeened samples in as-machined, friction stir welded and with the controlled introduction of defects; to characterise the loss of fatigue strength and the effect of stress amplitude on the degradation of fatigue life. Controlled LoP defects of 200 and 400 $\mu$m depth have been introduced during FSW. It was found that in the case of 200 $\mu$m defects there was no significant reduction in fatigue life when compared to the as-welded samples. However, for 400 $\mu$m defects, fatigue life was significantly reduced with considerable scatter in fatigue performance. This not only shows that 400 $\mu$m defects are providing a higher level of intensity of the local stress field, resulting in faster crack initiation but also that the defect geometry is critical for crack initiation.

Scanning electron microscopy examination is being carried out to accurately characterise the impact of defect geometry on crack initiation. Preliminary results have shown that crack initiation does not depend exclusively on defect depth. Crack initiation and propagation are influenced by the varying residual stress along the defect root, which affects the effective stress a crack will experience during cyclic loading. Destructive and non-destructive stress measurements are being conducted, along with the development of a finite element model capable of simulating this behaviour in a FSW joint containing a crack-like defect under different residual stress profiles.

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# #196 Quantification of fatigue damage and its effect on fatigue limit

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*Fatigue limit* *Coaxing effect* *Plastic strain energy*

**Abstract** In order to quantitatively analyze the impact of load amplitude and load sequence to fatigue limit, the variation of plastic strain energy under different loading conditions was observed based on the elastic unloading compliance method. Tension-compression fatigue tests for ferrite-pearlite two-phase steel with mechanical long precrack were carried out at room temperature. After obtaining the non-extention crack corresponding to the fatigue limit, the stress amplitude was increased by 5 MPa every $10^7$ cycles until the crack re-extends. The purpose is to analyze the effect of load variation on plastic strain energy. It was found that the plastic strain energy suddenly decreased to half of the state before the crack re-extension when load gradually increased. Moreover, the fatigue limit stress calculated under the re-extended crack length could not stop the crack extension again. Therefore, the calculated fatigue limit need to by modified by the plastic strain-energy ratio coefficient mentioned above. In addition, by observing the crack extension path and fracture surface, it was found that, after the crack re-extension, there was quite less slip band around the crack tip caused by dislocation emission, and crack shape was discontinuous. Moreover, the fracture surface was dominated by small flat facets. These characteristics indicate that the variation of plastic strain energy is the macroscopic mechanical manifestation, while the microscopic extension mechanism may have already changed.

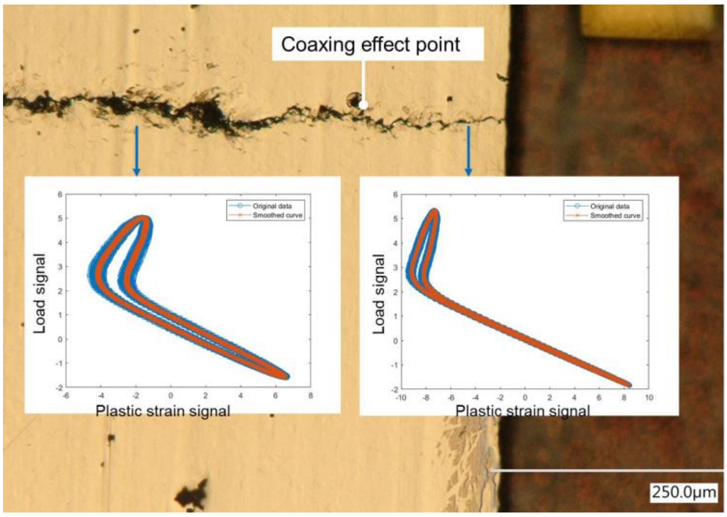


***Figure 1*** *– plastic strain energy variation by compliance method*

# #198 Effect of Stress Field on TRIP behavior and its influence on fracture behavior of Commercial Stainless Steels at cryogenic temperature

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*Stainless steel* *Liquified hydrogen* *Stress field* *TRIP*

**Abstract** Creating an economical supply chain of hydrogen is one of the key strategies to reduce the consumption of fossil fuels as energy resources. Considering the history of the establishment of the supply chain of LNG (Liquefied Natural Gas), one promising scenario from the viewpoint of the balance of economy and safety is to install a large liquified hydrogen storage tank made of stainless steel. In the 1990s and 2000s, a series of fundamental studies of the mechanical properties at the temperature of liquified hydrogen (20K) and after absorption of hydrogen at various temperatures was carried out in Japan. However, it has focused only on the fundamental characteristics and never showed whether the material can be used or not. In this study, picking up four kinds of commercial stainless steel, we report the characteristics of martensite transformation which is said to lead to a brittle fracture in the various stress field including the real load condition of the tank when an earthquake. We conducted the EBSD (Electron Back Scatter Diffraction) evaluation during some typical loading tests to measure the evolution of martensite: The stress fields loaded in the tests varied from compression to tension. Besides, we modeled the specific aspect of martensite transformation by FEM (Finite Element Method) to analyze the stability of the martensite, where martensite transformation could be interpreted as the process of expansion. Energy release rate during expansion is used to analyze the stability of martensite. We found the relationship between the experimental martensite transformation value and mechanical energy release rate calculated by FEM in proportion stress field varies. The prediction of martensite transformation in the means of energy release rate will provide the basis to select the material used for the large flat bottom cylindrical tank to store liquefied hydrogen.

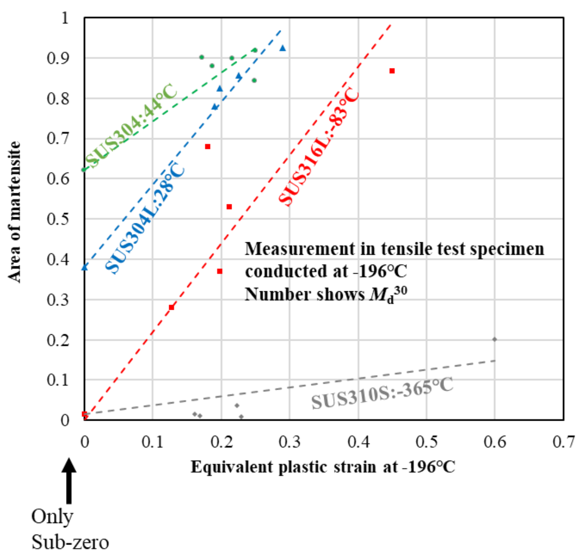


***Figure 1** – Relation between plastic strain amount and martensite transformation when mono-axis tension*

# #199 Effect of corrosion on fatigue behavior of welded AA2024-T3 alloy

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*Friction stir weld* *Corrosion* *Fatigue*

**Abstract** The demand for manufacturing large structures in the aerospace and structural industries has led to the development of new welding methods. Friction stir welding (FSW) is one such technique used for welding metals. Very often the welded components are subjected to a harsh environment in addition to the cyclic load, thereby affecting the component's service life significantly. The current study investigated the effect of corrosion on the fatigue crack growth properties of the friction stir welded aluminum alloy 2024-T3.

FSW was performed along the rolling direction of naturally aged AA2024 plates of thickness 6 mm. The weld transverse cross-section was considered for the microstructural analysis. The corrosion potential and charge transfer resistance of the welded joint samples were investigated in 3.5% NaCl solution using EIS Gamry. The specimens were immersed in the saltwater for different time intervals till 200hrs. A compact-tension specimen of size was extracted from the welded plates and corroded in NaCl solution for 100 hrs. After corrosion, both ΔK-decreasing and ΔK-increasing tests were performed to investigate the fatigue crack threshold and crack propagation rate. The fatigue crack growth behavior of corroded weld along the nugget zone was investigated at different load-ratios (R) of 0.1 and 0.5.

Microstructural analysis revealed fine grains in the stir zone and coarse grains in the heataffected zone of the welded joint. It was observed that the stir zone had higher corrosion potential compared to the base metal, attributed to grain refinement in stir zone. With an increase in the immersion time till 100 hrs., the charge transfer resistance of the stir zone decreases, as shown in Fig. 1(a), indicating an increase in the corrosion rate. Further increase in the immersion time had no significant change in the charge transfer resistance, thus indicating that after 100 hrs of immersion, passive oxide film formed over the surface protect it from further oxidation. Therefore, fatigue behavior of the welded specimens was examined after 100 hrs of immersion in the 3.5% NaCl solution. The charge transfer resistance was found to have a significant effect on the fatigue life of the welded component while no significant difference was observed in the crack propagation rate; the only change in the fatigue threshold region was due to crack closure phenomena induced by the oxide formation at the crack tip. Further efforts are still going on to understand the underlying damage mechanism under combined influence of fatigue and corrosion. The observed results along with possible underlying mechanisms shall be presented during the conference.

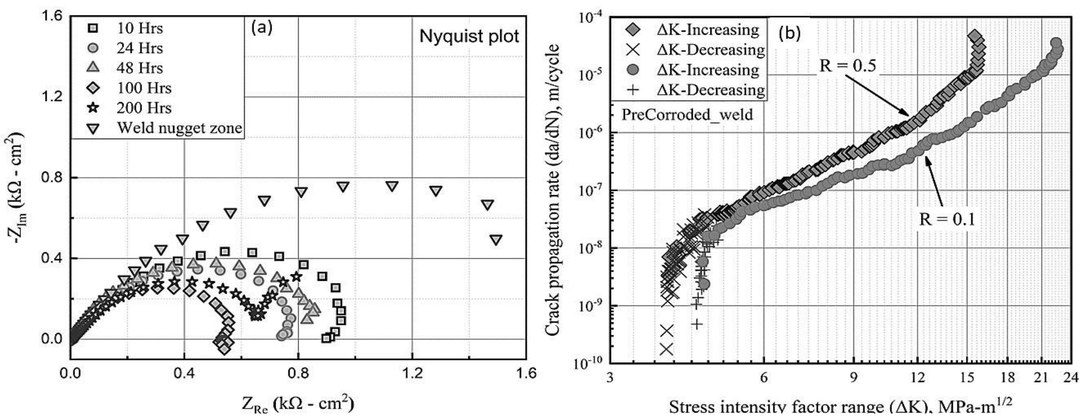


***Figure 1*** *– Charge transfer resistance curve (a) at different time intervals and (b) fatigue crack propagation behavior after100 hrs. of immersion in 3.5% NaCl solution.*

# #200 Robust and cost-efficient continuous-discontinuous description of failure: application to the simulation of complex crack paths

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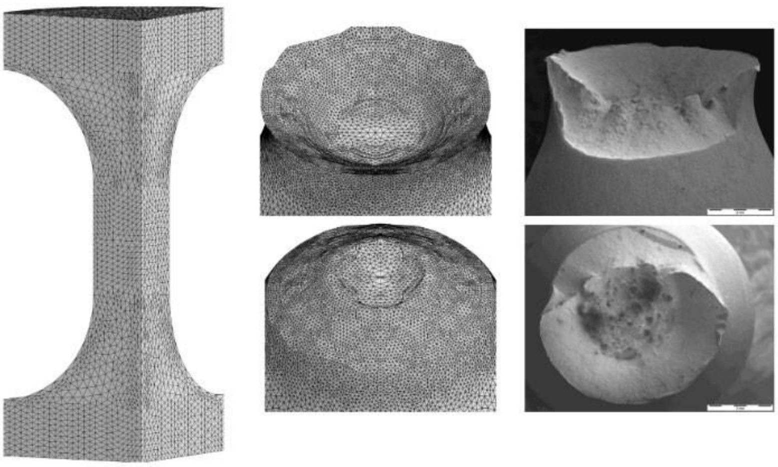
*Cup-Cone fracture   Mesh adaption   Discrete crack representation   Nonlocal GTN*

**Abstract** Prediction of crack initiation or complex crack propagation may require continuous–discontinuous strategies to insert a strong discontinuity into a continuous model [1]. The insertion is based on a scalar variable related to material degradation. Different propositions have been made in the literature [2,3]; however, some challenges remain due to the large number of issues to be addressed, particularly for 3D problems. These continuous–discontinuous strategies require the choice of several ingredients. Since these choices depend on each user's constraints, there cannot be an agreement upon a unique combination of these ingredients. However, in all cases, the selected ingredients must ensure sufficient robustness and cost-efficiency of the strategy to be easily applied to a large number of cases. With this objective in mind, some new contributions, regarding notably some rarely addressed points, are proposed in this work: (i) a simple geometrical approach to initiate realistic crack shapes in 3D meshes, (ii) a new 3D insertion criterion, (iii) a pragmatic remeshing procedure to refine only active process zones and enable automatic mesh coarsening at already cracked zones and (iv) a method to restore equilibrium for viscous materials meant to improve the convergence rate after the insertion of crack increments. The efficiency of the newly developed continuous–discontinuous model is demonstrated using several specimens used to identify constitutive laws that lead to non-trivial crack paths (cup–cone failure or slant fracture) or are challenging in simulation (blunting and long cracks with large strains). The simulations were performed in various frameworks: 2D axisymmetric, 2D plane strain, and 3D using Z-set finite element software package [4].



a) Initial 3D mesh   b) Cup—cone fracture surfaces from the 3D simulation using the proposed procedure   c) Cup—cone fracture surfaces from experimental results

***Figure 1*** *–predicted cup–cone crack surfaces are smooth, well defined, and qualitatively in agreement with what can be expected from the experimental results*

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# #201 Stress corrosion assisted collapse in flat tensile specimens of high-strength structural steel

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*High-strength steel* *Stress corrosion cracking* *Failure mechanisms*

**Abstract** This work is aimed at exploring a testing method to characterize the stress corrosion cracking behavior of a high-strength, low alloy martensitic steel bars used in structural engineering. The research is based on tensile testing of notched flat specimens that are simultaneously subjected to slow strain rate loading and environmental damage in the notched area as produced by hydrogen uptake at 50ºC in the aqueous thiocyanate solution FIP. Test interruptions at load levels considerably lower than the tensile bearing capacity of the specimens in air, followed by short-time heating at 280ºC, allowed not only the tinting of the previously developed crack, but also the specimen dehydrogenation. Subsequent tensile testing in air revealed a complex failure mechanism, largely influenced by the transition from the plane strain to plane stress condition along the subcritical cracking front. As shown in Figure 1, this produces a central crack of triangular shape that stably propagates until the specimen rupture, that occurs by ductile shearing. The same mechanism develops in the specimens subjected to non-interrupted tests whose full analysis and discussion are presented in the extended paper.

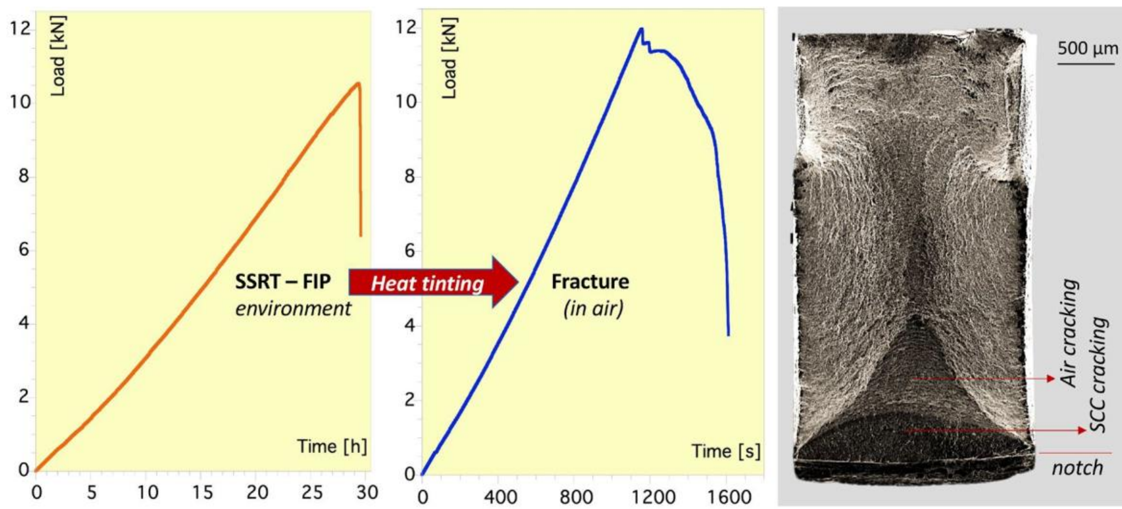


***Figure 1** – Assisted collapse of a rectangular bar specimen: a) Load – time curve in an interrupted SSRT test in FIP environment at 50ºC; b) Load – time curve in subsequent tensile fracture in air; c) Front view of the fracture surface*

# #202 Integrated model for predicting deformation and cavity growth caused by Coble creep

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*Coble Creep* *Grain boundary diffusion* *integrated model* *Microstructure*

**Abstract** An integrated model for predicting the Coble creep is proposed to simulate deformation and cavity growth caused in a three-dimensional polycrystalline considering the microstructure. The proposed model is a combination of models of creep deformation and of cavity nucleation and growth. A creep deformation model was a modification of previous works that extends the applicability from only two-dimension to three-dimensional. A model of cavity nucleation and growth was developed considering nucleation, growth, coalescence, sintering of multiple cavities and interactions among grain boundaries. The model was validated briefly by comparing with the theoretical formula of Coble creep and tendency of experiments. The model was able to evaluate the effects of factors that could not be taken into account in the conventional theoretical equations.

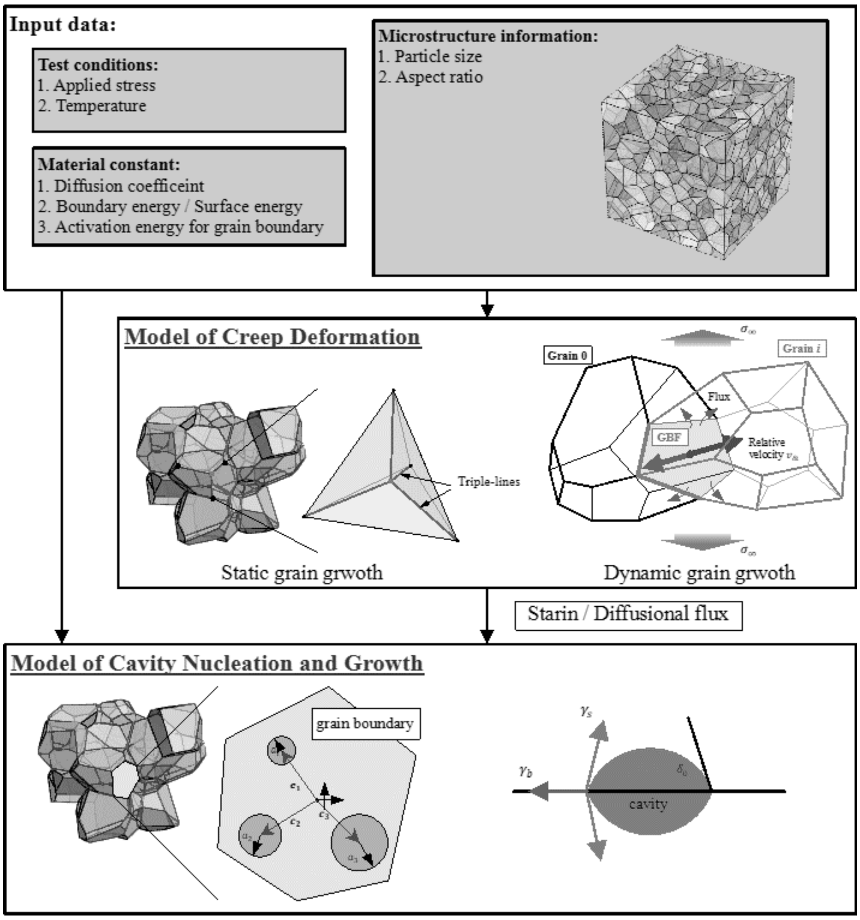


***Figure 1*** *- Outline of proposed integrated model for predicting deformation and cavity growth caused by Coble creep*

# #203 In vitro study of the deployment performance of 3D printed stents in the diseased artery with the lipid arterial plaques.

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*Lipid Plaque* *Additive Manufacturing* *Stents*

**Abstract** Atherosclerotic plaque is one of the arterial diseases which builds up in the arterial wall and can be identified by the composition of the plaque that includes lipid core (LC), calcium (Ca), collagen (Col) and other substances from the blood (Libby, et al. 2011). Atherosclerosis causes the narrowing or occlusions of the arterial lumen leading to cardiovascular event. Percutaneous (keyhole) endovascular stenting has become the most common revascularisation method due to its minimum invasive nature and low complication rate. The stents, mostly fabricated by laser machines, have uniform geometries which are not ideal to treat the diseased arteries with lesion-specific properties. In addition, the effect of arterial plaque compositions on the performance of stents is not fully investigated. In this study, the deployment performance of the stents with the varied design, made of the 316L stainless steel and fabricated by additive manufacturing (AM) technology, were investigated.

An in vitro experiment was conducted to test the influence of the atherosclerotic plaque compositions at 55% stenosis on the commercial and AM fabricated stents. Two lipid plaques with similar composition were prepared manually and their mechanical testing were conducted using an unconfined compression test. Two types of stents, printed and commercial stents, were used to treat the diseased artificial artery, and the data of the pressure and diameter were collected simultaneously when the stent inflation pressure was applied. The results show that the mechanical property of the artificial lipid plaques was very similar to the real lipid plaque that observed from clinical study. In addition, it was observed that there is a linear relationship between pressure and arterial wall movement with lipid plaque in both printed and commercial stents.

# #204 Failure of a composite riser pipe under operational and spooling loads

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*Finite element modelling* *Thermomechanical analysis* *Composite failure criteria*

**Abstract** Fibre-reinforced composite riser pipes are on the cusp of deployment in deep waters where high specific strengths and moduli and resistance to corrosion are extremely advantageous. During operation the pipes are subjected to pressure and tension in combination with large through-wall thermal gradients that arise from the mismatch between temperatures of the pipe contents and surrounding ocean. In this work, finite element (FE) stress analysis is performed for thermoplastic composite pipe (TCP), consisting of fibre- reinforced laminate with unreinforced inner and outer liners, under loads illustrative of deepwater riser operation. Temperature-dependent, three-dimensional (3D) material properties are considered. For different load combinations, yielding of the liners is evaluated, while fibre- and matrix-dominated failure modes for reinforced layers are evaluated according to Maximum Stress and Hashin criteria. Special attention is paid to increasing the pipe internal temperature, which may vary drastically while the ocean temperature will remain virtually constant. Different laminate stacking sequences are analysed and a multi-angle stack is shown to be effective for both pressure- and tension-dominated scenarios.

TCP is bent onto spools for storage and transportation, potentially in different thermal environments. TCP bending at reduced and elevated temperatures is also investigated by FE modelling in this work. Temperature change causes deviation from the symmetry expected between stresses at tensile (top) and compressive (bottom) sides of the pipe under simple bending. Unidirectional layers orientated at a high fibre angle are susceptible to transverse tensile failure at the top of the pipe. Conversely, layers orientated at a low angle are susceptible to compressive fibre failure at the bottom. TCP can be optimised for spooling by orientating unidirectional layers at an ‘intermediate’ angle that promotes utilisation of in- plane shear strength. Practical benefits are demonstrated by quantifying minimum bending radii for optimal and sub-optimal configurations in line with the industry TCP design standard, DNVGL-ST-F119. It is clear that optimising the layer stacking sequence to minimise spooling radius will adversely affect performance in deepwater operation and vice- versa. Future work should be directed at assessing the accuracy of established and novel criteria for predicting failure of unidirectional layers under these load cases. With strong experimental validation a case can be made for reducing highly conservative safety factors currently specified in design guidelines.

# #205 Quantification of the Strain Rate Effect in VHCF Testing of Structural Steels

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*structural steel* *VHCF* *experimental*

**Abstract** Traditionally in the fatigue design of steels, a fatigue limit is considered at around $10^6$ cycles, beyond which the life is assumed to be infinite. In recent years, however, it has become apparent that this infinite life assumption is not accurate, and thus to ensure extended service lives of industrial components, the behaviour in the very high cycle fatigue (VHCF) regime must be evaluated. Testing to this number of cycles using traditional fatigue testing methods is prohibitively time consuming and expensive. As such, ultrasonic fatigue testing (UFT) machines have been developed, capable of running cyclic loading tests at 20 kHz and producing fatigue results in a fraction of the time of traditional methods. UFT however, has several drawbacks which are yet to be fully understood, chiefly among which is the strain rate effect. The increased strain rate of the 20 kHz loading can have significant influence on the material properties, thereby making S-N curves produced through UFT difficult to compare to traditional S-N curves and difficult to use for design. This strain rate effect is particularly notable in ferritic structural steels, which are commonly used throughout industry. As such, until a method can be developed to take the strain rate effect into account, the usability of UFT is very limited for this ubiquitous class of materials.

The aim of this paper is therefore to investigate the influence of strain rate on the material properties of structural steels and thus quantify the corresponding effect on the UFT behaviour. Ultimately, a method will be developed which allows the UFT S-N curve to be related to the traditional S-N curve in order to produce a master curve which can be used for component design in the VHCF regime.

To achieve this, S-N curves are being produced for several different grades of structural steels at frequencies of 20 Hz, 200 Hz and 20 kHz. Samples have been waterjet cut from flat steel plates, then turned to produce the desired geometry in a CNC lathe and polished to a mirror finish. To mitigate the influence of the size effect, the same UFT specimen gauge geometry has been used for the samples at all frequencies. The 20 Hz, 200 Hz and 20 kHz samples are being tested using Instron 8801, Instron E3000 and Shimadzu USF-2000A machines respectively. After testing, the difference between the S-N curves at low and high loading frequencies will be compared for the different steels, in order to evaluate how the influence of the strain rate varies between the materials.

Additionally, for one of the steels, the stress-strain behaviour will be evaluated at a range of high strain rates from 50 - 300 $s^{-1}$. The locus of material properties such as yield strength and ultimate strength will be plotted against the strain rate, producing curves which describe how the material properties change with strain rate. The S-N curves for different load frequencies can then be normalised by dividing the stress amplitude by the strength values at the corresponding strain rates, thereby producing a master curve which allows comparison between UFT and traditional fatigue data.

# #206 On the effect of residual strength on debonding mechanism in the direct shear test

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*Analytical modeling* *Shear-lag model* *Debonding*

**Abstract** The effect of residual strength (friction) of the interface in debonding behavior of composites is herein studied through the cohesive zone model and finite fracture mechanics failure criterion. The shear-lag model is used to provide simple closed-form solutions for mathematical modeling of the problem. After satisfying the proper boundary conditions for direct shear tests, according to each model, expressions for the evolution of the debonding load, maximum load, and effective bond length are proposed. Comparisons with experimental data available in the literature are provided to illustrate the accuracy of the proposed models, which predict higher debonding load for higher residual strength. Furthermore, it is worth noting that the parameters needed to determine the failure load for different bond geometries can be extracted by testing just one geometry.

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# #207 Use of width-tapered cantilever beam for assessment of adhesion strength in PV modules aged in the hot and humid climate of southern India

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*Adhesion strength* *Photovoltaic modules* *Polymeric encapsulation*

**Abstract** Photovoltaic (PV) modules are multi-layered structures with an architecture of glass/ethylene vinyl acetate (EVA)/solar cell/EVA/backsheet. EVA acts as an adhesive layer in a PV module. It is well known that the EVA films degrade due to environmental stressors like humidity, temperature and solar radiation during the field operation of the modules. Degraded EVA loses its adhesive nature and can result in delamination at various interfaces of a module[1]. Due to EVA's delamination, the electrical performance of the PV modules can reduce. Therefore, it is essential to study the retention of the adhesive properties of EVA in the field degraded modules.

In this work, the adhesion strength of a PV module (Fig. 1) installed at Auroville, India (hot and humid climate) for 14 years has been determined. Furthermore, the degradation of the EVA film has been characterized through Fourier transform infrared (FTIR) spectroscopy and X-ray photoelectron spectroscopy (XPS) to understand the effect of the climatic factors. The determination of the adhesion strength has been done using the width tapered cantilever beam method[2]. The method involves the removal of the backsheet and back-side EVA layers, followed by the removal of the back metallization of the solar cell to access the solar cell's surface. A titanium beam, with tapered width along its length, is adhered to the cell surface. The solar cell and EVA layers underneath the beam are diced along the periphery of the beam to separate them from the rest of the module. During the test, the apex of the beam is extended from its tip at a 10 μm/sec rate to record the load (P) vs displacement (Δ) diagram. From this P vs Δ diagram, a plateauing load ($P_c$), the final load-line displacement ($\Delta_f$) and the final length of delamination ($a_f$) are noted. Using the following equation, the adhesion strength (i.e., the critical value of strain energy release rate) is determined [2]:

$$G_c = \frac{P_c}{2\tan\left(\frac{\theta}{2}\right)} \frac{\Delta_f}{a_f^2} \ \ (\mathrm{J/m^2}) \qquad \ldots 1$$

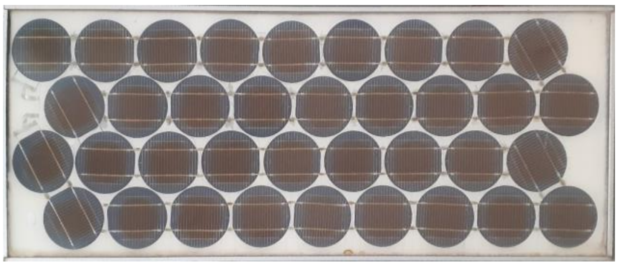

***Figure 1 -*** PV module installed at Auroville, India (hot and humid climate) for 14 years.

The assessment of the adhesion strength for the field degraded modules, especially, for the Indian climatic condition has not been reported previously. The insights presented here would be useful for the PV module manufacturers and standard committees to develop accelerated test protocols.

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# #208 Coefficients of the Williams Power Expansion of the Near Crack Tip Stress Field of Continuum Fracture Mechanics at the Nanoscale

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*Molecular Dynamics    Williams' series expansion    Atomistic stress*

**Abstract** The contribution presents the molecular dynamics simulations of the stress field in the neighborhood of the crack tip implemented in a classical molecular dynamics code LAMMPS (Large-scale Atomic/Molecular Massively Parallel Simulator). The molecular dynamics simulations are aimed at computing continuum linear elastic fracture mechanics parameters such as stress intensity factors, T-stresses and higher order coefficients of the Williams power series of the stress field in an isotropic linear elastic material. The overwhelming objective of the study is the comparison of continuum and atomistic approaches for the estimation of the near crack tip fields. Stress intensity factors, T-stresses and higher order coefficients of the Williams series expansion for a copper plate with a central crack under Mode I and Mixed Mode loadings are evaluated by atomistic modelling. The wide class of the computational experiments in LAMMPS is realized. The atomistic values of stress intensity factors and higher order terms of the Williams series expansion are compared with the values obtained from the classical solutions of continuum linear elastic fracture mechanics. It is shown that the continuum fracture theory successfully describes fracture and the near crack tip fields even at extremely confined singular stress field of only several nanometers (figure 1). The circumferential distributions of the stress tensor components from atomistic modeling are retrieved and compared with the angular distributions of the stresses from linear elastic fracture mechanics. The comparison shows good agreement between two approaches.

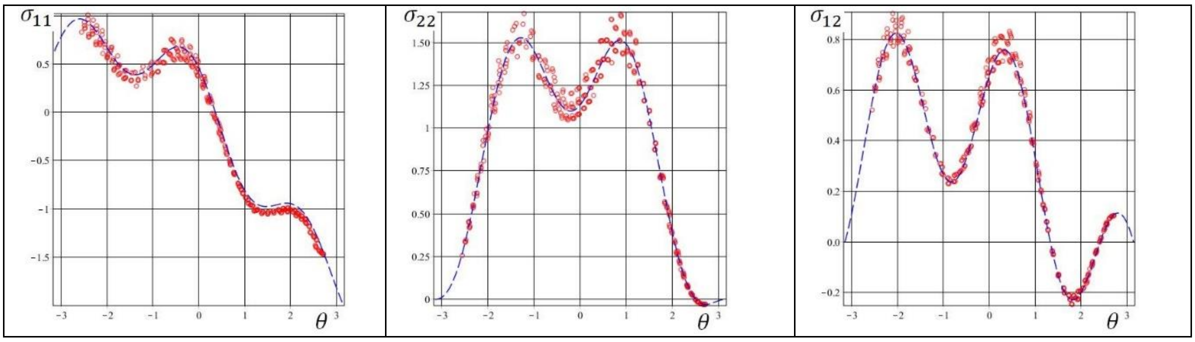


***Figure 1 -*** *The angular distributions of stresses: atomistic solution (red points) and continuum theory (blue lines)*

The work is supported by the Russian Science Foundation (project 21-11-00346).

# #210 Structural integrity of endodontic files using transient thermography and eddy currents testing

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*Structural Integrity* *NDT* *Endodontic Files*

**Abstract** The purpose of this study is to compare the fatigue resistance to rotational bending of endodontic files of different generations made of nickel-titanium (NiTi). Additionally, it is intended to investigate the possibility of using Non-Destructive Testing (NDT), mainly eddy currents testing (ECT) and thermography, to detect fatigue microcracks responsible for most of the fractures of the endodontic files in a clinical environment.

The instruments were placed in rotation in an experimental setup designed to simulate a root canal with a radius of curvature of 4.7 mm applied over an angle of 45 °. Six HyFlex ™ EDM rotary files (Coltene, Switzerland) of two sizes were tested and compared with the results obtained for two HyFlex ™ CM files of size 20 / .04. Their fracture surfaces were analysed using a Leica DMI 5000 M electronic microscope.

For the NDT application, an artificial defect was introduced in the apical region of a HyFlex CM file. Subsequently, ten customized ECT probes, were designed, produced and validated experimentally. In addition, numerical simulations were carried out, replicating the parameters and conditions of the two probes that showed better detectability. Finally, a thermographic inspection of the defective instrument was performed using a Fluke Ti 400 thermographic camera.

Experimental results showed that the newer generation of instruments manufactured by Electrical Discharge Machining (EDM) process is much more resistant to fatigue when compared to CM files.

Concerning NDT, the methodologies developed for the inspection of files through ECT proved unable to detect the faulty region unambiguously, mainly due to NiTi alloys' taper and the electromagnetic properties. In addition, numerical simulations corroborated the experimental results. On the other hand, thermography could detect the defect introduced in the endodontic file, although with some difficulty due to its small size.

# #211 Influence of the fin to baffle distance on temperature, stress distribution and fatigue life of a cooled Exhaust Gas Recirculation (EGR) system

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*Exhaust Gas Recirculation* *Fatigue Life* *Product Design*

**Abstract** Environmental concerns and the decline of Earth's natural resources are among the most prominent issues in today's society, leading to stringent policies regarding commercial vehicle emission products, such as nitrogen oxides ($NO_x$) and carbon dioxide ($CO_2$) emission levels. Aiming to reduce their environmental footprint, car manufacturers have chosen to integrate the Exhaust Gas recirculation (EGR) Cooler technology in their vehicles decades ago, as this is a resourceful and effective technique for reducing $NO_x$ emissions. This technique is still applied in current hybrid cars and is foreseen to be used in future hydrogen/gasoline moved vehicles, proving its contemporaneity, adequacy, and relevancy.

Nevertheless, this technology requires that different factors be considered during the design phase, such as high gas temperatures, mechanical vibrations, and other loads, as these may affect overall performance and durability. Therefore, the purpose of this study is to assess the impact that varying the length of the inner fins has on the applied loads and how it may affect the EGR Cooler efficiency.

To this end, Computer-Aided Engineering (CAE) tools using numerical methods, such as Finite Element Method (FEM) and Finite Volume Method (FVM), were applied. This investigation revealed that varying the inner fin´s length affects each of the applied loads differently, and increasing the length was shown to improve the heat transfer process of the EGR; however, it also increases the thermally induced stresses at the hottest region due to the high-temperature inlet gas, diminishing the fatigue resistance of the component.

The advantages and disadvantages of several configurations understudy were addressed in work carried out.

# #212 Ab initio study of hydrogen embrittlement in binary nickel alloys

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*Hydrogen embirttlement* *First-principles* *Stress intensity factors*

**Abstract** One of the current limitations of Ni-based alloys is their sensitivity to hydrogen embrittlement (HE). To design new alloys with improved resistance to HE it is essential to determine key factors that tune their resistance, that couple electronic structure and mechanical properties. It has previously been proposed that in transition group element alloys, the HE increases with the density of states at the Fermi level N(Ef) [1]. We show first how the nature of the X solute (V, Mo, Co, Nb, Ti, W, Fe, Cr) acts on electronic-structure quantities that give qualitative trends towards the selection of solute candidates in Ni-X binary alloys. In the second part, we consider a nano inverse hydrogen-enhanced decohesion mechanism which takes into account the effect of hydrogen on crack tip phenomena [2]. This mechanism proposes that for pure Ni embrittlement occurs in presence of H due to lowering of the stress intensity factor for cleavage ($K_{Ic}$) below the stress intensity factor for ductile dislocation emission and crack blunting ($K_{Ie}$). This approach is here extended to binary nickel alloys to investigate the influence of alloying elements on HE. First-principles calculations were performed to calculate $K_{Ie}$ and $K_{Ic}$ as a function of solute concentration. Further $K_{Ie}$ and $K_{Ic}$ are also calculated at varying H concentration for these alloys to further understand effect of H. These calculations are meant to provide quantitative inputs to the future design of optimal nickel alloys that are the most resistant to hydrogen embrittlement.

*Keywords: Hydrogen embrittlement, first- principles, stress intensity factor*

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# #214 Fatigue limit estimation of Ti6Al4V specimens produced by selective laser melting in as-built surface condition by using fracture mechanics approaches

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*Fatigue Limit* *Additive Manufacturing* *As-built surface*

**Abstract** Understanding the influence of stochastic surface roughness patterns on the fatigue behavior of additively manufacturing metallic components is one of the major challenges for their certification. This paper applies classical fracture mechanics-based approaches to estimate the fatigue limit of Ti6Al4V samples produced by selective laser melting by considering the as-built surface roughness pattern as an equivalent crack or defect having size determined from standardized surface roughness parameters. To this purpose, constant amplitude fatigue tests on cylindrical as built Ti6Al4V specimens were carried out to obtain both the finite life region of the fatigue curve and the endurance limit at a run-out level set to $10^7$ cycles. Before each test, the standardized surface roughness parameters (according to ISO 4287) were measured from a 2D profile extracted from 3D surface acquisition using an optical profilometer. Two existing definitions of equivalent crack size based on roughness parameters have been adopted and compared with theoretical estimates by using the material fatigue threshold curves proposed by Murakami [1] and Atzori Lazzarin Meneghetti (ALM) [2], respectively. Notably, the ALM curve has been evaluated by using an empirical model proposed by Rigon and Meneghetti [3] for estimating the required material properties, which relies on the Vickers hardness and a material dependent microstructural length. Finally, the fatigue limit estimations performed by means of both the Murakami and ALM models were found to be in good agreement with the experimental value. A graphical abstract that schematically illustrates the work is reported in Fig. 1.

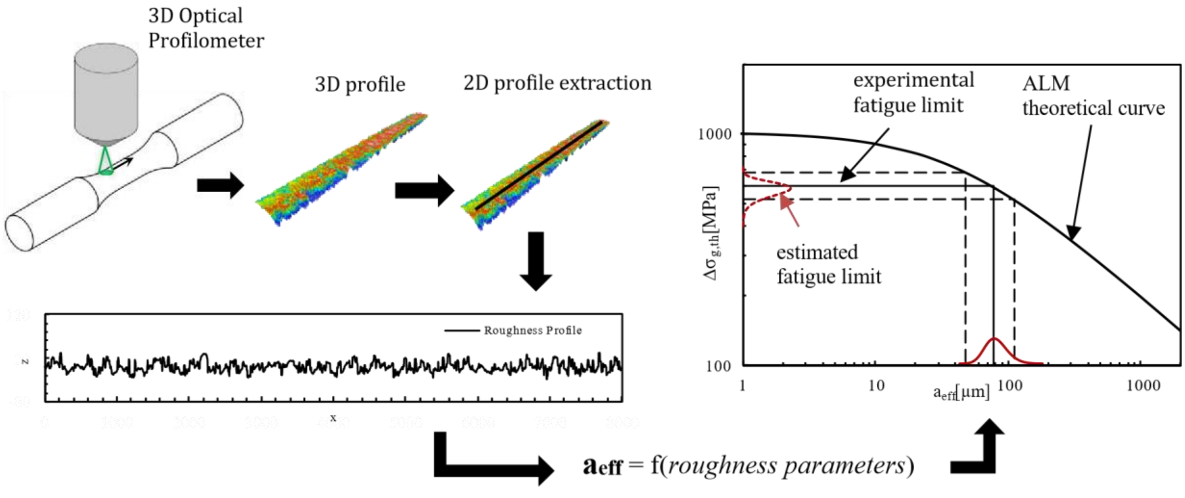


***Figure 1** – Graphical abstract*

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# #215 Modelling of the fracture process zone in wood under mode I condition

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*DCB test* *Fracture process zone* *R-curve*

**Abstract** A numerical model incorporating an exponential cohesive law [1] has been presented for calculating the FPZ length in wood under mode I condition. The present model was validated by comparing the R curve predictions obtained for reference cohesive properties from two different methods. In the first method, the crack length was evaluated indirectly from the current specimen compliance [2] whereas in the second method it was calculated directly by adding the lengths of cohesive elements that are currently damaged. It has been found that both methods give very similar results and that the FPZ development ends in the post-peak stage of deformation. The present model has been applied to reproduce results of crack growth tests coupled with DIC technique performed by Xavier et al [3] on DCB specimens which showed two different FPZ lengths in the same wood species. It has been confirmed that the different fracture behavior of specimens is caused by the inherent variability of FPZ properties leading to narrow and broad forms of the cohesive law. In order to simulate the crack length extracted from DIC measurements, it was assumed that DIC technique is able to capture the crack length extension only from the onset of fiber bridging [4]. Taking this assumption into account, good agreement has been found between numerical and experimental results of crack growth tests in terms of load, crack length, specimen compliance and strain energy release rate. Combining these results with the FPZ length evolution, it has been shown that the FPZ development and crack growth are not correctly represented by DIC measurements. The experimental observations significantly underestimate the crack extension due to FPZ. The onset self-similar crack propagation by DIC measurements takes place before the peak load is reached. Another drawback is that the fracture resistance obtained from DIC measurements overestimates the energy required for formation of microcracks. It has been established that the initial fracture energy by DIC measurements corresponds to the energy required for formation of microcracks and can be used to estimate a measurement error. All of this sheds a new light on the idea of using DIC technique to detect the real crack tip in materials that exhibit fiber bridging.

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# #216 Fracture testing of adhesive joints in mixed-mode I+III

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*Adhesive Joints* *Mixed Mode I + III* *J-Integral*

**Abstract** Established fracture mechanical test setups in mixed-mode loading usually deal with combinations of modes I and II. In these tests, it is possible to superimpose both fracture modes as long as assumptions of linear elastic fracture mechanics (LEFM) are satisfied. If this is not the case, as for example in the case of a nonlinear fracture behavior of an adhesive, the established tests have only limited applicability.

The Mixed-Mode Controlled Double Cantilever Beam (MC-DCB) test has been developed to test samples under mixed-mode loading in a combination of mode I and mode III. The mixed-mode ratio is defined based on J-integral and the principle of superimposition holds even in the case of nonlinear fracture behavior. This mixed-mode ratio is externally controlled to be constant during the entire test duration by realizing the MC-DCB test setup as a dual-actuator test in a biaxial testing machine. MC-DCB test results on hyperelastic and elastic-plastic adhesive joints have already been published by Loh and Marzi [1, 2] a couple of years ago.

In this work, further test results at constant mode-mixity on two different kinds of adhesive joints are presented: elastic-plastic adhesive joints made of SikaPower 498™ as well as rather brittle adhesive joints made of Teroson EP4510GB™. These recently achieved test results give more detailed information on the fracture behavior of the particular adhesive joints. With regard to cohesive zone modelling of possible joint failure, the traction-separation behavior at the initial crack tip has been evaluated by considering the crack-tip opening displacement, which has been measured by digital image correlation in the experiments. Furthermore, information on resistance curves under mixed-mode I+III loading is given.

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# #217 Evaluation of fatigue parameters estimation methods with regard to specific ranges of fatigue lives and relevant monotonic properties

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*Fatigue parameters* *Estimation methods* *Evaluation*

**Abstract** In an attempt to develop acceptably accurate alternative to complex, expensive and long-lasting experimental determination of fatigue data, numerous methods for estimation of fatigue parameters from materials' monotonic properties have been proposed in the literature so far. New approaches and estimation methods are still being developed and proposed, with recent efforts shifting notably from empirical/analytical approaches and models to machine learning-based predictive models. For evaluation and comparison of performance of estimation methods, the error criterion (fraction of data points within a certain scatter band) is most frequently used along with additional criteria proposed in [1]. However, existing evaluations and comparisons of estimated and experimental fatigue lives are regularly performed for complete range of fatigue lives and materials with wide range of monotonic properties, resulting in significant averaging of results of evaluations and possibly erroneous conclusions on individual estimation methods accuracy. This was confirmed in a preliminary study [2] of a few selected estimation methods using very compact and consistent dataset on a single low-alloy steel featuring different heat treatments. Significant differences which were determined in performance and accuracy of the reviewed estimation methods for low- and high-cycle fatigue lives and for two subgroups of materials regarding their ultimate strength were the main motivation for this research. According to the detailed evaluation methodology described above, a comprehensive evaluation of the established fatigue parameters estimation methods, as well as those proposed more recently, was performed. Analysis was based on an extensive number of detailed fatigue datasets on unalloyed, low-alloy and high alloy steels and on aluminum and titanium alloys, collected from relevant literature. Obtained results provide detailed insight on the accuracy of the individual estimation methods and their applicability for the estimation of fatigue parameters of various materials divided to strength-based subgroups and for particular fatigue regimes (low- and high-cycle fatigue). For certain methods, the variability in their accuracy between strength-based subgroups and in different fatigue regimes/lives is particularly pronounced. The determined values of evaluation criteria can be used as a reference for evaluations of newly developed estimation methods as well as of predictive models based on machine learning.

Acknowledgements

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# #218 Preliminary phase field implementation for bone fracture considering heterogeneous elastic and fracture properties

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*Long bone fracture* *Phase field method* *Heterogeneous fracture*

**Abstract** Bone fracture prediction by CT-based Finite Element Analysis has been studied based on maximum principal strain criterion. This simplified criterion can predict fracture initiation load within 20% error (conservative prediction). It cannot predict the crack path which may also be of interest for clinical application. In an attempt to improve bone fracture prediction, FEA and Phase Field Models (PFMs) are investigated. CT-based mesh and heterogeneous Young modulus $E(x)$ are imported into FEniCs for linear elastic FEA and PFM implementation for a humeral bone under compressive loading condition. Comparison with experimental results indicates PFM does not capture fracture location by only considering density-based heterogeneous $E(x)$ . Introducing an assumed density-based heterogeneous fracture toughness $G_c(x)$ leads to good prediction of fracture location (Figure 1). Density-based correlation of bone fracture toughness is investigated through three-point bending fracture testing on cortical bone specimens and estimation of critical stress intensity factor $K_{Ic}$ and energy release rate $G_c$ using Digital Image Correlation (DIC).

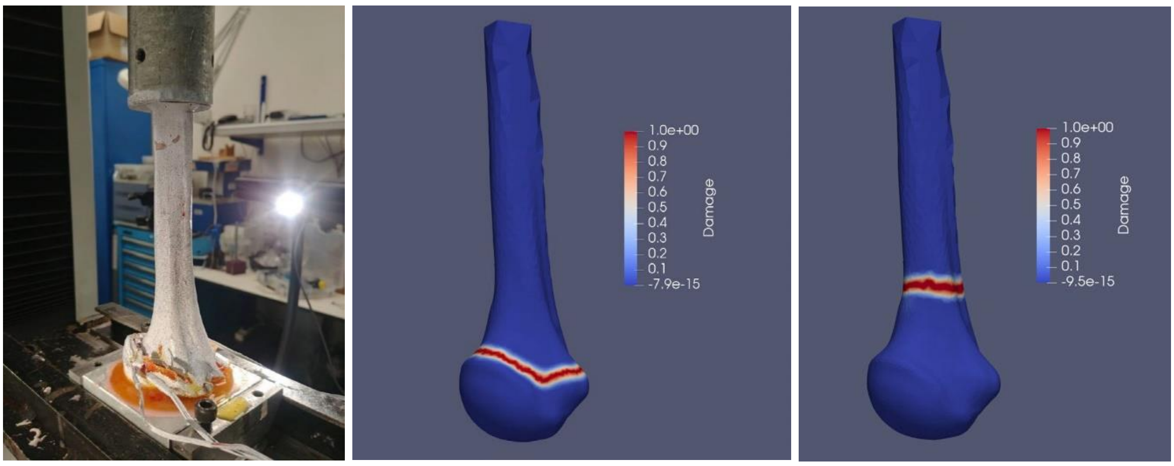


***Figure 1*** *- Phase field implementation for predicting fracture location in humeral bone under compressive loading applied on top boundary (distal) and fully clamped on bottom boundary (proximal). From left-to-right: experimental observation, PFM considering heterogeneous* $E(x)$ *and* $G_c(x)$*, PFM only considering* $E(x)$*.*

**Acknowledgement:** This research has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Sklodowska-Curie grant agreement No. 861061 – NEWFRAC Project. The authors thank also Prof. Corrado Maurini (Sorbonne Université) for assistance and insights.

# #219 Crack Propagation Life Prediction of a Single Lap Shear Joint: A Linear Elastic Fracture Mechanics Based Machine Learning Approach

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*Crack* *Joint* *Prediction*

**Abstract** Estimation of fatigue life in the aerospace industry plays a key role in terms of safety, certification, and inspection. Individual aircraft tracking programs aim to calculate the fatigue index for each individual aircraft based on its own load history. Therefore, accurate estimation of fatigue life on the basis of unique load spectra for each aircraft plays a crucial role. The purpose of this study is to predict the crack growth life of a single lap shear joint for an aircraft based on different spectral loads using random forest regression and k-nearest neighbors regression. A finite element model was built using the Huth fastener flexibility method to obtain fastener loads and stress values on the structure under maneuver loads. Then, finite element results were compared to analytical calculations. Based on Fighter Aircraft Loading Standard for Fatigue and Fracture (FALSTAFF) spectra, 90 different spectrums were developed to be used for the calculation of crack growth life. The AFGROW software was used to calculate the crack growth life based on the load spectra and the findings of the finite element model. Analytical calculations of crack growth lives and features of individual load spectrums were fed to machine learning models. Finally, the crack growth life predictions of the machine learning models were compared with analytical calculations. According to the findings, a good correlation was observed between the analytical and predicted crack growth lives.

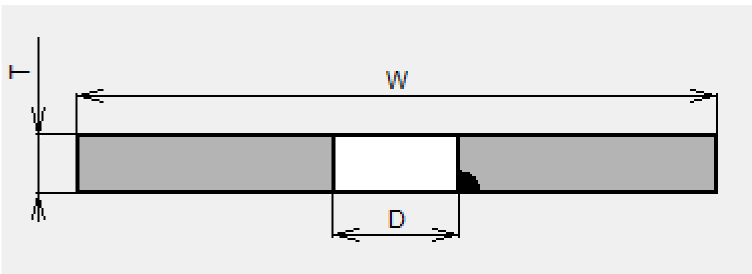


***Figure 1** – Single corner crack at hole*

# #220 Analysis of unfolding failure in unidirectional and cross-ply CFRP curved laminates: Numerical and Experimental Study

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*Unfolding Failure* *Composites* *Phase field*

**Abstract** The delamination experienced by curved composite laminates when they are loaded under bending moments is termed unfolding failure. This failure is characterized by the interlaminar tensile strength (ILTS) and is generally obtained by the four-point bending test when applied to a curved unidirectional laminate with plies oriented at 0 °. When the same test is applied to laminates with different ply orientations, the specimens fail at a load significantly lower than the predicted value. This reduction in load has been explained by the concept of induced unfolding, where the damage is initiated by intralaminar transverse cracks and further propagates as delamination in the presence of high interlaminar stresses. The present study focuses on understanding the failure mechanisms in unidirectional and cross-ply curved laminates.

Unidirectional curved laminates fail by pure interlaminar delamination, and this delamination is modelled using Abaqus cohesive elements at the 0°/ 0° interfaces. Since delamination propagation is very unstable and leads to convergence issues, a control algorithm is used to capture those instabilities and obtain a stable post-damage behavior.

Cross-ply layup configurations, defined and tested to illustrate the induced unfolding failure, exhibit multiple transverse cracks in weaker plies after failure. In order to show that failure in these configurations is initiated by matrix-dominated intralaminar damages, the phase field variational approach in terms of the UMAT/HETVAL subroutine is used. To show the interaction between intralaminar and interlaminar failure modes, models combining phase field elements with interfacial cohesive elements are used.

Finally, the reliability of the mentioned approaches is examined by correlating the numerical and experimental results for both configurations.

# #221 Fracture toughness and morphology of block copolymer toughened epoxy

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*Toughness* *Epoxy* *Block Copolymer*

**Abstract** Toughening of thermosetting polymers such as brittle epoxy resins is a key for their usage in fibre reinforced composites for structural applications in aeronautic, automotive and the energy sector. To overcome the inherent matrix brittleness especially nanoparticles have shown their potential to extrinsically toughen epoxy resins. Instead of dispersing powdery nanoscale fillers such as silica or alumina in the epoxy a new approach introduces block copolymers (BCP). BCP are molten and mixed with liquid epoxy resin and the curing agent. During the curing process, the BCP in situ phase separate at specific temperature and reaction turnover into nanoscale structures, e.g. spherical particles. Thus, the extensive shear forces usually needed to dissolve powdery nanoparticles are evaded, and furthermore, the risk of particle filtering and local concentrating at fibers during fiber composite manufacturing processes such as resin transfer molding is avoided.

The current research work systematically investigated the fracture toughness of epoxy resins from renewable and non-renewable natural resources. Resins were toughened by Poly(dimethylsiloxan) (PDMS) and Poly(butylacrylate) (PBuA) in situ phase separating block copolymers. Their toughening effect was correlated with microstructural features of the resulting composites via fractography using the scanning electron microscope (SEM), and via atomic force microscopy (AFM) coupled with in situ infrared spectroscopy and thermal analysis (nano-TA) revealing the characteristic morphology on the nanoscale. Experimental results indicate a relationship between the ratio of the interparticle distance (2c, “matrix bridge”) and the BCP dimension (dp) with the critical energy release rate $G_{Ic}$ of the composite (Fig. 1, left). $G_{Ic}$ strongly increased as (2c/dp) decreased with rising BCP concentration. EP/PBuA undergo a phase transition from nano- to micro-scale and a co-continuous morphology was observed (Fig. 1, center). AFM topography imaging with superposed infrared spectroscopy data (Fig. 1, right) reveal both EP-rich and BCP-rich phases as characteristic morphological features. In the composite with PDMS, however, a nanophase size of ca. 15 nm was maintained over the full range of concentrations.

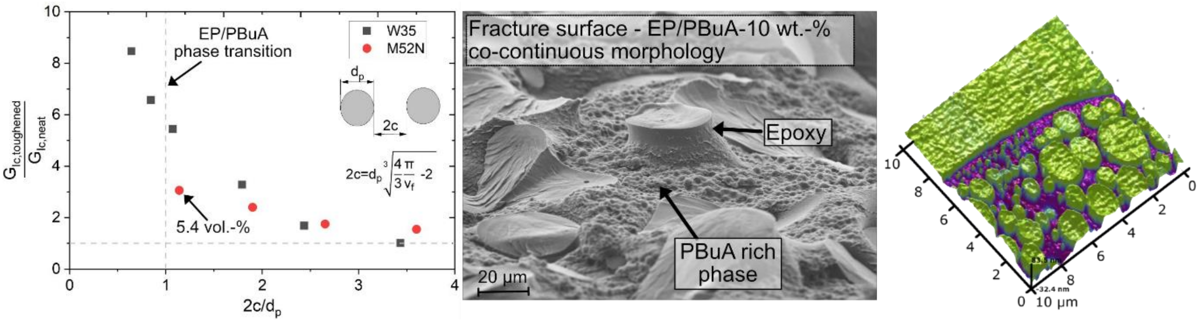


***Figure 1.*** *Left: Normalized critical energy release rate as a function of nanophase dimension $d_p$ and the interparticle distance 2c. Center: SEM-micrograph of the fracture surface of EP/PBuA. Right: AFM-micrograph with superposed topography and IR-spectroscopy images reveal the characteristic morphology at interphases of the composite.*

# #222 Temperature and strain rate dependence of the mechanical response of polymeric syntactic foams under tension and compression loading

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*Polymeric Syntactic Foams Temperature Dependence Hopkinson Bar*

**Abstract** Polymeric syntactic foams (PSF) are a kind of composite material, which consists of hollow thin-wall glass microspheres and polymer matrix. Because of their low density, low moisture absorption, relatively high specific strength and stiffness, PSF are often employed in aerospace and submarine applications in which they are subjected to a wide range of temperature conditions. Due to the temperature sensitivity of the polymer matrix, the physical and mechanical behaviour of PSFs is highly sensitive to temperature variations. Besides, the mechanical response of polymer syntactic foams is significantly affected by the strain rate. This research investigates the temperature and strain rate dependence of the mechanical behaviour of polyurethane, epoxy and nylon syntactic foams under compressive and tensile loads. Quasi static experiments were conducted at a strain rate of $10^{-3}$ $s^{-1}$ using a Zwick Z250 screw driven machine; high strain rate experiments were carried out at strain rates in the order $10^{3}$ $s^{-1}$ utilizing compression and tension Split Hopkinson Bar apparatuses. Temperatures range from -25 °C to 100 °C for all considered materials. The experimental results highlight an evident temperature and strain rate sensitivity of both compressive and tensile responses (Fig 1).

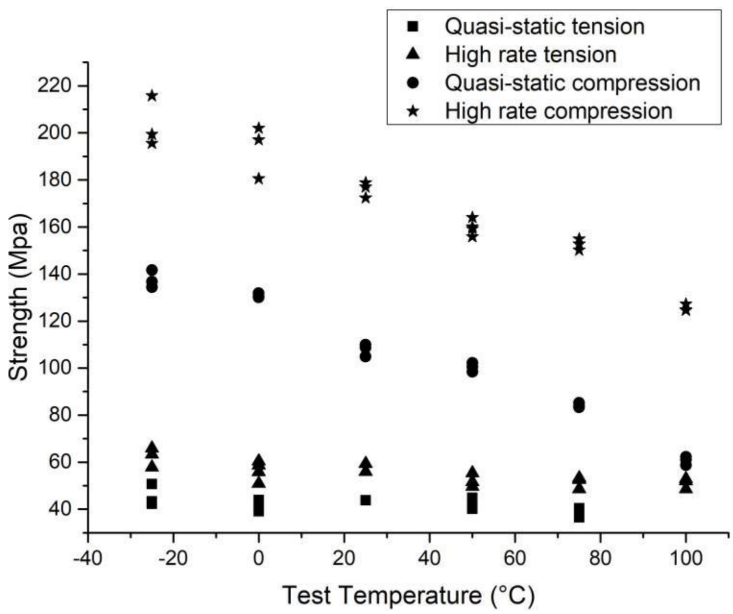


***Figure 1*** *- Test temperature and strain rate dependence of strength of epoxy based syntactic foam.*

# #223 Damage Assessment for Steel Structures Subjected to cyclic pre-strain

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*Brittle fracture* *Pre-strain* *Material damage*

**Abstract** The structure's size has been increased over time, and it means that thicker plates steels and high-strength materials are being used frequently. When unexpected events happen in specific conditions, such as earthquakes or impact loads on structures under low temperature, the brittle fracture can take place leading to accidents or disasters. Hence, the pre-strain phenomenon caused by cyclic loads during an earthquake that implies the deterioration of fracture toughness needs to be deeply studied. Although it is difficult to represent the effect of cyclic pre-strain on toughness degradation, an accurate estimation method able to predict the material behavior after the phenomenon has been strongly desired.

This work aims to confirm a simplified method to assess the consequences of cyclic pre-strain on brittle fracture. To obtain the necessary data for analysis, the pre-straining tests using specially designed four-point bending specimens with different plate thicknesses were carried out. Also, they are utilized to compare the effects of stress multiaxiality. The specimens were submitted to a process of pre-strain cycles in order to evaluate the material's behavior under diverse cyclic pre-strain patterns. In addition, specimens without pre-strain were included in the experiments to compare results with pre-strained specimens. The CTOD test results were analyzed considering the cumulative fracture probability distribution (so-called Weibull stress criterion) with critical CTOD as a parameter. It is worth mentioning that the MOTE (Minimum of three equivalent), which is commonly used as an engineering minimum value, was regarded as a representative critical CTOD value for each pre-strain condition. In order to obtain direct evidence for the effect of multiaxiality on damage evolution, a novel in-situ miniature cruciform tensile test system was developed. By this system increase of dislocation was being monitored by EBSD (Electron Back Scatter Diffraction) throughout the tensile loading process up to several plastic strain amounts. As a result of the miniature tests, it has been revealed that the larger damage is imposed in the higher multiaxiality condition. Corresponding to this, toughness changes after pre-strain in four-point bend specimen can be classified by pre-strain specimen thickness. The authors also modified the term of acceleration of fracture by plastic strain in the Weibull stress criterion to interpret the experimentally observed fracture timing observed in the cyclic pre-strain test. That is, it is confirmed that brittle fracture is likely to occur for short time after load reversal. Finally, by conducting many additional Weibull stress calculations, an equation, in which only simply obtained macro parameters are employed, was proposed as a method to evaluate accurately the material damage taking into account impacts of stress multiaxiality and pre-strain direction. In the end, applying the Strain Gradient Plasticity theory, it was attempted to track the movement of dislocations near the crack-tip.

# #224 Improvement of fracture toughness based on auxetic patterns fabricated by metallic extrusion in 3D printing

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*Auxetic cell pattern* *Metal 3D printing* *Fracture toughness*

**Abstract** Advanced structured materials by Additive Manufacturing is a rising domain where the performance of materials can be increased by combining various materials to achieve better properties than a single constituent or by shaping the material or constituents into a specific structure. Some of the complex geometries of structured materials can enhance mechanical properties or react dynamically. This study aims to evaluate the effect of using auxetic patterns on the fracture toughness of 3D printed metallic parts fabricated by metallic extrusion of 17-4PH stainless steel. When it is pulled in the horizontal direction, the auxetic material expands along the vertical axis. This occurs since it has a negative Poisson's ratio. The purpose of this work is to apply auxetic cells in fracture mechanics on Single Edge Notch Bending SENB specimens to improve the fracture toughness dynamically during applied loading.

SENB specimens were designed with three different cell patterns: (i) Auxetic pattern at 0° parallel to the notch direction; (ii) at 90° perpendicular to the notch direction and (iii) a conventional honeycomb pattern. All samples were defined with an equivalent cell density on the specimen surface (Figure 1). Three-point flexural tests have been carried out. The relative dissipated energy was compared with respect to a fullfiled specimen without pattern taken as reference.

The results show that every specimen with cell patterns absorbs more relative energy than the solid specimen does. Although the solid specimen is the stiffest, both cell patterns exhibit higher performance indices considering the importance of mass reduction. For around 35% of reduction in the maximum measured load, the auxetic pattern at 0° can absorb up to 88% more energy compared to the solid specimen. This proves its capability of delaying the crack initiation and enhancing the material toughness.

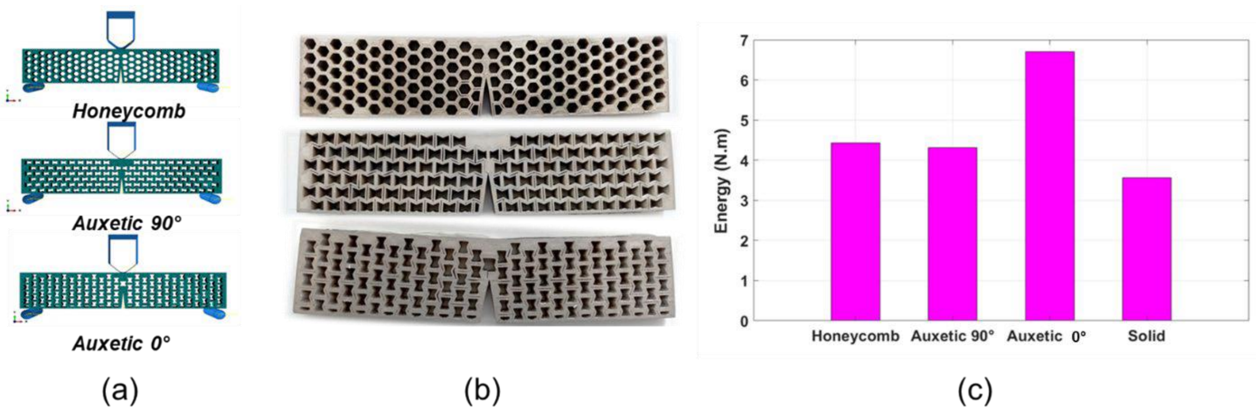


***Figure 1** – (a) Specimens geometries – (b) Damage observation (c) Experimental material toughness*

# #225 Strength calculations and fatigue tests of welded bus bodywork nodes

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*FEM calculation* *Laboratory fatigue test* *Predicted fatigue life*

**Abstract** Laboratory fatigue life tests were performed for several structural variants of welded nodes of thin-walled profiles of a bus bodywork. The laboratory fatigue tests were supported by FEM calculation and strain gauge experimental stress analysis. S-N curves were evaluated and used to predict the fatigue life of these structural nodes under random operational loading of the vehicle bodywork. Measuring systems for on-line monitoring of stresses in the vehicle bodywork have been developed and applied.

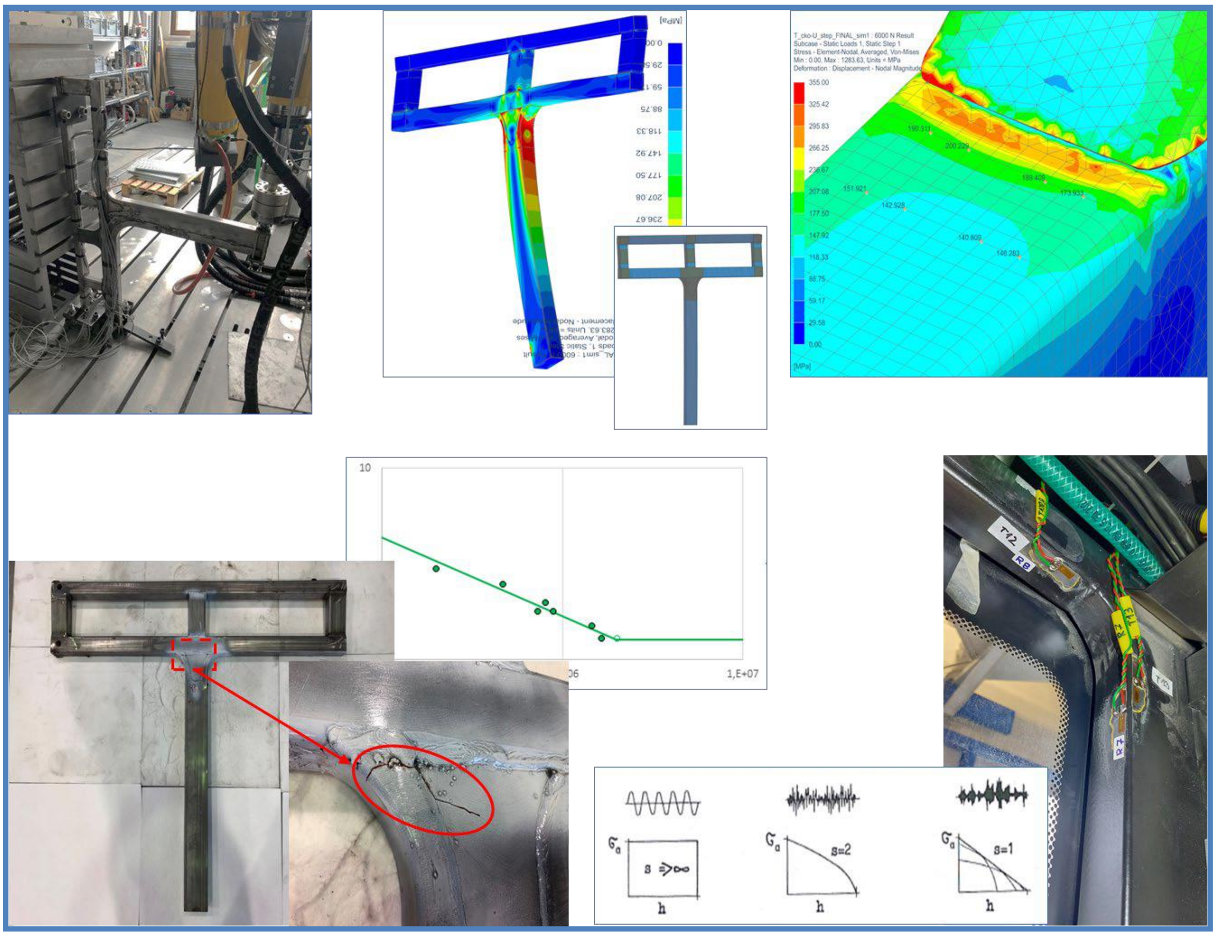

***Figure 1*** *- Symbolic graphic interpretation of the paper.*

# #226 Structural steel crack propagation experimental and numerical analysis


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*structural steel* *crack propagation* *experimental numerical*



**Abstract** Structural steels are used widely in the industry for equipment that are subjected to varying loads in harsh environments. Fatigue and fracture material properties are of great interest for equipment design and assessment. However the generation of specific material property data such as crack propagation rates for the purpose of simulation of structures under cyclic loading can be very expensive. This paper focuses on various grades of structural steel crack propagation rate experimental and numerical evaluation based on the compact tension test piece and the ASTM E647 standard. The ANSYS Workbench Mechanical SMART (separating, morphing, adaptive, remeshing tool) fracture mechanics Finite Element Analysis (FEA) technology was first used with estimated material properties. The CMOD (crack mouth opening displacement) gauge measurements from FEA results were related to the crack length based on the compliance of the test piece. This was found to give a close estimation of the crack length since the actual CMOD knife edge location was modelled precisely and a half symmetric 3D solid finite element model as shown in Figure 1 was used rather than a plane stress assumption as in the ASTM E647 methodology.

For the experimental work compact tension test pieces were manufactured from steel plates with waterjet cutting, CNC machining and notch preparation with EDM (Electric Discharge Machining). The experimental work was carried out using the Instron 8801 hydraulic testing machine at AMRL (Advanced Materials Testing Laboratory), University of Strathclyde. The loading was zero based and cyclic with a specified load amplitude at 20Hz. The data files generated by the Instron recorded the number of cycles, load, displacement, and the CMOD extensometer output at certain intervals.

The next step was to evaluate and compare the Paris Law: $\frac{da}{dN} = C(\Delta K)^m$coefficients $m$ & $C$ for the different grades of structural steels by processing the recorded data. The CMOD data was first used with the compliance relationship evaluated with the FEA to estimate the crack length. Then the logarithmic regression method is used to obtain the material properties $m$ & $C$. ANSYS SMART FEA tool is then used to simulate the crack propagation on the compact tension test piece based on the experimental & numerically obtained material properties rather than estimated properties. The experimental and numerical methods gave a very good comparison for the investigated grades of steel material for crack propagation.


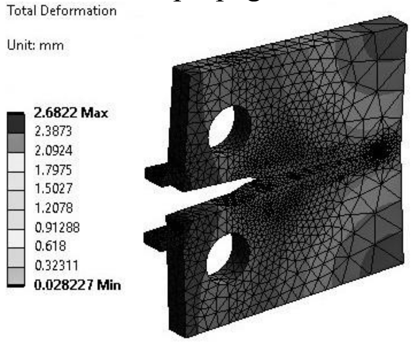


***Figure 1*** *– Compact tension test piece finite element model*

# #228 Hydrogen diffusion behavior in iron under static loading

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*Hydrogen diffusion* *Iron* *Hydrogen embrittlement*

**Abstract** The demand for high strength steels is increasing due to saving energy and resources. However, their high susceptibility to hydrogen embrittlement is one of the problems for utilization of the high strength steels. Since hydrogen diffusion and segregation associated with the embrittlement easily occur in steels, understanding the hydrogen diffusion behavior is key to clarifying the hydrogen embrittlement mechanisms. In addition, the effects of stress and strain on hydrogen diffusion must be considered because most steel structural components are normally used under loading. Therefore, in this research, the effects of stress and strain on hydrogen diffusion behavior in iron were investigated by measuring the hydrogen permeation current under loading conditions.

We used a pure iron (purity: 99.5 wt.%) sheet. The iron sheet was cut into flat dog-bone tensile specimens, and the specimens were electropolished. The hydrogen detection side of the specimen was electroplated with Ni. The Devanathan-Stachurski cell was set on the specimen. The cell for the hydrogen detection was filled with a 1.0 M NaOH aqueous solution and the specimen was polarized at 0.1 V vs. Hg/HgO. After the passive current became below 1 $mA/m^2$, the cell for the hydrogen entry side was filled with a 0.1 M NaOH aqueous solution. The specimen was subjected to static loading and hydrogen was subsequently absorbed into the specimen by a cathodic polarization at −1.1 V vs. Hg/HgO. The hydrogen permeation current was measured and hydrogen diffusivity was calculated using the breakthrough time method[1)].

A certain time after the hydrogen entry side started to be polarized, the hydrogen permeation current increased. Since the hydrogen permeation current behavior depended on stress and strain applied to the specimen, the hydrogen diffusivity in the iron specimen was calculated for each loading condition. The hydrogen diffusivity in the iron specimen decreased with the increase of plastic strain. On the other hand, the hydrogen diffusivity in the iron specimen was almost constant regardless of the stress with each plastic strain.

Boes *et al*. reported the effect of deformation on the hydrogen diffusivity by a mathematical analysis[2)]. The hydrogen diffusivity is related to the concentration of dissolved hydrogen, the number density of hydrogen trap, and the kinetic parameters of trapping and untrapping reactions. Since the density of hydrogen trap sites including dislocations increased with the introduction of plastic strain, the hydrogen diffusivity decreased with increasing the plastic strain. On the other hand, the change in the interstitial distance due to stress below the tensile strength has not a specific effect on the hydrogen diffusivity in the iron.

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# #229 Electrochemical detection of hydrogen desorption during deformation in austenitic stainless steels

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*Austenitic stainless steel* *Hydrogen desorption* *Electrochemical method*

**Abstract** Austenitic stainless steels (ASSs) are widely used in hydrogen containing environment owing to their excellent resistance to hydrogen embrittlement. However, metastable ASSs suffer from hydrogen embrittlement and the hydrogen embrittlement resistance of ASSs is known to strongly depend on the austenitic stability. The metastable ASSs show deformationinduced martensitic phase transformation. The martensitic transformation causes local changes in hydrogen diffusivity and solubility. Therefore, it is important to investigate the change in hydrogen behavior associated with martensitic transformation in order to elucidate the hydrogen embrittlement mechanism of the metastable ASSs. In this study, we investigated the hydrogen desorption behavior of ASSs with different austenite stabilities during deformation utilizing an electrochemical technique.

The materials used in this study were type 304 and 316L ASS sheets. The sheets were cut into dog-bone-shaped tensile specimens with 40 mm in gauge length, 20 mm in width, and 1 mm in thickness. The specimens were galvanostatically polarized at $-10$ A/m$^2$ for 4 days in 0.1 M NaOH aqueous solution to introduce hydrogen. Then, the specimens were plated with nickel. We modified Devanathan-Stachurski method [1] to measure hydrogen desorption behavior during deformation. The specimens were set in the electrochemical cell and mounted on a tensile testing machine. Prior to the tensile testing, the specimen was polarized at +0.1 V vs. Hg/HgO in 1.0 M NaOH aqueous solution so that the hydrogen desorption current due to diffusion became constant. The tensile tests were conducted at an initial strain rate of $5 \times 10^{-5}$ s$^{-1}$. The hydrogen desorption current was measured during the tensile test.

The hydrogen desorption current of both type 316L and 304 ASSs did not change before deformation and under elastic deformation. When the plastic deformation began, the hydrogen desorption current of the type 316L ASS increased slightly and then became constant. In contrast, the hydrogen desorption current of the type 304 ASS increased continuously during plastic deformation. The difference in the hydrogen desorption behavior is attributed to the difference in the phase transformation behavior associated with deformation.

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# #230 Reformation of Pop-in Judgment in CTOD Standard Using Novel Brittle Crack Propagation Model Incorporating Logical Energy Consumption Law

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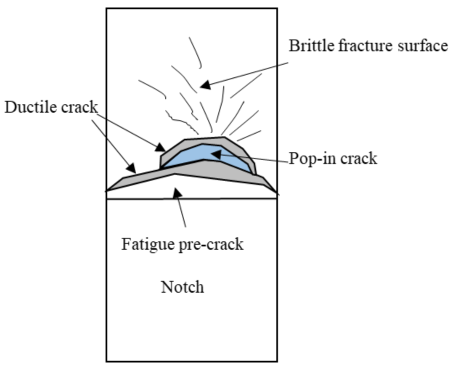
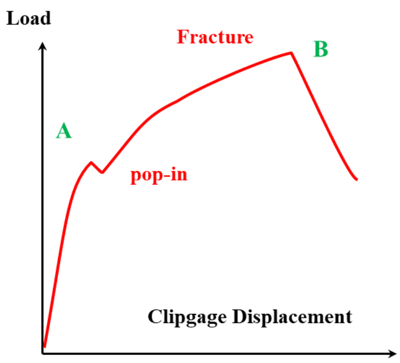
*Pop-in* *Brittle Fracture* *Fracture Surface Energy*

**Abstract** A pop-in is a small, arrested brittle crack that occurs during a fracture toughness test. This is one of the important factors of the CTOD assessment of a welded joint because the fracture toughness of material differs by the significance of the pop-in. The current standard of the pop-in is said to be too conservative because of the reasons below; the absence of the test methodology which ensures the generation of pop-ins, and the difference of the loading mode between the CTOD test and the real structures. The objective of this study is to investigate the mechanism of the pop-in formation and to improve the pop-in acceptance criteria. This study is aimed to come up with a new standard of pop-in significance determination with the idea of the local critical stress criterion and newly proposed crack propagation model incorporating energy consumption theory. That is, the CZM considering that the critical stress works as the local crack propagation criterion, and the fracture surface energy expressing plastic dissipation beneath the running crack wake is defined in each propagation, has been proposed. When the stress of the crack tip approaches the critical fracture stress, the cohesive strength is lost, and the fracture surface is created. When the cohesive strength is lost, it takes away the fracture surface energy. In the physical aspect, the fracture surface energy is increased as the fracture surface roughness increases. The Charpy test with the three-sided specimen is conducted to find the relationship between the fracture surface roughness and the fracture surface energy. The appropriate value or function of the fracture surface energy is determined by the roughness of the fracture surface and trial and error of the FEM analysis. The result of the FEM analysis is well validated with the experimental data. Finally, the authors calculate many extrapolated conditions of toughness distribution and LBZ width and conclude the current pop-in judgment criterion is too severe and propose a new rational one.




(a) Fracture appearance




(b) $P$-$V_g$ curve

***Figure 1** – Typical pop-in which is sometimes seen in CTOD test of steel weldments*

# #232 Hydrogen diffusion behavior in a stretch-formed high strength steel sheet

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*High strength steel* *Hydrogen embrittlement* *Hydrogen diffusion*

**Abstract** The strength of automotive steel sheets has recently increased for weight reduction and impact resistance. However, hydrogen embrittlement susceptibility increases with increasing the strength of steels. Since the high strength steels are used for automotive structural parts after press-forming, the effect of stretch-forming on hydrogen behavior is important to clarify hydrogen embrittlement property. Therefore, in this study, hydrogen diffusion behavior in the stretch-formed specimen was investigated using hydrogen visualization technique with an Ir complex. Based on the hydrogen mapping results, the relationship between hydrogen diffusion, plastic strain, and residual stress was discussed.

A tempered martensitic Cr-Mo steel sheet was stretch-formed using a hemispherical punch. The Ir complex whose color changes with the hydrogenation reaction was sprayed onto a side of the specimen surface. While hydrogen was electrochemically introduced from the other side of the specimen surface for over 24 hours, the Ir complex was observed with a digital camera. Hydrogen breakthrough time, which indicates the time required for hydrogen permeation through the specimen, was analyzed using the color change of the Ir complex. The distributions of the hydrostatic stress and the equivalent plastic strain in the stretch-formed specimen were calculated using finite element method (FEM).

The color of the Ir complex on the stretch-formed specimen became dark during hydrogen charging, which indicated that the Ir complex reacted with hydrogen permeated through the specimen. The hydrogen breakthrough time was longer at the center of the specimen than at the other locations. From the result of FEM, the equivalent strain was higher at the center of the specimen than at the other locations. The gradient of the hydrostatic stress from the hydrogen entry side to the hydrogen detection side was positive at the center of the specimen. These results indicated that the effect of equivalent strain on the hydrogen breakthrough time was greater than that of the hydrostatic stress. This was because the density of hydrogen trap sites increased with the introduction of plastic strain, which thereby decreased the hydrogen diffusion coefficient and increased the hydrogen breakthrough time.

# #233 A continuum fatigue damage model enriched by information from the grain structure

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*Fatigue Modeling* *Continuum Damage Model* *Grain Microstructure*

**Abstract** Thermo-mechanical fatigue in large polycrystalline metallic components can be modeled by continuum damage mechanics approaches. This is computationally efficient, but the influence of the grain microstructure is accounted for in a homogenized way only. Studies on semiconductor devices [1] show that the grain structure determines the positions at which voids and cracks are likely to form under thermo-mechanical cycling. To account for this findings the continuum damage mechanics approach developed in [2] is enriched by information on the grain microstructure. In the present work the model is enriched based on triple-junction distributions and grain misorientation angles taken from EBSD images. Computational parameter studies show that the morphology of the predicted crack pattern as well as their evolution with load cycles are sensitive to these morphological descriptors of the grain structure.

**Acknowledgments** This work was funded by the Austrian Research Promotion Agency (FFG, Project No. 863947).

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# #234 Thermo-mechanical fatigue damage modeling and material parameter calibration for thin film metallizations

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*Semiconductors* *Fatigue modeling* *Fatigue test methods*

**Abstract** Numerical fatigue damage models can help to save cost and time when studying fatigue damage in the metallization layers of power semiconductor devices. However, their predictive capabilities strongly depend on the parameters associated with these models. This paper presents a strategy for calibrating parameters of a numerical fatigue damage model using experimental results from thermomechanical fatigue experiments. Fatigue damage is predicted by the Fatemi–Socie critical plane method in combination with a Coffin–Manson law. Experimentally, test devices are utilized which can reproduce loading conditions that approximate those occurring in real semiconductor devices. Damage is measured in form of visible surface cracks by the means of surface imagery. Experimental results from devices with pronounced lateral thermal gradients are used for calibrating the parameters of the fatigue damage law. Eventually, the model with the calibrated fatigue parameters is used to predict fatigue damage for another set of experiments with different loading conditions. For all investigated test devices the numerical predictions are in good agreement with experimental results. The simulations show that significantly more damage occurs in regions with higher maximum temperatures and that the surface topology has a strong influence on local fatigue damage.

**Reference** Paul Hoffmann et al. *Thermomechanical fatigue damage modeling and material parameter calibration for thin film metallizations*, International Journal of Fatigue, Volume 155, 2022, 106627. https://doi.org/10.1016/j.ijfatigue.2021.106627.

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# #235 An Investigation of T-Stress Effect on Fatigue Crack Deviation in Thick Rolled Plates of 2050-T84 Aluminum Alloy

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*Aluminum* *Fatigue* *Crack deviation* *T-stress*

**Abstract** The increasing demand for limiting environmental impact pushes the need to improve the performance of the materials while decreasing their density. This point is crucial for a wide range of industrial applications of aeronautical Al-alloys, especially for aircraft structures. Recent advances have led to the use of Al-Cu-Li alloys, such as Constellium’s Airware alloy 2050-T84, for which the addition of 1% of lithium reduces the density while increasing both strength and damage tolerance properties, compared to incumbent products.

The studied material is a 128 mm thick plate of 2050-T84 obtained by hot rolling. Its microstructure is with grains elongated in the rolling direction (Nizery et al. 2015). In this material, a fatigue crack propagation test, for instance using standard compact tension (CT) specimen for pure mode I loading, may display deviation of the crack when the rolling direction is not orthogonal to the applied loading. When deviation occurs, the final crack path tends to align with the rolling direction. In a nutshell, the crack path is a function of both the loading and the rolling direction. This phenomenon has been highlighted in 2xxx and 7xxx aluminum alloys series, under mode I (van der Veen et al. 2016) and polymodal (mode I+II) loadings (Joyce et al. 2016), and also in stiffened structures closer to in-service conditions (Nizery et al. 2019). The aim of this paper is to propose a robust criterion able to model observed crack deviation. Within this framework, the non-singular term in the Williams expansion of the stress field at crack tip, also known as T-stress, appears to strongly impact the crack deviation phenomenon. It is observed that, based on an isotropic criterion accounting for T-stress effects (Pettit, 2000), the crack may deviate sooner than predicted by usual criteria. More precisely, positive values of T-stress are foreseen to enhance the crack propensity to deviation (Llopart et al. 2006). Moreover, in previous studies on L-S loaded C(T) and M(T) specimens of 2050-T84 (Guelzim et al. 2021), for equivalent stress state at crack tip, M(T) specimens have shown no crack deviation, unlike in C(T) specimens, which is correlated with negative values of T-stress. In order to investigate the interaction between T-stress and rolling direction on crack deviation, tests are performed on M(T), ESE(T), C(T) and DCB specimens, between which significant variations of T-stress values are expected. In fact, T-stress is negative and decreases during crack growth in M(T) specimens. For ESE(T) specimens, T-stress is initially negative but approches null values after crack propagation. Finally, T-stress is positive in C(T) and even larger in DCB specimens. The effect of T-stress is explored on both crack paths and crack growth rates (FCGR).

The impact of both T-stress and SIF value, are discussed in the light of size and shape of the plastic zone at the crack tip, obtained by digital image correlation technique. In the L-S loading direction particularly, fatigue crack paths and FCGR results are highly scattered. However, the FCGR results share a noticeable plateau in ΔK-da/dN graph, before the deviation. The plateau shows up at slower rates for large positive T-stresses. To complete the study, it is noted that the larger the T-stress is, the sooner the crack deviates.

# #236 Fatigue Crack Extension Mode Analysis in 18%Ni Steel

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*Damage accumulation mode* *18%Ni steel* *Fatigue crack extension*

**Abstract** The crack extension mode definition so far is normally based on the loading and deformation condition. However, the crack extension behavior could not correspond perfectly to crack extension modes. As classifying the fatigue crack extension mode, able to predict fatigue behavior, contributes to engineering design, it is significant to precisely define crack extension modes by the fatigue crack extension phenomenon but not by the loading conditions. Therefore, two crack extension modes have been defined: “plastic deformation mode” in which crack grows by the repetition of alternating slip, and “damage accumulation mode” in which crack propagates by the damage accumulation. However, the method to identify the modes is complex and time-consuming. Therefore, in this study, the features of fatigue crack extension mode are investigated, and the mechanism of these features is discussed~~,~~ for a more simple and convenient identification approach. Rotating bending fatigue tests (stress ratio of -1) are carried out at different nominal stress amplitude to identify the fatigue crack extension mode of smooth 18%Ni steel specimen. Meanwhile, investigations of the fracture surface and crack extension behavior are conducted. Through the results, taking microstructure inhomogeneity and damage accumulation evolution mechanism into consideration, these investigations are discussed, and the crack extension mode~~s~~ in this material is identified. Few features which could be gained simply are proposed to be the classification method of different fatigue crack extension modes.

# #237 Couple analysis of DIC and FEM to quantify strain fields and crack-flank displacements in structural materials under cyclic mixed-mode I/II fracture

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*DIC* *FEM* *Mixed mode*

**Abstract** Mixed mode cyclic fracture (MMCF) under multiaxial stress-strain state is critical for the generation of appropriate damage tolerance methodologies. To this end the elaborated approach is dedicated to full range of mixed mode loading for elastic-plastic plane problem. The subject of the numerical and experimental study is a compact tension shear (CTS) specimen manufactured from steel, aluminum and titanium alloys. The test setup included a Zwick/Roell HA100 servo-hydraulic test frame with a Zwick CUBAS control system. A S-shape grips is utilised to deliver mode mixity between pure mode I and pure mode II loading conditions. The MMCF tests were performed at a load ratio R = 0.1 with discrete applied force direction. In the present study, the displacement and strain fields around of the crack tip in the CTS specimen was measured using digital image correlation (DIC). The images were captured using an Isi-sys 3D-Micro-DIC stereo sensor system.

The displacement field measured by DIC in full range of cyclic mixed mode fracture was used to obtain the strain field through standard procedure. For the correct implementation of DIC, one of the faces of the specimens was prepared by spraying a black speckle over a white background. During mixed mode fatigue tests, the loading cycle was periodically paused to allow the acquisition of a sequence of images at uniform increments through a complete loading and unloading cycle. In this study, the DIC experimental results are represented as contours as well as radial and tangential strain distributions in the local system of coordinate centered at the current crack tip position along curvilinear crack path. Special attention is directed to crack-flank behavior according to phase field fracture methodology.

As a complement to the DIC measurement, finite element (FE) modelling of the displacement and strain fields around the crack tip in the SEN specimen was performed in order to reproduce experimental mixed mode loading conditions. In this study, for comparison aim we used the mechanism-based strain gradient (MSG) and classical HRR plasticity theories to evaluate the coupled effect of the material plastic properties and the mode mixity on the crack tip behaviour. The new material model is implemented in a commercial finite element (FE) software package ANSYS 2021R1using a user subroutine.

The intention with this work was to complement the DIC measurements as well as acquire more detailed information about the local strain ahead of the crack tip and the crack opening. From a sensitivity analysis it has been established that the DIC value depends significantly from the location along the crack direction of the pair of points selected before and behind the crack tip. The analysis of a full mixed mode range allowed identifying the fracture length scale in the phase field model. As a result of the FE calculations of strain distributions, the effects of both the fracture mode and the material properties are determined. It is found that the strain gradient plasticity model shown a better correlation with the DIC deformation fields at the crack tip relative to conventional HRR-theory.

# #238 Comparison of Macroscopic and Local Cleavage Fracture Assessment of a Reactor Pressure Vessel Steel Weld at Various Loading Rates

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*Cleavage Fracture* *Elevated Loading Rates* *Local Approach*

**Abstract** Cleavage Fracture must be avoided in safety-relevant nuclear components such as reactor pressure vessels. In addition to quasi-static loading conditions, elevated loading rates are also of interest due to beyond-design events, such as earthquakes or explosions. Fracture toughness assessment can be performed by macroscopic or local (approach) concepts. The former is characterized by comparing global load parameters like $K_I$ or $K_J$ with experimental fracture toughness values. The probabilistic Master Curve Concept (ASTM E1921) is a very prominent example of this type of methodology. In contrast, local concepts assess fracture behavior by numerically analyzing local stresses, strains, and stress states, therefore considering real micromechanical processes that lead to failure. The potentially sharper analysis ability of local concepts is confronted with the established and practical assessment by macroscopic methods. Building on previous results regarding this comparison for the base metal of a German RPV steel, the present work deals with a RPV weld loaded in the range of $10^0$-$10^4$ MPa√m/s.

Previous research has shown that elevated crack tip loading rates can have severe impact on fracture assessment, regarding both macroscopic and local methodologies. In particular, the additional mechanisms of adiabatic heating and local crack arrest strongly impact fracture behavior, which are not included in these methodologies. This work compares the results of the Master Curve methodology and local approach concepts for the weld, with and without consideration of these dynamic mechanisms.

The experimental data showed adiabatic heating effects and local crack arrest incidences in similar magnitude compared to the base material. However, the experiments showed material inhomogeneity that could be linked to microstructural parameters. The Master Curve shows better agreement with the data when considering an inhomogeneity analysis, but only for low crack tip loading rates. Here, a »dynamic« adjustment with an increased shape factor of p = 0.03 /°C leads to better results, which was also observed for the base material. The local approach was performed considering heat generation and heat conduction. A previously developed micromechanical crack arrest criterion was considered to account for the local arrest phenomena. The assessment generally appears to show similar results compared to the Master Curve approach. It is argued that the microstructurally-induced material inhomogeneity strongly interacts with the dynamic mechanisms depending on crack tip loading rate. However, the inhomogeneity is not directly considered by the local approach and should be included.

# #239 Probabilistic Safety Assessment of Cast Iron Containers

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*Cast Iron* *Probabilistic* *Fracture Mechanics*

**Abstract** Prior to storage into a final long-term disposal facility, nuclear waste is stored in a dry state in special cast iron transport and storage containers. The storage time in these containers is supposed to be more than 40 years. Throughout this period, structural integrity of the containers must be guaranteed, especially considering transportation accidents and other impacts scenarios. According to current standards, the structural integrity is assessed in a very conservative deterministic manner, in which the most unfavorable material properties, loading conditions and defects are postulated. While this methodology is conservative and well established, it provides several disadvantages, i.e. that no statistical variation of material properties is considered.

The objective of the present contribution is to develop and verify a microstructure-based, probabilistic safety assessment procedure that allows to determine a statistically quantifiable failure probability for cast iron. Initially, the the failure behavior of cast iron was analyzed experimentally as a function of temperature, loading-rate and stress-state and correlated with variations in microstructure parameters. In this investigation, rather different deformation and fracture behavior patterns were observed. The experimental data were used to simulate and study the failure mechanisms dependent of microstructural parameters and loading conditions. In particular, a probabilistic microstructural simulation was performed in which a statistically representative set of microstructural volume elements was generated and analyzed by means of the finite element method. As a result, numerical data for initiation and initial propagation of cracks through the cast iron microstructure is available (Fig. 1). The numerical procedure complements the experimental data and can be used in parametric studies for prediction of crack initiation in cast iron microstructures other than the ones investigated experimentally.

The experiments and simulations were statistically processed and used to develop and enhance analytical models for probabilistic fracture assessment (strain-based failure criterion, failure assessment diagram).

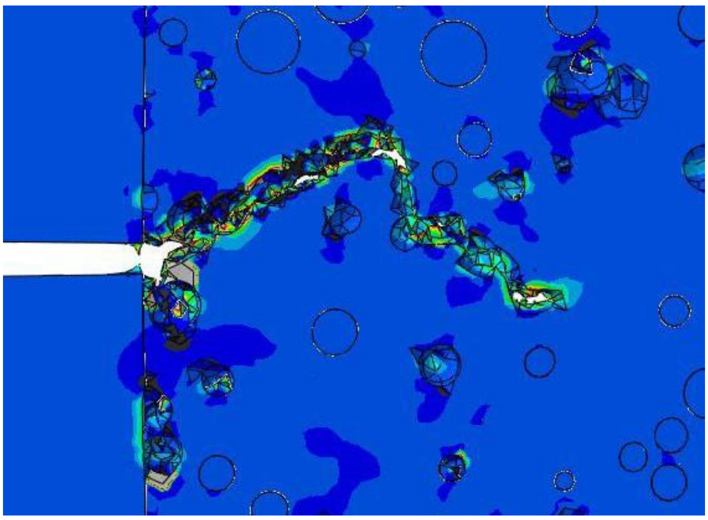

***Figure 1** – Probabilistic FEM analysis of crack propagation through the microstructure*

# #240 Nickel-Titanium peripheral stents: can fracture mechanics shed light on their fatigue failure?

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*Shape memory alloy* *Biomedical device* *Cyclic behavior*

**Abstract** The major concern about Nickel-Titanium (Ni-Ti) stents, which are the gold standard in the treatment of occlusive peripheral disease, is fatigue and the consequent fracture in vivo. Indeed, their failure might be responsible for severe drawbacks, among which is the reocclusion of the treated artery. Although many phenomenological approaches have been proposed to study this topic, the current literature lacks extensive knowledge on the Ni-Ti local damage mechanisms produced by the cyclic loads that promote crack nucleation and lead to failure of thin struts, such as those of stents. Moreover, due to the super-elastic property of the alloy, the standard approach for interpreting fracture of metals might be not accurate for this case. This work aims at increasing awareness of fatigue failure in super-elastic Ni-Ti thin struts, such as those of stents. To do so, multi-wires specimens, sharing the same dimensions and thermo-mechanical treatment of the stent struts, were fatigue tested under different strain levels and the number of cycles to failure, when happening, was recorded for each sample. The fracture surfaces of each specimen were successively analyzed using a Scanning Electron Microscope (SEM) to detect the type of defect at the origin of the fatigue failures. Successively, fracture mechanics-based approaches were implemented to perform the life predictions.

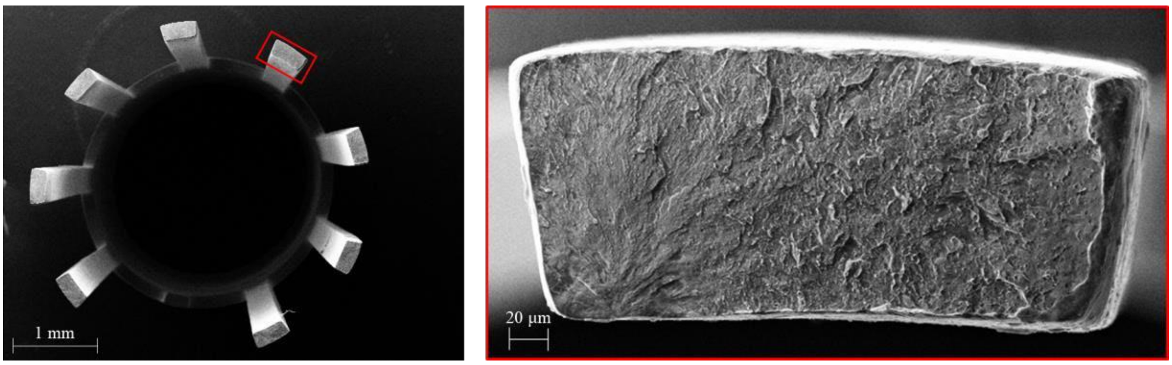


***Figure 1** – SEM acquisitions of one Ni-Ti multi-wires sample, with a focus on the fracture surface of a single wire*

# #243 On the driving force for creep crack growth

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*Creep crack growth* *Crack driving force* *Configurational forces*

**Abstract** If a structural component with a crack operates at elevated temperatures, creep deformation becomes significant and the traditional concepts and parameters of linear elastic or elastic-plastic fracture mechanics cannot be applied any more. Instead, other parameters have been worked out in order to estimate the behavior of cracks under these conditions, the $C^*$-integral, the $C(t)$-integral, and the $C_t$-parameter [1]. However, very crucial questions are still unsolved, such as “How can we quantify the driving force of cracks in creeping materials?” and “How are the above mentioned parameters related to the crack driving force?”

In the current presentation, the driving force of cracks in elastic−plastic, creeping materials is derived from the concept of configurational forces, which are thermodynamic forces on defects in materials [2]. To do this, a $J$-integral for elastic−plastic, creeping materials, $J^{epc}$, is defined analogously to the incremental plasticity $J$-integral, $J^{ep}$, for elastic−plastic materials [3,4]. $J^{epc}$ is path dependent due to the occurrence of bulk configurational forces within the creep zones. It is shown that the crack driving force is given by $J^{epc}$ evaluated for contours drawn around the crack-tip creep zone, denominated as $J^{epc}_{CZ}$. $J^{epc}_{CZ}$ can be simply evaluated for small-scale and transition creep conditions. In such cases, the crack driving force is equal to the conventional $J$-integral, which was originally derived for non-linear elastic materials. It is difficult to determine $J^{epc}_{CZ}$ for extensive creep conditions, since the crack-tip creep zone cannot be easily separated from the back-face creep zone.

In a numerical study, the variation of the crack driving force $J^{epc}_{CZ}$ with increasing creep time is compared to the behaviors of the conventional creep crack growth parameters. This is performed for the assumption of stationary cracks in C(T)-specimens made of Waspaloy at 700°C. The loading conditions are varied so that small-scale creep, transition creep, or extensive creep conditions prevail. Either the load or the load-point displacement are held constant. It is shown that, for the considered cases, the conventional creep crack growth parameters, $C^*$, $C(t)$ and $C_t$, do not reflect the crack driving force, but qualitatively follow a behavior similar to the (absolute value of the) time derivative of the crack driving force $J^{epc}_{CZ}$.

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# #244 Search for Good Local Compression Process Condition with Bayesian Optimization


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*Fracture toughness* *Local compression* *Bayesian optimization*



**Abstract** ISO 12135 provide a unified method of test for the determination of quasistatic fracture toughness. This test is conducted by using three-point bending specimen with a notch and fatigue pre-crack, and with regards to the fatigue pre-crack, ISO 12135 and ISO 15653 require some requirements such as minimum length and straightness. A base material specimen often meets the requirements without any special techniques, however, welds specimen cannot meet them due to welding residual stress. In order to meet the requirements, the local compression technique is used in general and ISO 15653 provide the recommended conditions as shown in Figure 1. However, some interested parties have reported that the recommended conditions decrease the fracture toughness values. Based on the above, the authors developed prediction method for fatigue pre-crack straightness and fracture toughness evaluation value with numerical analysis and searched the good local compression condition, such as shape, size and location, with Bayesian optimization. As a result, we found that the area and location significantly effect on the fatigue pre-crack straightness and fracture toughness evaluation value and proposed new recommended local compression condition, which securing a straight fatigue pre-crack while maintaining the fracture toughness evaluation value. This proposed condition is validated through fracture toughness test and the fracture toughness evaluation values were compared with ISO recommended condition and so on. These experimental results also showed the effectiveness of proposed condition.


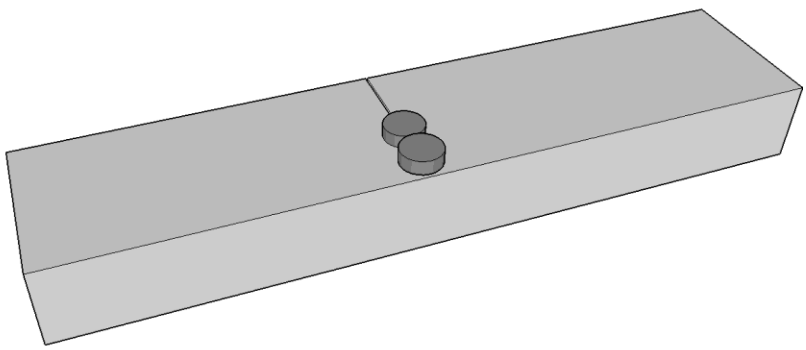

***Figure 1** – Local compression recommended in the ISO standard*

# #245 Fractographic challenges for the determination of the critical hydrogen content in high-strength steel wires

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*Hydrogen embrittlement* *Critical hydrogen content* *Slow strain rate test*

**Abstract** The determination of the critical hydrogen content allows to compare different materials and to set appropriate application limits with respect to hydrogen embrittlement. In contradiction, critical hydrogen content determination has its vulnerability in the correct interpretation of the fracture surface. This work describes the method to determine the critical hydrogen content with a focus on the correct interpretation of the embrittlement range. The embrittlement range describes the transition from the brittle to the ductile area of the fracture surface and needs to be measured accurately to determine the critical hydrogen content. A progressively cold-drawn C65 steel wire is used as test material. Applied methods to evaluate the critical hydrogen content are hydrogen charging, slow strain rate testing, fractographic analysis, hydrogen analysis and numerical simulation.

The critical hydrogen content of the hot-rolled carbon steel wire is 0.93 wt.ppm. The cold-drawn conditions show higher critical hydrogen contents due to a better ability to trap hydrogen, but also much higher hydrogen uptake under several conditions.

# #247 Experimental research of dissimilar metal weld and reactor pressure vessel weld metal in the ductile to brittle transition regime

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*Dissimilar metal weld* *Reactor pressure vessel* *Miniature specimen*

*Ductile to brittle transition*

**Abstract** The structural integrity of the reactor pressure vessel (RPV) is of utmost importance for safety and long-term operation (LTO) in a nuclear power plant (NPP). During operation, RPV is subjected to neutron irradiation and thermal aging, which can result in materials embrittlement and enhance the ductile-to-brittle transition temperature. In this paper, results on the ductile to brittle transition behavior from two projects are presented.

The focus of FEMMA (*Forum for the Effect of Thermal Aging and Microstructure on Mechanical and EAC Behaviour of Ni-base Alloy Dissimilar Metal Welds*) project was to compare the fracture behavior of dissimilar metal welds (DMWs) of safe-end between narrow gap DMW and DMW with buttering layers in as delivered and thermally aged conditions. The fracture mechanical investigations were done according to ASTM standard E1921 by determining the transition temperature $T_0$ for these two DMW mock-ups with 5x10x50 mm$^3$ single edge notched (SE(B)) specimens. Metallographic characterization was applied to identify the initiation and propagation of the cracks. There are indications that though the crack has initiated at the heat affected zone (HAZ) region in some specimens, the crack may jump and propagate along the fusion boundary. As for cracks that initiated at the fusion boundary, also propagated along the fusion boundary. Additionally, the effect of thermal ageing on fracture toughness was very moderate for specimens with crack initiated at the fusion boundary.

In BRUTE (*Barsebäck RPV material used for true evaluation of embrittlement*) project a comparison of thermally aged weld metal of reactor pressure vessel head (RPVH) and weld metal of core region of decommissioned RPV was the main target. Determination of $T_0$ was performed with miniature compact tension (C(T)) specimens. In the BRUTE project the investigated decommissioned weld metal, fracture toughness test results of the RPVH material show inhomogeneity, and consequently, the multimodal approach of potentially inhomogeneous data sets give the most dependable $T_0$ estimates. Also, the applicability of miniature C(T) specimens to study weld metals was found very suitable.

# #249 Fatigue damage evaluation of stainless AISI 347 steel by advanced microstructure-sensitive NDT analysis

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*Fatigue life evaluation* *Nuclear engineering* *AISI 347*

**Abstract** There is an increasing need to test and evaluate the integrity of ageing components and structures in nuclear engineering. Since materials for nuclear applications are subjected to thermal, corrosive, tensile, and fatigue loads during their service life, a deep understanding of microstructural degradation is desirable, as it can be gained by nondestructive testing (NDT) methods.

In this study, an innovative fatigue testing setup and NDT methods are combined to develop new, efficient and reliable concepts to evaluate fatigue life and damage mechanisms. For this purpose, specimens of metastable austenitic stainless AISI 347 (X6CrNiNb1810, 1.4550) steel, relevant for pipe components, are tested in a setup allowing in-situ measurement of temperature, micromagnetic, electric and electrochemical NDT parameters. Strain-controlled multiple and constant amplitude tests were performed and various physical measurements were used for a fatigue life analysis by short-time evaluation procedures. In-situ NDT parameters are linked to the microstructural evolution of the metastable austenite during cyclic loading. Extensive microstructural analysis through methods like electron backscatter diffraction have been performed in initial condition and at defined fatigue conditions to correlate data development versus life time. Fractographic investigations using scanning electron microscopy allow fatigue crack mechanisms to be linked with microstructural degradation.

It is shown that an advanced test setup based on temperature, electric, micromagnetic and electrochemical measurements is suitable to indicate fatigue damage-related mechanisms in a metastable austenitic material. In future these methods and findings could enable mobile testing systems to evaluate components in service regarding their remaining fatigue life.

# #250 Effects of welding on fracture of ASTM A131 steel: statistical investigation

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*Fracture statistics* *Residual Stress* *Microstructure*

**Abstract** The fracture toughness of a weldment is a function of complex geometrical, metallurgical, and environmental factors [1]. Thus, sources of inter and intra-weld inhomogeneity will contribute to the scatter in the fracture toughness across welded structures. The inhomogeneities can be categorized into two components: material inhomogeneity from welding heat and chemical inputs and inhomogeneity in locked-in stresses caused by welding. Neither are fully characterized yet as they are governed by a multitude of complicated, interconnected and sometimes random factors including: welding heat input, non-uniform cooling rates and pollution of the fusion zone by common alloying elements during the welding process. The aim of this research is to quantify the contributions of each category on variations in toughness of submerged arc-welds. The fracture toughness of several ASTM A131 ferritic steel plate butt-weldments were examined to determine the relative contributions to the overall statistical dispersion in fracture toughness caused by welding from welding residual stress and microstructural features. To investigate the contribution of these factors, their variations across the welding fusion zone were characterized. Welding residual stress was mapped using the contour method in several locations along the weld direction in the transverse perpendicular plane. Microstructural effects were characterized by spatial variation in Charpy impact energy along the weld direction. Our statistical analyses [2] suggest no linear or obvious non-linear correlations exist between Charpy impact energy, welding residual stress and spatial position along the weld direction; furthermore, Charpy impact energy and welding residual stress are individually inadequate estimators of weld fracture toughness variability. Investigating the joint responsibility of either inhomogeneity using principal component analysis suggests that microstructural embrittlement (via Charpy impact energy) accounts for the vast majority of the variability in weld fracture toughness data with the contribution from welding residual stress remaining non-negligible.

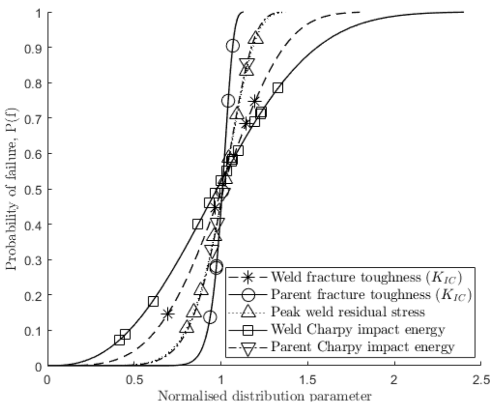


Figure 1 - Normalised Weibull CDF probability of failure vs. applied distribution parameter distributions derived from the experimental parent and weld fracture toughness (KIC), parent and weld Charpy impact energy and peak welding

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# #251 The effects of stress triaxiality on the neck initiation and fracture of high-density polyethylene (HDPE)

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*Stress triaxiality* *Necking* *HDPE*

**Abstract** This study analyses the mechanical behaviour and deformation of neck initiation, propagation and fracture of injection molded polymers composed of high-density polyethylene (HDPE) as a function of initial stress triaxiality. Three different specimen geometries namely

i) Simple tension, ii) Plane strain and iii) Shear specimens were cut-out from HDPE plates and tested experimentally in uniaxial tension to introduce different stress triaxialities. These specimen geometries are standard for material characterisation of metals. However, for polymers such specimen geometries have not comprehensively been studied. Standard shear specimen geometry was further optimized using finite element models to avoid out-of-plane deformations arising at large strain. Different specimens were mechanically tested with a speckle pattern, i.e. digital image correlation (DIC) that helped quantifying the neck initiation in the two principal material directions. The major and minor strain paths from DIC measurements were used to find stress triaxiality values at both elastic limit and neck initiation. The strain at failure was measured using gridlines, as shown in Figure 1, opposed to DIC because of the difficulty to follow the stochastic pattern at larger local strain. This study showed that within elastic limit the stress triaxiality values obtained from tests were close to the ideal values found in previous studies. However, as neck initiates and propagates, the triaxiality values for all geometries shift closer to the measured value in a simple tension specimen.

*a) Simple tension* *b) Plane strain* *c) Shear*

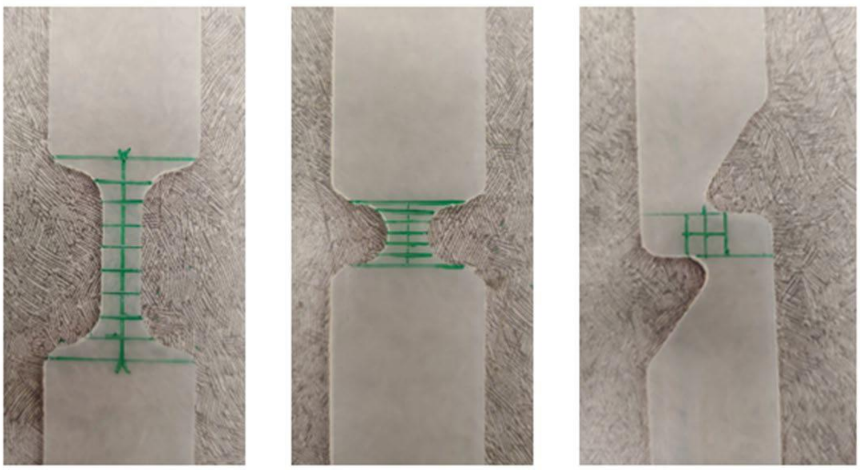

***Figure 1.*** *Different specimen geometries a) Simple tension b) Plane strain c) Shear*

# #252 Precise dynamic disintegration of concrete structures by controlling wave motion

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*Controlled disintegration* *Fracture dynamics* *Wave interaction*

**Abstract** By applying more safely usable electric discharge impulses and based on the theory of wave and fracture dynamics, we try to establish more effectively controllable techniques for precise partial disintegration of concrete structures. The models experimentally examined in the field and numerically studied in the laboratory include (un)reinforced concrete blocks, realistically large concrete slabs and steel-concrete composite structures. In order to guide three-dimensional wave interaction and ensuing dynamic fracture development in the models exactly as desired, we make use of free surfaces and pre-existing planes of weakness such as interfaces between concrete, reinforcing steel bars, steel girders and headed stud shear connectors. We also introduce, in addition to blast holes containing energy sources and emitting waves, empty dummy holes and slits in the models, and find that the development of fracture network and the final structural disintegration pattern depend sensitively on the geometrical settings of the above inhomogeneities. Our ultimate goal is to crush and remove only concrete material while other parts of structures like headed stud shear connectors and steel girders remain undeformed for later renovation work, even in densely populated urban areas.

# #253 Opportunities and partial problems of HFMI implementation in design of welded structures of rail vehicles

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*High-strength steels* *HFMI* *Railway vehicles*

**Abstract** This paper highlights the main impacts of HFMI (High Frequency Mechanical Impact) technology on increasing the fatigue resistance and extending the fatigue life of welded joints. In the case study there are SN curves of T-welded joints made of two different steels (conventional steel S235JR and high strength steel S460MC). For both materials there is a comparison of SN curves with and without HFMI treatment. Both samples are loaded by bending for cycle asymmetry R = 0. The failure criterium is a decrease in stiffness caused by the formation of a macrocrack. The results of fatigue testing are then applied in a parametric study, which assumes a random loading of a selected structural detail in a railway application. Opportunities and barriers of the implementation of HFMI in practice are mentioned and documented according to results of laboratory experiments, which take place in cooperation with the university research center and the manufacturer of railway vehicles.

***Figure 1** – HFMI application*

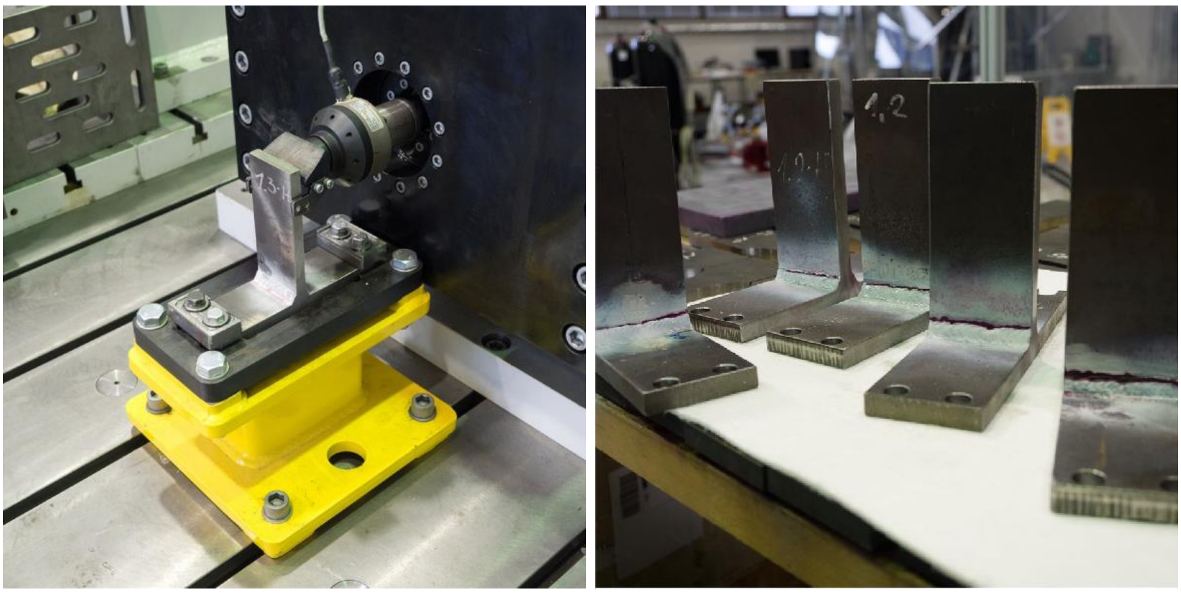


***Figure 2** – Test stand and some of the tested samples*

# #256 Strength and Fracture Resistance in Laser Powder Bed-processed AlSi10Mg and 18Ni-300 Maraging Steel

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*Mechanical performance* *Anisotropy & meso-structure* *Heat treatment*

**Abstract** Engineering materials processed using additive manufacturing (AM) techniques such as laser powder bed fusion (LPBF) often exhibit unique microstructures and defects that must be controlled to obtain peak performance in mechanical properties and as such a level of damage-tolerance that cannot be achieved in cast alloys. However, our understanding of how processing conditions control micro- and mesostructure and, in turn, mechanical performance, particularly regarding crack resistance, is weak. Furthermore, heat treatments that have been designed to achieve peak performance in cast alloys are often not optimized for alloys that have been processed using AM techniques. Here, we report our work on the effect of processing parameters such as layer thickness, hatch spacing, and scan strategy on both tensile stress-strain behavior and crack resistance curve (R-curve) behavior in different orientations of LPBF-processed AlSi10Mg and correlate mechanical performance with meso- and microstructural features such as melt pool arrangement, cell morphology, grain size, grain orientation, and texture. Compared to that we show how heat-treatments impact strength and fracture resistance as well as their anisotropy in two orthogonal orientations in an LPBF-processed 18Ni-300 maraging steel. Our work on AlSi10Mg reveals that micro- and meso-structural features that depend on the various processing parameters significantly affect strength and fracture toughness of the material. In the 18Ni-300 maraging steel, on the other hand, solution heat-treatment dissolves LPBF-characteristic cellular sub-structures and melt pool meso-structures thereby disabling AM-features that are required for mechanical performance. However, the combination of thermal cycling + aging without prior solution treatment enables a location-specific transformation-induced plasticity (TRIP) mechanism that results in outstanding combinations of strength, ductility and fracture toughness thereby providing damage-tolerance at a level that cannot be achieved in cast material

# #257 On the Limitations of Simultaneous Enhancements of Strength and Toughness in CrMnFeCoNi High-Entropy Alloys

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*High-entropy alloys* *Damage tolerance* *Deformation mechanisms*

**Abstract** Damage tolerant materials with a good combination of strength and toughness are key for the increasing complexity of structural applications and a long sought-after goal for both mechanical engineers and materials scientists. Compositionally complex alloys, often termed high-entropy alloys (HEAs), provide a potential solution to this issue. HEAs are alloy systems with at least five principal elements in (near-)equimolar ratios. They can crystallize as single-phase solid solutions with simple crystal structures despite containing high concentrations of elements with very different crystal structures. Additionally, they can display a good combination of mechanical properties making them attractive for a wide range of applications. The most studied HEA to date, the Cantor alloy CrMnFeCoNi, is a face-cantered cubic material that has been shown to exhibit strength levels above 1 GPa and fracture toughness values well above 200 MPa.m½ at room temperature. Interestingly, the alloy's strength, ductility and fracture toughness improve simultaneously with decreasing temperatures, a trend that is the opposite for most other materials. Based on our work on this alloy we will examine compositionally modified variations of this material. We will show how their failure resistance develops in the same temperature range when compositionally triggered deformation mechanisms such as transformation induced plasticity (TRIP) or twinning induced plasticity (TWIP) are enabled and additionally compare their behavior to a similar alloy that contains a second phase. Using a combination of advanced electron microscopy imaging techniques, we will show how deformation modes such as planar dislocation slip, deformation-induced nano-twinning, and transformation-induced plasticity control mechanical properties.

# #258 Experimental and Numerical Analysis of Crack Tip Flipping During Dynamic Fracture Propagation in High-Grade Pipeline Steel

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*Dynamic Crack Propagation* *FEM* *Ductile Failure*

**Abstract** In order to ensure structural integrity over several decades, high-grade steels used in pipeline construction are subjected to an extensive fracture analysis using lab-scale fracture testing. Recently, a Dynamic Tensile Tear Test (DT3) was introduced to address the issues related to the Charpy V-Notch (CVN) and the Drop Weight Tear Test (DWTT). The DT3 method applies a dynamic tensile load to mimic actual loading conditions of in-service pipelines. A high-speed stereo Digital Image Correlation (DIC) setup was implemented in the testing setup to analyse the dynamic behaviour of the propagating crack. An uncommon phenomenon called Crack Tip Flipping (CTF) was observed on the obtained images as well as the final fracture surfaces. CTF can be identified by the ductile slant appearance which alternates between shear planes. Using the stereo DIC data, an out-of-plane loading component was identified and implemented into a Finite Element Model (FEM). Ductile crack propagation was simulated using the Modified Bai-Wierzbicki (MBW) damage model. The numerical model was able to reproduce the experimental fracture surface showing ductile slant alternating between shear planes. Furthermore, a good correlation between numerical and experimental data was obtained for X70 grade pipeline steel. Finally, numerical data suggests that the CTF mechanism does not influence the force-displacement data. Consequently, it is expected that energy-based predictions on the fracture behaviour of a material are not affected with the occurrence of CTF.

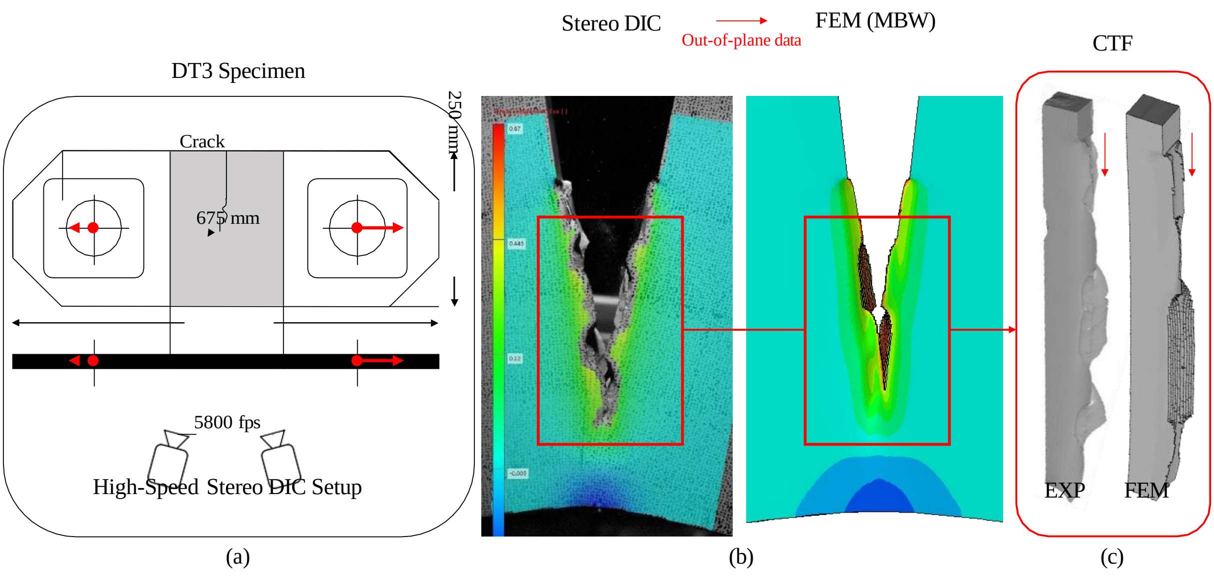


***Figure 1** - Overview of a DT3 specimen with a schematic of the High-speed Stereo DIC camera setup (a), Obtained DIC image and correlation with the numerical model (b) Experimental and numerical fracture surfaces showing Crack tip flipping phenomenon (c).*

# #259 Phase-field modeling of brittle fracture in heterogeneous bars

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*Heterogeneity* *Damage* *Phase-field*

**Abstract** Phase-field modeling of brittle fracture, first proposed by Bourdin et al. [1] as regularization of Francfort and Marigo's variational approach to fracture mechanics [2] and later re-interpreted as a special family of gradient damage models [3], provides a remarkably flexible variational framework to describe the nucleation and propagation of cracks with arbitrarily complex geometries and topologies in two and three dimensions.

The approach is based on the assumption that the brittle material exhibits homogeneous elastic and fracture properties (fracture toughness). On the other hand, many brittle materials are characterized by strongly heterogeneous properties, one important category being biological tissues such as bones. Phase-field modeling of fracture in these tissues is particularly attractive due to their typically complex crack patterns, yet it requires the extension of the approach to the case of heterogeneous mechanical properties.

Previous studies addressing fracture in heterogenous materials have adopted a pragmatic approach, by simply substituting the constant fracture toughness of the original model with a fracture toughness depending on the material point [4, 5]. However, the implications of heterogeneous material properties on the key predictions of the phase-field model have not been thoroughly investigated yet.

In this contribution, we perform such investigation for the one-dimensional case. We revisit the fundamental mathematical analysis in [3] by assuming that the material properties are heterogeneous with different possible profile shapes. Our main goal is to quantitatively assess how the heterogeneity in material properties influences the fracture toughness and the tensile strength of a one-dimensional bar.

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# #260 Towards a simplified, iteration-free calibration strategy for a non-local GURSON-TVERGAARD-NEEDLEMAN-type damage model

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*J-R-curve* *look-up diagrams* *crack-tip constraint*

**Abstract** Ductile failure can be successfully modelled by non-local damage mechanics approaches that prevent the loss of well-posedness of the governing field equations. These models offer different advantages compared to classical fracture mechanics calculations, such as a complete description of the failure process from crack initiation up to crack growth and the intrinsic effect of stress triaxiality. In the past few years, we developed a robust, gradient-enhanced extension to the Gurson-Tvergaard-Needleman (GTN) model [1,4], provided an efficient implementation within commercial FEM-software [3,4], and proposed an iterative calibration strategy [2,4]. However, the calibration of the model parameters is still challenging and thus inefficient for practically working engineers, despite the well-known potential and possible benefits of this model, such as the good prediction of the crack-tip constraint influence. The current work aims to simplify the previously developed iterative calibration procedure of the non-local GTN-model [2,4] to overcome this key obstacle. The main idea is to provide look-up diagrams, which are generated once beforehand from FE simulations for typical values of strain hardening exponents and relative material strengths, covering a wide range of engineering materials. The method is based on a unified power law description of the strain hardening curve and the unique influence of specific GTN-model parameters on the crack growth resistance curve (J-R-curve) in terms of fracture toughness and tearing modulus, respectively. As input data, a user only needs information of the stress-strain behavior and a J-R-curve from standard tests (e.g., tensile test and compact tension test), which are often even available from data sheets of suppliers. Using these data, the GTN parameters can be calibrated from the look-up diagrams without a single FE simulation. The proposed iteration-free calibration method is demonstrated and evaluated for several materials. Moreover, the predictive capabilities of the underlying GTN-model, in combination with the parameter calibration procedure, are validated by different kinds of experiments.

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# #261 An experimental investigation on the TRM to masonry bond

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*TRM* *Masonry,* *Bond strength.*

**Abstract** The utilisation of high-performance composite materials for the repair and strengthening of existing masonry structures is nowadays common practice among the engineering community. To this point, textile reinforced mortars (TRM) have been proven to be an efficient technique for the strengthening of the unreinforced masonry. TRMs comprise a textile fibre material impregnated within an inorganic matrix that is externally bonded to the masonry surface. A key parameter that controls the effectiveness of any externally bonded system is the bond between the mortar, the reinforced fibres, and the substrate; this has been often identified as the weak link in TRM strengthening. The effect of the strengthening mortar on the bond strength is not widely investigated. However, in some studies, the strengthening mortar defines as one of the crucial parameters to the TRM to masonry bond behavior. Hence, a number of experimental campaigns has been conducted to highlight the bonding performance of TRM. However, results are in many cases contradicting due to the inherent complexity of the problem that stem from the uncertainties characterizing the constituent material structural properties. Therefore, more experimental results are required to inform the investigation on the TRM to masonry bond mechanics. In this work, preliminary results from an experimental campaign on the masonry to TRM bond by means of single-lap shear tests with regards to 150mm bond lengths are presented. Parameters of investigation were the type of the textile (heavy and light carbon) and the mortar matrices.

# #262 High-temperature interfacial damage in CGI: 3D numerical analysis

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*Compacted graphite iron* *Interfacial damage* *Numerical simulation*

**Abstract** Compacted graphite iron (CGI), a type of cast iron, forms an integral part of industry worldwide thanks to its good thermal and mechanical properties, excellent wear resistance, and competitive price [1]. Despite the extensive research on cast irons since the 1950s, their thermomechanical behaviour and, especially, their fracture at the microscale are not yet fully understood. This is because of its complex microstructure, which consists of irregularly shaped, randomly oriented graphite inclusions embedded into a metallic matrix, which can be *pearlite*, *ferrite* or a *mixture* of both. As a result, a thermomechanical response of CGI is primarily affected by both graphite morphology and matrix phases [2, 3].

Interfacial debonding as the primary fracture mechanism of CGI is investigated in this research employing 3D numerical analysis [4]. CGI microstructures are characterised with scanning electron microscopy and the obtained scans are assessed with image processing tools. The results are subjected to statistical analysis to obtain the inputs required for development of 3D model. Representative volume elements (RVEs), generated using a Python script, comprise a ferritic/pearlitic matrix and graphite particles of various shapes (represented as ellipsoids) embedded in the matrix and are used with a finite-element approach. An elastoplastic behaviour is assumed for both constituents. The validation of simulations is based on comparison with the literature. The main focus of this work is the understanding of the response of CGI subjected to tensile loads at high temperatures. The influence of matrix phases on graphite debonding as the main mechanism of fracture in CGI is also investigated. The obtained results are expected to be useful for the design and optimisation of parts made of this engineering alloy and similar metal matrix composites.

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# #263 Dynamic fracture of additively manufactured continuous-fibre composites under ballistic impact: experimental and numerical study

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*Additive Manufacturing* *Dynamic Fracture* *Numerical Modelling*

**Abstract** Interest to additive manufacturing (AM) has gained a significant attention thanks to its ability to manufacture structures with complex architecture and reduced material waste compared to traditional manufacturing methods. The AM process (also known as *3D printing*) allows fabrication of parts through layer-by-layer adhesion of material. Fused deposition modelling (FDM) is the most popular AM method that uses thermoplastic polymers such as poly-lactic acid, acrylonitrile butadiene styrene, polycarbonate, and nylon. However, the application of 3D-printed polymers is limited mostly to prototypes as these materials show poor performance compared to bulk polymers, mainly due to manufacturing defects like porosity and weak strength at interfaces. Recent studies showed that optimising the manufacturing parameters and adding reinforcing fibres (carbon fibre, glass fibre, Kevlar) can dramatically increase the strength of 3D-printed composites, especially using continuous fibres, thus allowing the application of such parts beyond prototyping. Yet the scope of research for these materials still remains limited predominantly to quasi-static loading.

To elucidate the dynamic fracture behaviour of 3D-printed composites with continuous-fibre reinforcement, destructive experiments under dynamic loading conditions of ballistic impact were accompanied by development of a numerical model in this study. Understanding the performance of these structures in dynamic conditions would allow fabrication of high-performance products such as customised protective gear, prostheses as well as complex automobile and aerospace structures. To analyse the fracture behaviour of AM composites under high-velocity impact, ballistic studies with spherical steel projectiles and plates of nylon-matrix composite reinforced with continuous carbon fibres were conducted using an in-house gas gun. Additional quasi-static (tensile and compressive) testswere carried out to determine the elastic-plastic properties (strength, moduli) of the 3D-printed composite structure. They were accompanied by microscopy (both optical and electron), with micro computed tomography performed to assess the fibre volume fraction and porosity in the printed composite. Finally, the experimental conditions of the impact problem were replicated in finite- element simulations. The Hashin damage model used to model traditional composites was employed to model the material behaviour through a user-defined subroutine. Furthermore, a bilinear traction-separation law was employed for the contact surfaces of the 3D printed layers to characterise the delamination failure. The modelling outputs demonstrated a good comparison with the experimental findings.

# #264 Crystal Plasticity modelling of local microstretches effect on the cyclic behaviour of stainless steel

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*Hysteresis loop* *Crystal plasticity* *Elastic follow-up*

**Abstract** Crystal plasticity finite element (CPFE) modelling can capture the macroscopic response and meso-scale behaviour of crystalline materials, such as 316H stainless steel which is used as a structural material in the thermal power generation industry. The information gained from CPFE modelling provides a deeper understanding of the physical mechanisms and behaviours that lead to deformation, which will result in better informed lifetime assessments. In this paper we investigate the predictive capabilities of a CPFE model for cyclic deformation and local environment effects. The initial study consists of predicting the outcome of cyclic experimental tests on 316H stainless steel via CPFE. An intragranular stress term had been added to the model to accurately predict the peak hardening associated with cyclic deformation. With this term, the model's prediction of peak stresses for the first 10 cycles accurately matches that of the experimental data, which confirms that the constitutive relations employed by the model can correctly predict the early stages of hardening associated with cyclic deformation. The second section focuses on using the model that was calibrated and validated for cyclic deformation to quantify how the local environment sur- rounding a grain will alter its mechanical response. To investigate this, six studies were constructed which involve loading the model through one full cycle (±0.75% strain). The central grain was given three distinct orientations which were placed within two different microstructures. The mechanical response of the central grain is most strongly influenced by the orientation of the central grain itself, and then by the misorientation between the central grain and its surrounding environment. The deformation associated with this is captured by the CPFE model and quantified by calculating the elastic follow-up factor for the six cases.

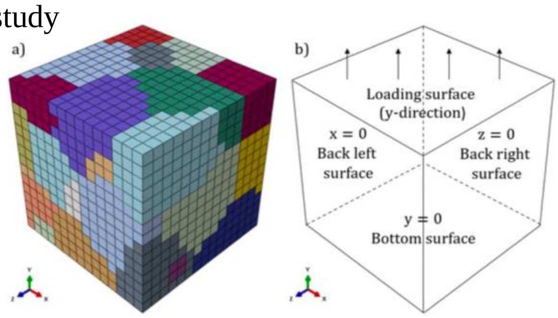
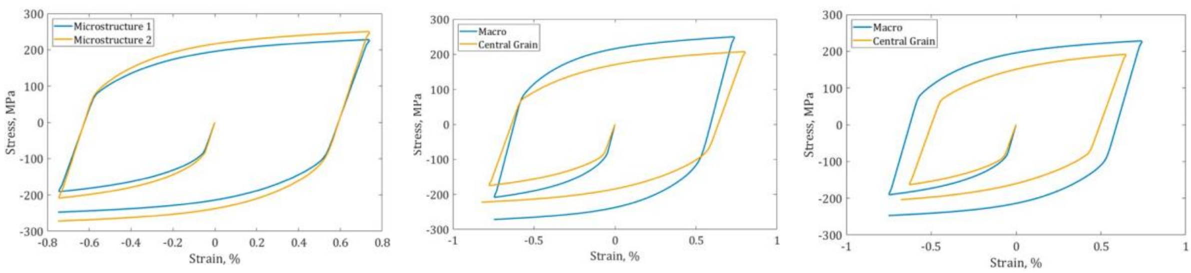



*Figure 1 - a) The RVE containing 41 grains, created using DREAM.3D. b) The loading and boundary conditions applied to the RVE*




(a) (b) (c)

*Figure 2- Comparison of the similar microstructure response with two different central grain orientation (a) macromechanical response of the two microstructure (b) macromechanical and central grain micromechanical response of microstructure 1 with a soft central grain (c) macromechanical and central grain micromechanical response of microstructure with a hard central grain.*

# #265 Statistical Evaluation of Fatigue Properties of L-PBF Manufactured Cellular Lattice Material Using a Strain Energy Density Approach

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*Cellular material* *Fatigue* *Strain energy density*

**Abstract** Development of additive manufacturing (AM) processes such as Laser Powder Bed Fusion (L-PBF) has provided the opportunity to develop tailored cellular materials for various loading conditions, including static and fatigue. However, the fatigue resistance of these structures is highly dependent on their geometry, morphology, and process parameters.

The current study aims to predict the fatigue life of cellular lattice materials printed with and without filleted junctions using the Strain Energy Density (SED) approach. The stress concentration factors in the strut junctions are estimated by taking into account the presence of filleted junctions and the surface irregularities induced in the specimens by the manufacturing process. The L-PBF printed specimens are subjected to X-ray computed tomography (CT) to evaluate their geometrical and morphological characteristics, which are used to develop a beam model of the complete specimen. Furthermore, solid models of the junctions are generated from the CT scans and subjected to the loads obtained from the statistical beam model. The fatigue stress concentration factor ($K_f$) is estimated for different junctions by applying tensile and compression loads and by varying the location of the junction inside the specimen. The $K_f$ values in the solid models are evaluated by calculating their SED over different critical radii. A statistical distribution of the $K_f$ values is obtained for different loading conditions and locations. The results indicate that using a critical radius of 0.1 mm for SED evaluation best predicts the fatigue life of the junctions and is in alignment with the experimental predictions.

# #266 Hydrogen Embrittlement Property of Nitrogen Added TRIP-aided Martensitic Steels

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*TRIP-aided steel* *Hydrogen embrittlement* *Nitrogen addition*

**Abstract** The effects of 0-200 mass ppm nitrogen addition on hydrogen embrittlement property of TRIP-aided steels with martensitic matrix (TM steels) were investigated by using tensile testing with varied strain rates. Tensile strength of approximately 1400 MPa and total elongation of more than 12 % were obtained in the TM steels due to the martensitic matrix and the strain- induced martensitic transformation of metastable retained austenite. Nitrogen addition hardly affects not only the improvement of tensile strength but also the increase in total elongation in the TM steels without hydrogen. When the TM steels were charged with hydrogen, the total elongation decreased with decreasing strain rate. Particularly, hydrogen charging significantly decreased the total elongation of TM steels containing 0 and 200 mass ppm nitrogen at the strain rate of less than $10^{-3}$ /s. In contrast, hydrogen charging slightly decreased the total elongation of the TM steel with the addition of 100 mass ppm of nitrogen at a slow strain rate. Fracture surface observation indicated quasi-cleavage fracture occurring around AlN precipitates of the nitrogen-added-TM steels charged with hydrogen. In addition, the size of the quasi-cleavage region of the steel with 200 mass ppm of nitrogen was large in comparison with that of the steel with 100 mass ppm of nitrogen because the size of AlN precipitate of the steel with 100 mass ppm of nitrogen was smaller than that of the 200-mass ppm-nitrogen-added steel.

Hydrogen analysis was conducted by means of thermal desorption spectrometry. The hydrogen concentration in the TM steels increased with increasing nitrogen content. The large amount of hydrogen in the steel containing the highest amount of nitrogen might be caused by the hydrogen trapping at the large-sized AlN and/or at matrix/AlN interfaces.

Deterioration of total elongation due to the hydrogen absorption in the 200-mass ppm-nitrogen-added steel at slow strain rate was attributed to a large amount of hydrogen trapping at matrix/large sized AlN interfaces whereas the suppression of decrease in the total elongation of the hydrogen-charged steel with 100 mass ppm of nitrogen might be due to the small amount of hydrogen trapping at fine and small amount of AlN precipitates.

# #267 Evaluation of butterfly wing formation in bearing steel: the role of non-metallic inclusions and hydrogen

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*Bearing steel* *Hydrogen assisted degradation* *Bending test* *Fractography*

**Abstract** Offshore wind energy plays an important role in meeting Europe's renewable energy targets. Wind turbine gearboxes are known to have high downtime per failure. The damage in the bearings in the gearboxes is frequently associated with the phenomenon known as White Etching Cracks (WECs). WECs are subsurface cracks often formed around manganese sulphide, non-metallic inclusions, situated in the area of the highest Hertzian stresses. The initial stage of damage occurs around these inclusions as WECs in the form of butterfly wings. This is followed by the propagation stage, in which the WECs form networks and cause premature failure. The damage formation mechanisms are still under debate. In this work, the influence of both the steel cleanliness and the presence of hydrogen on the damage mechanism is investigated systematically by performing bending experiments. For this purpose, two SAE 52100 bearing steels were cast on a laboratory scale, in one of which the amount of Sulphur was kept intentionally low, resulting in a lower amount of non-metallic inclusions. In-situ hydrogen bending tests are performed and compared with air tests as a reference condition. It is found that the clean material shows lower stress and elongation at fracture in both conditions (air and hydrogen pre-charged). As expected, hydrogen pre-charged samples undergo an extreme decrease in ductility. Complementary fractography analysis by scanning electron microscopy is done as well. The fracture surfaces of the samples tested in air consist of fracture going through the carbides, while the hydrogen pre-charged samples display a mixed type of fracture surface, i.e., through the carbides and inter-granular, for both materials. When looking at the tension surface of both materials, the samples tested in air form cracks parallel to the fracture surface. In contrast, the hydrogen pre-charged samples present a similar type of cracks as air-tested samples with additional cracks perpendicular to the fracture surface. Interestingly, both conditions (air and hydrogen pre-charged) demonstrate the same butterfly type of cracks around the non-metallic inclusions. White Etching Area (WEA) is missing because there is no rolling contact loading and, consequently, no rolling contact fatigue occurring, which would ensure rubbing of the crack surfaces and, subsequently, the appearance of WEA. In conclusion, this work shows that clean material suffers a significant decrease in ductility compared to typical SAE 52100. The addition of hydrogen affects fracture mode from fully brittle through carbides to mixed type, i.e., carbides and inter-granular. The analyses of the tension surfaces of samples tested in air and hydrogen pre-charged for both materials revealed that hydrogen does not influence the formation of butterfly wings. These results support the hypothesis that the first stage of butterfly formation starts as a fatigue type of crack around non-metallic inclusions.

# #269 Environmentally induced changes in fatigue life and durability of marine structures and vessels

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*Fatigue life* *Composites* *Marine environment*

**Abstract** Failure and fatigue life prediction becomes more important for design of composite marine vessels and structures as their application as constructive material increases. Harsh environmental operational conditions have a great impact on such structures. Realistic environmental input parameters for structural modeling of marine structures are crucial and can be obtained by conducting tests in real sea environment for prolonged periods, as opposed to usual accelerated laboratory experiments. The needed changes in the approach to the modelling of S-N curves for composite materials prescribed by the Classification societies, considering the material properties degradation due to the effects of water absorption, fouling marine organisms and prolonged exposure to the marine environment are discussed here. Regression analysis results for experimental data collected during a 2-year period are presented and a procedure for the decrease estimation of expected fatigue life is given for glass/polyester composite material for three different fiber layout configurations. All the submerged coupons with different fiber layout configuration exhibited a significant loss of ultimate tensile strength (UTS) which consequently shortened their fatigue life and decreased durability.

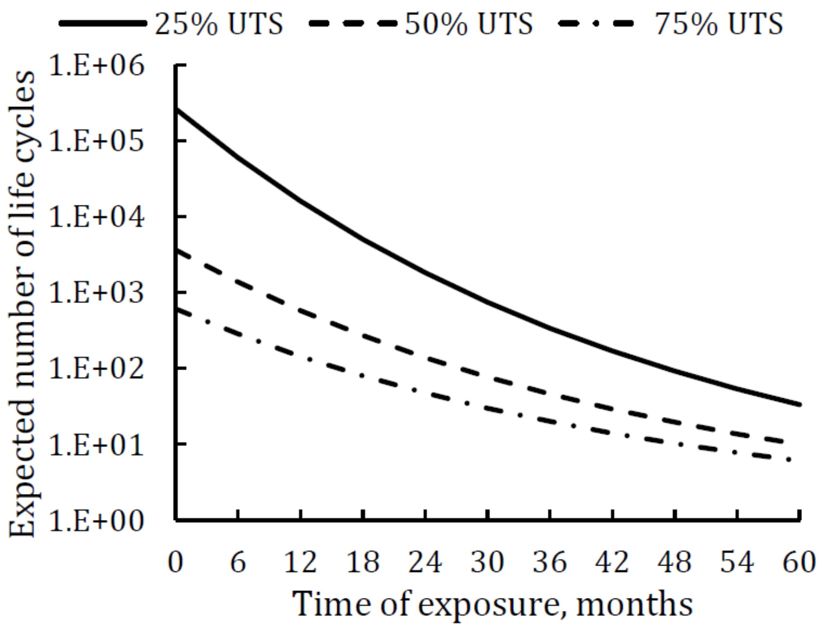


***Figure 1** – Decrease of fatigue life due to marine environment exposure*

# #270 Effects of coating on the fatigue endurance of FDM lattice structures

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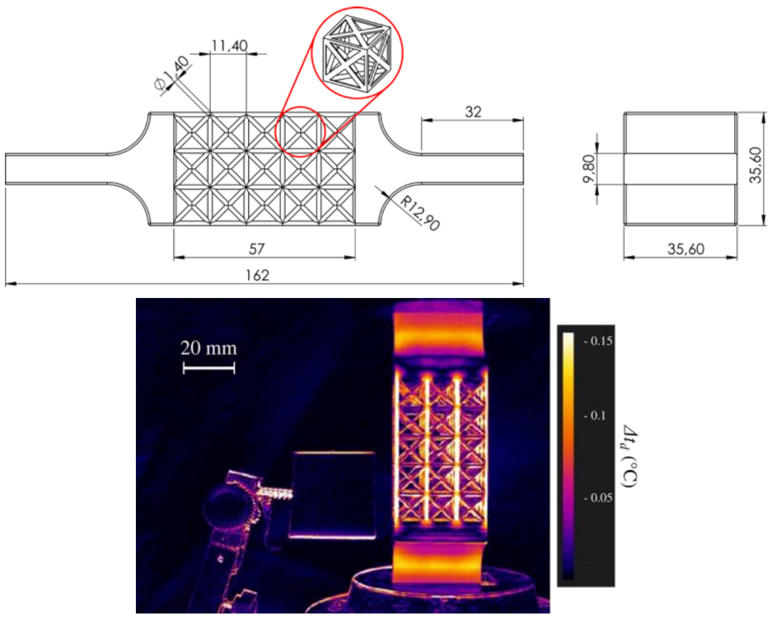
*Coating* *Fatigue* *Lattice structure*

**Abstract** Additive Manufacturing (AM) techniques such as Fused Deposition Modeling (FDM) are widely used to produce lattice structures with complex unit cell geometries. These structures can be designed to meet specific needs in a wide range of application fields, ranging from biomedical to mechanical sectors. The mechanical behaviour of these structures can be often impaired by a low surface quality. However, the mechanical strength of polymer lattice structures can be significantly improved with the use of post-processing treatments. Coating post-processing is one of the treatments that showed the best results. Nevertheless, research interest is often targeted at studying the static mechanical properties rather than the fatigue behaviour of polymer components. In this work, the effect of a coating on the fatigue life of PLA lattice structures produced by FDM was investigated. The specimen has been designed to enable the application of both tensile and compressive loads, as shown in Figure 1a. Before the fatigue analysis, preliminary tensile tests were carried out to assess the static strength of the specimen. Experimental fatigue tests were performed with varying testing frequencies and displacements. Numerical and thermographic analyses were used to provide a better understanding of the fracture behaviour of the material with or without coating. The use of thermography has further aided in defining the acceptable boundary for test frequencies and displacements to avoid excessive material overheating (Figure 1b), which could be an issue for thermoplastic polymers such as PLA. The results showed how coated and non-coated components present a different behaviour when subjected to different test frequencies and loading conditions. The presence of coating produced an increase in fatigue endurance across different testing frequencies over a particular displacement range.

***a)***




***b)***

***Figure 1*** *– Specimen geometry used for static and fatigue testing* ***a)****, and total temperature variation ($\Delta t_d$) after 1000 cycles at 30 Hz and 0.3 mm of displacement amplitude (R=-1)* ***b)***

# #271 Prediction of Failure Envelope of Calcified Aneurysmatic Tissue

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*Aneurysm* *Anisotropic tissue* *Phase-field*

**Abstract** The abdominal aortic aneurysm (AAA) consists of a varying degree of calcification where calcium particles are found in different geometrical configurations. The impact of calcification on the failure of aneurysms is not very clear as literature shows contradictory results. This work is dedicated to investigating the impact of calcification on the failure strength of an aneurysmatic wall using micromechanical simulations. Considering plane stress assumption, Representative Volume Elements (RVE) consisting of circular and elliptical particles are generated in a 2-dimensional framework with different volume fractions. A twofibre model is used for modeling anisotropic tissues. Calcium particles are assumed to be elastic. An anisotropic phase-field model is employed to model the failure in tissue. A unique set of representative material parameters as well as phase-field parameters, like critical fracture energies for isotropic and anisotropic parts, are determined by fitting the model to experimental data, available in the literature, for biaxial loading. Finite element simulations are being performed on the RVE to generate a failure envelope of the calcified tissues. This study will help in better understanding and better prediction of failure in aneurysms.

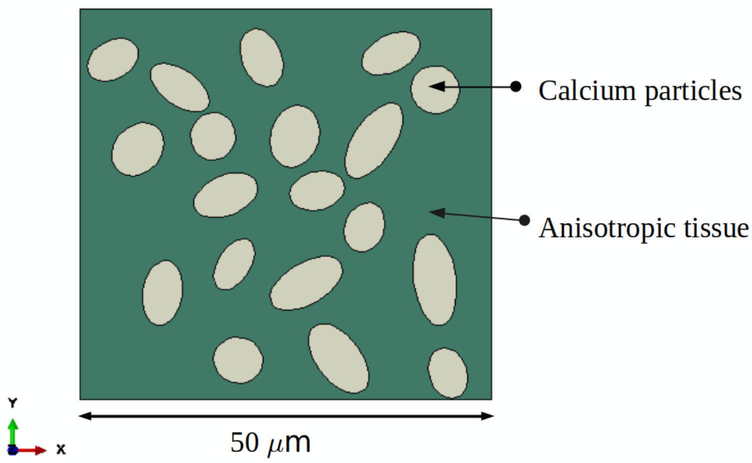


***Figure 1** – RVE of calcified tissue with 0.24 volume fraction*

# #272 A numerical modelling strategy for accurately simulating dynamic crack propagation in a 3D solid based on s-version of finite element method

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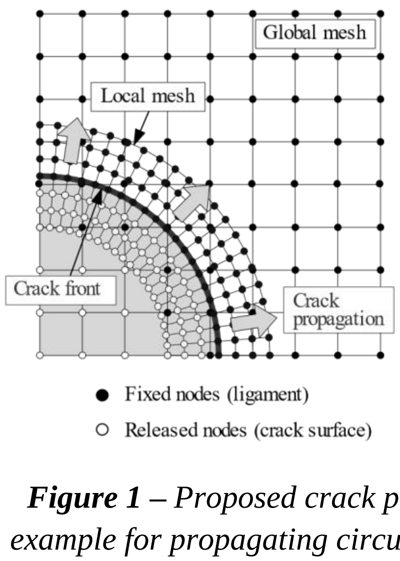
**Keywords** *s-version finite element method Dynamic crack propagation*

*Local fracture stress criterion* *Stress intensity factor*

**Abstract** Accurate numerical simulation of the brittle crack propagation phenomenon is very effective in preventing critical damage to structures. Although recent studies have demonstrated that using the local fracture stress criterion as the fracture condition is effective, the most critical issues are the numerical accuracy and the cost of local stress evaluation. To address this issue, this paper proposes a numerical modelling strategy for analysing dynamic crack propagation in a 3D solid on the basis of the s-version finite element method (s-method). By utilising an advantage of the s-method that the local mesh can be flexibly defined in the domain, the crack front geometry can be ideally modelled by a series of edges of the local elements. The dynamic crack propagation is modelled based on a combination of the nodal force release method and local mesh update. The proposed modelling strategy was verified by evaluating the accuracies of the local stress and the stress intensity factor in stationary and dynamically propagating circular crack problems.



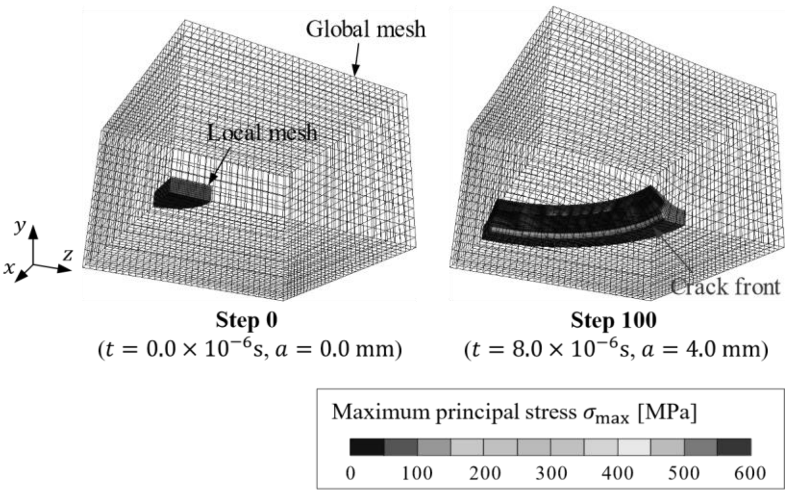




***Figure 1*** *– Proposed crack propagation analysis strategy example for propagating circular based on s-version FEM.*

***Figure 2*** *– Numerical crack problem.*

# #273 Modification of the Theory of Critical Distances to predict the effect of multiple stress-rising features on resulting fatigue failure of SLM Ti-6Al-4V

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*Fatigue* *Notches* *Critical distance*

**Abstract** Selective Laser Melting (SLM) is an additive manufacturing practice that produces metal alloy-based parts. While facilitating the design of complex geometry, SLM leads to fabrication of a unique material structure that showcases distinct behavioural characteristics relative to their traditional methods of material manufacture. Defects innate to SLM inspire the presence of a compositional material outlook that is inhomogeneous in nature and therefore hinders part efficiency.

This study succeeds previous work that was conducted in [1], in which it was originally shown that the Theory of Critical Distances (TCD) could predict the performance of as-built SLM Ti-6Al-4V material to an acceptable level of accuracy. This involved the analysis of external stress-rising features (Fig. 1(a)), ranging from initially larger sized design-induced notches, right down to the same size range of process-inherent material surface topology which is typically evident in SLM manufactured specimens.

The authors are now seeking to assess the viability of the TCD model to forecast the effect of increasingly complex material compositions that may feature multiple stress concentrating features acting simultaneously to each other. In this regard, special attention is paid towards analyzing the current TCD model's ability to predict fatigue resistance of AM components that contain some form of external stress-rising feature in parallel with internal porosity (processinherent or otherwise) that is located in its nearby vicinity (Fig. 1(b)).

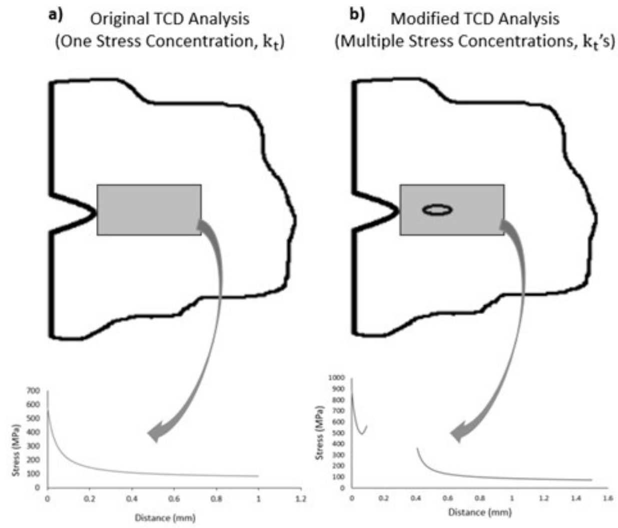


***Figure 1 -*** *(a) Original stress-distance curve data with one stress-rising feature & (b) Interrupted stress-distance curve data due to multiple stress-rising features*

[1] B. Gillham, A. Yankin, F. McNamara, C. Tomonto, D. Taylor, and R. Lupoi, "Application of the Theory of Critical Distances to predict the effect of induced and process inherent defects for SLM Ti-6Al-4V in high cycle fatigue," *CIRP Ann.*, vol. 00, pp. 4–7, 2021, doi: 10.1016/j.cirp.2021.03.004.

# #274 Phase Field Approach to Fracture of Thin-ply Laminates

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*Thin-ply composites* *Phase Field* *Fracture*

**Abstract** Thin-ply carbon fiber reinforced polymer (CFRP) composites are gaining significant appeal in the aerospace world as they provide significant weight reductions without compromise in plain strengths. However, their inclusion in design is hindered by the lack of proper design tools for them (i.e., robust and efficient modeling techniques). Thin-ply CFRPs present a homogeneous quasi-brittle type of fracture, and, as mentioned by Arteiro et al. [1], modeling can be more efficiently done at the macroscale, by means of an equivalent single layer (ESL) representation. For that, the Phase Field (PF) method is considered here, and its anisotropic formulation based on Teichtmeister et al. [2] is extended to properly refer to a multidirectional (MD) laminate. The proposed implementation is based on the analytical model presented by Camanho and Catalanotti [3] that defines the fracture toughness of MD laminates using the intralaminar fracture toughness of the 0° ply, the lay-up of the laminate and the lamina elastic properties. The model capabilities and range of application are demonstrated by means of numerical off-axis open-hole tension (OHT) results of a MD thin-ply laminate, while it is also validated against existing experimental results for different laminate configurations under uniaxial loading.

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# #275 The interaction of hydrogen with retained austenite in quenching and partitioning (Q&P) and transformation induced plasticity (TRIP) steels

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*Retained austenite* *Hydrogen trapping* *Hydrogen embrittlement*

**Abstract** This work characterizes the role of retained austenite on the hydrogen embrittlement (HE) in quenching and partitioning (Q&P) steel. The specific heat treatment to produce a Q&P steel results in a two-phase microstructure consisting of a martensitic matrix with metastable retained austenite islands . Upon mechanical deformation, retained austenite shows a behaviour similar to transformation induced plasticity (TRIP) steel, resulting in an increased ductility. Moreover, austenite is assumed to protect the steel against HE due to its higher solubility and lower diffusivity compared to martensite. However, this ignores the phase transformation of austenite, causing highly stressed fresh martensite. After transformation of the hydrogen-containing austenite, this fresh martensite is supersaturated with hydrogen, and hence extremely brittle, serving as a possible initiation site for fracture. The objectives of this study are threefold. At first, the trapping ability of retained austenite is verified, by a combined approach using thermal desorption spectroscopy (TDS) and hydrogen permeation technique. Secondly, the effect of retained austenite, and its strain-induced transformation to martensite, on the mechanical properties is evaluated. Finally, the results on Q&P steel are compared with the findings on TRIP steel. TDS analysis shows that retained austenite is not able to trap hydrogen. However, electrochemical permeation testing under in-situ applied mechanical load shows that the hydrogen diffusion is decreased, even at the lower elastic stresses. This is in contradiction with earlier work on, e.g., a dual phase steel (ferritic-martensitic microstructure, without the presence of retained austenite). Therefore, the trapping ability of retained austenite is further elaborated by performing subsequent TDS tests on the mechanically loaded permeation samples. This reveals that trapping of hydrogen does occur at retained austenite when the samples are experiencing the external applied load, indicated by a higher temperature TDS peak. Differential calorimetry spectroscopy and high temperature XRD confirm the relation between the TDS peak and the decomposition of retained austenite. Furthermore, insitu slow strain rate tensile tests present a significant loss of ductility. Complementary postmortem XRD shows that fracture already occurs after low amounts of austenite have transformed upon deformation. This can be related to the high internal stress of the fresh martensite resulting from the strain-induced transformation of retained austenite. Since fracture is initiated before all retained austenite transforms, austenite cannot enhance the plasticity as it should do, turning this material to be prone to HE. A comparison with a TRIP steel is again performed to generalize these findings for retained austenite embedded in a ferritic matrix.

# #276 Exploring new concepts to design "damage tolerant" ceramics using additive manufacturing

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*Damage tolerance ceramics* *Textured architectures* *3D printing*

**Abstract** The combination of ceramics with other materials has enabled the fabrication of hybrid systems with exceptional structural and functional properties. However, a critical issue affecting the functionality and reliability of these systems is the initiation and uncontrolled propagation of cracks in the brittle ceramic parts. Bio-inspired design concepts in current ceramics engineering have proved successful in obtaining highly reliable ceramic materials with enhanced fracture resistance. For instance, tuning the location of "protective" layers within a ceramic multilayer architecture can significantly increase its fracture resistance, while retaining high strength. The use of tailored residual stresses in embedded layers can act as an effective barrier to the propagation of cracks from surface flaws, providing "damage tolerance". Moreover, by orienting (texturing) the grain structure, similar to the organized microstructure found in natural systems such as nacre, crack propagation can be controlled within the textured ceramic layers.

In this contribution, the potential of employing lithography-based ceramic manufacturing (LCM) process to design multi-phase layered architectures is presented, which can contribute to the fabrication of future 3D ceramic components with enhanced damage tolerance. Two examples are presented: (i) A multi-material approach to combine alumina-zirconia layers sandwiched between pure alumina layers, yielding a characteristic strength higher than 1 GPa on the multi-material system, compared to ~650 MPa in monolithic alumina. (ii) 3D-printed highly textured alumina fabricated combining the LCM technology and Templated Grain Growth (TGG) during sintering to provide higher toughness while retaining strength.

These studies open new possibilities in the fabrication of complex 3D ceramic-based multi-material geometries with tailored microstructures, which could be a new pathway for designing complex parts with outstanding mechanical strength and reliability.

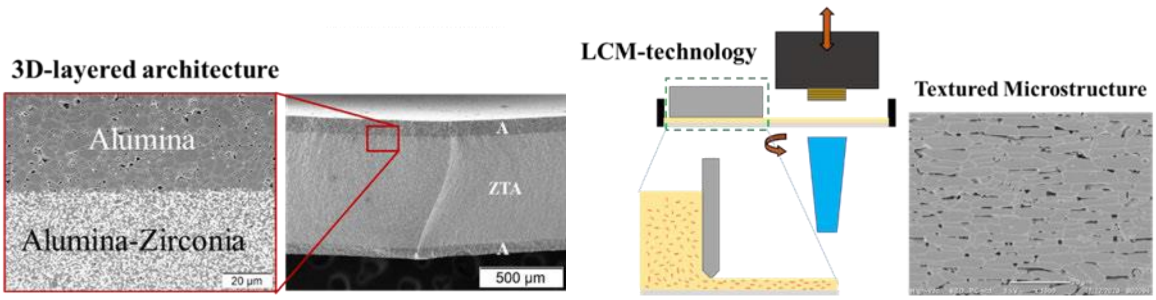


***Figure 1** – Schematic of 3D printed architectures using a multi-material approach and tailored microstructures.*

# #277 New resonance horn and specimen designs for mixed mode ultrasonic fatigue test

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*Ultrasonic fatigue* *Very high cycle fatigue* *Mixed mode stress condition*

**Abstract** The needs for evaluating very high cycle fatigue (VHCF) properties of engineering materials are constantly rising. To conduct fatigue tests in high frequencies, ultrasonic fatigue test machines have been developed. It is very convenient to obtain VHCF properties using ultrasonic vibration, but the system should be carefully designed to resonant in desired mode. Analytic solutions for axial resonance of hourglass shape specimens have been established but bending nor torsional stress conditions are not considered enough. In this study, new resonance horn and specimens are proposed to produce mixed mode stress conditions. Using finite element method (FEM), modal analyses were conducted to obtain natural frequencies and mode shapes, and the frequency response function of the designed ultrasonic fatigue test systems were obtained. The FEM results show that the new horn and specimen designs produce both axial and torsional stresses under 20 kHz frequency. The designed horn and specimens were prepared, and the ultrasonic fatigue tests were conducted. The displacement and strain occurred at the horn and specimens were measured to observe the actual loading condition. The experiment results show that the specimens under mixed mode condition exhibit lower fatigue strength than the axial loading condition. The variation of fatigue properties under various stress conditions will be modeled in this study.

# #279 The effect of material orientation on void growth

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*Anisotropy* *Void growth* *Unit-cell calculations*

**Abstract** In this work, we have performed finite element calculations to identify the effect of material orientation on void growth. For that task, we have used a cubic unit-cell model with a spherical void at its center and subjected to periodic boundary conditions. The behavior of the matrix material is defined with an elastic isotropic, plastic orthotropic constitutive model with yielding described by Yld2004-18p criterion (Barlat et al., 2005). The multi-point constraint subroutine has been used to enforce constant values of macroscopic stress triaxiality and Lode parameter in calculations that have been conducted for different stress states resulting from the combination of $T=0.33$, $1$ and $2$ with $L=-1$, $0$ and $1$ (axisymmetric tension, generalized shear and axisymmetric compression, respectively). Firstly, we have considered the loading directions are parallel to the orthotropy axes of the material, so that the principal directions of macroscopic stress and strain coincide. The finite element results of the cases for which the minor loading axis of the unit-cell corresponds either with the rolling, the transverse or the normal direction, has demonstrated that the initially spherical void turns into an ellipsoid whose growth rate and eccentricity depend on both stress state and material orientation. A key outcome is that for specific material orientations the anisotropy switches the effect of Lode parameter on void growth, reversing the trends obtained for isotropic von Mises materials. Secondly, we have performed calculations with a novel strategy considering angular misalignments within the range $0^{\circ} \leq \alpha \leq 90^{\circ}$, so that one loading direction is parallel to one of the symmetry axes of the material, and $\alpha$ is the angle formed between the other two loading directions and the second and third orthotropy axes. Indeed, to the authors' knowledge, these are the first unit-cell calculations ever reported in which a macroscopic anisotropic yield function with prescribed misalignment between loading and material axes and, simultaneously, the macroscopic stress triaxiality and the Lode parameter are controlled to be constant during loading, models the material. The finite element calculations bring out that the misalignment between loading and material axes forces the void and the faces of the unit-cell to rotate and twist during loading. Furthermore, the main contribution of this work is the identification of an intermediate value of the angle for which the void growth rate reaches an extreme value (minimum or maximum), so that the finite element results show that material orientation and angular misalignment can be strategically exploited to control void growth, and thus promote or delay localization and fracture of anisotropic metal products. We have shown that the conclusions of this research is valid for three different materials (aluminum alloys 2090-T3, 6111-T4 and 6013) and selected comparisons have also been conducted using two additional yield criteria (CPB06ex2 and Yld2011-27p).

**Acknowledgement**
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# #283 Wear and corrosion behavior of 18Ni-300 maraging steel produced by laser-based powder bed fusion and conventional route

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Maraging steel Wear Corrosion

**Abstract** Maraging steels, such as 18Ni-300 (1.2709), are characterized by high yield and tensile strength together with good ductility making them interesting materials for aerospace, automotive and tooling sectors, as well as for bearing gears parts. The low carbon martensite matrix combined with the nanosized intermetallic precipitates are responsible for the peculiar mechanical properties. These steels are also easily weldable thanks to their very low carbon content, and therefore are suitable for additive manufacturing (AM) techniques, such as laserbased powder bed fusion (LPBF). Indeed, this technique was recently adopted in tooling and molding industry to produce inserts with conformal cooling channels capable to improve inserts and cores lifetime, enhancing productivity. Considering that these types of components usually undergo severe stress conditions, wear phenomena and even corrosive environments, the aim of this work was to compare the tribological and corrosion properties of 1.2709 maraging steel samples produced by both forging and LPBF technique. Forged samples were investigated after solution annealing and aging treatment, while AM samples were directly aged from the as-built condition. In particular, the aging parameters were adapted to achieve the same hardness values for both conditions. Microstructural analyses and hardness measurements were carried out on aged samples. The samples sliding wear behavior was investigated by means of pin-on-disc tests, using a 100Cr6 steel ball as counterpart (ASTM G99) at three different sliding velocities. Polarization corrosion tests (ASTM G5) were carried out on samples immersed in a 3.5 wt % NaCl solution at room temperature. The corrosion damage and the wear mechanisms were investigated by means of scanning electron microscope (SEM) equipped with an Energy Dispersive Spectroscopy (EDS) microprobe. For the considered conditions, the AM samples showed excellent wear and corrosion resistance, comparable to the that of forged ones, demonstrating the reliability of AM maraging steel for applications where such kind of properties are mandatory.

# #284 Hydrogen embrittlement behaviors in TRIP-aided bainitic ferrite steel with different deformation temperatures

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*Hydrogen embrittlement* *TRIP-aided steel* *Deformation temperature*

**Abstract** Transformation-induced plasticity (TRIP)-aided steels have been attracted to significant attention because of excellent balance of mechanical properties and cost performance. However, one of the problems is the occurrence of hydrogen embrittlement [1]. In addition, TRIP-aided steels used as automobile structural parts were inevitably exposed to different temperatures and hydrogen environments during production and service [1]. Hence, it is important to understand the effects of deformation temperature and hydrogen on the transformation behavior of retained austenite (RA) and mechanical properties in TRIP-aided steels.

The cold-rolled steel sheet with a chemical composition of 0.4C-1.5Si-1.5Mn (mass%) was austenitized at 900 ℃ for 1200 s, followed by austempering at 400 ℃ for 1000 s, and then quenched in oil to room temperature [2]. Electrochemical hydrogen charging to the tensile specimens was performed in a 3 wt.% NaCl aqueous solution containing 3 g $L^{-1}$ NH4SCN at a constant current density of 10 A $m^{-2}$ for 48 h. The tensile tests were performed on a tensile machine equipped with a thermostatic chamber at an initial strain rate of $1\times10^{-4}$ $s^{-1}$ at deformation temperatures of -100, -30, 21, and 100 °C. The hydrogen desorption behavior was analyzed using thermal desorption spectroscopy. The fracture surface and microstructure were characterized using scanning electron microscope, and electron backscatter diffraction, respectively. The volume fractions of RA before and after tensile test were measured using X-ray diffractometry [2].

The initial microstructure consisted of bainitic ferrite and RA. The deformation temperature dependence of ultimate tensile strength with and without hydrogen charging exhibited similar variations. Hydrogen charging slightly increased the yield strength and deteriorated the uniform elongation at all the temperature ranges. The hydrogen content of specimens after tensile test was approximately 1.5 mass ppm. The volume fraction of RA after tensile test decreased with a decrease in the testing temperature. In the hydrogen-uncharged specimens, with an increase in the deformation temperature from -100 to 100 ℃, fractographic features changed from the quasi-cleavage and quasi-cleavage/ductile mixed modes to ductile mode. When hydrogen was introduced to the tensile specimens, quasi-cleavage features were observed for specimens fractured at -100 and -30 ℃. Hydrogen-charged specimens deformed at 21 and 100 ℃ exhibited mixed quasi-cleavage/ductile fracture features. It was concluded that the hydrogen embrittlement behaviors was attributed to the transformation behaviors of retained austenite owing to the synergistic effects of deformation temperatures and hydrogen absorption.

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# #285 Influence of twin wire arc spraying and machine hammer peening on the corrosion fatigue of ZnAl4 coatings on S355 J2C + C substrate

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*Corrosion fatigue* *Corrosion protection* *Machine hammer peening*

**Abstract** ZnAl-based coatings are used as corrosion protection for offshore application, e.g., offshore wind turbines. These applications are subjected to superimposed mechanical and corrosive stresses, e.g., wind, tide, seawater and mist.

Thermally sprayed coatings processed by twin wire arc spray process and the mechanical post-treatment machine hammer peening (MHP) process were investigated. The coating consisting of ZnAl4 was deposited on a S355 J2C + C substrate. In addition to two conditions produced with different process parameters during MHP post-treatment, uncoated and as-sprayed conditions were evaluated as reference. The aim was to determine the effect of the coating and its properties, such as hardness, porosity and roughness, on the corrosion and corrosion fatigue behavior. In this study, potentiodynamic polarization tests and instrumented corrosion fatigue tests using a self-designed corrosion cell were performed in 3.5 % NaCl solution. Mechanical and electrochemical measurement techniques in combination with fractographic and microstructural examinations were used to characterize corrosion fatigue damage mechanisms.

MHP resulted in a uniform coating thickness with lower roughness and porosity in comparison to the as-sprayed coatings, which were further reduced by adjusting the process parameters of MHP. The electrochemical potential of the ZnAl coating provides passive corrosion protection for the substrate. The coating system improved corrosion fatigue resistance at high cycle fatigue regime. While as-sprayed and MHP post-treated specimens run-out at 280 MPa, uncoated specimens failed at 260 MPa. The open circuit potential (OCP) curves plotted during the corrosion fatigue tests can be correlated with the damage mechanisms. Crack initiation and propagation in the coating and crack propagation in the substrate can be identified from the OCP curves.

# #286 Mode I/II Fracturing of Adhesively Bonded Joints: A modified short bend beam specimen

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**Abstract** Adhesively bonded joints (ABJs) offer a number of benefits, including more uniform stress distribution along the bonded region, good damping characteristics, the ability to bond dissimilar materials with differing coefficients of thermal expansion, and the ability to efficiently bond thin substrates [1]. As a result, they're widely used in a variety of industries, including aerospace, automotive, and civil engineering. Cracks can occur at the bonding region under applied loads due to factors such as poor surface cleaning, the existence of voids in the adhesive, and others. In the cracked adhesive parts, various types of loading cause in-plane and out-of-plane fracture modes. Therefore, measuring the fracture characteristics of the cracked part subjected to in-plane and out-of-plane fracture modes is necessary to assure the structure's safe performance. Some specimens, including the Double Cantilever Beam (DCB) [2], End-Notched Flexure (ENF) [3], Mixed-Mode Bending (MMB) [4], and others, have been recommended in the literature for evaluating the in-plane fracture characterization of ABJs. However, these specimens have some drawbacks, including the difficulty to introduce the full range of mode mixities, the need for complex testing jigs and fixtures, high testing costs, and non-linearities owing to large deformation.

As a result, the current study presents a new, simple, and efficient specimen to solve the challenges and concerns associated with traditional specimens. The fracture parameters of the common specimen were calculated using the ABAQUS commercial code for a range of geometrical and loading parameters. The results showed that the suggested test specimen may be utilized to introduce entire mode mixities for ABJs, ranging from pure mode I to pure mode II. As a consequence, the suggested test specimen can be considered as a possible candidate specimen for full range in-plane fracture studies of ABJs.

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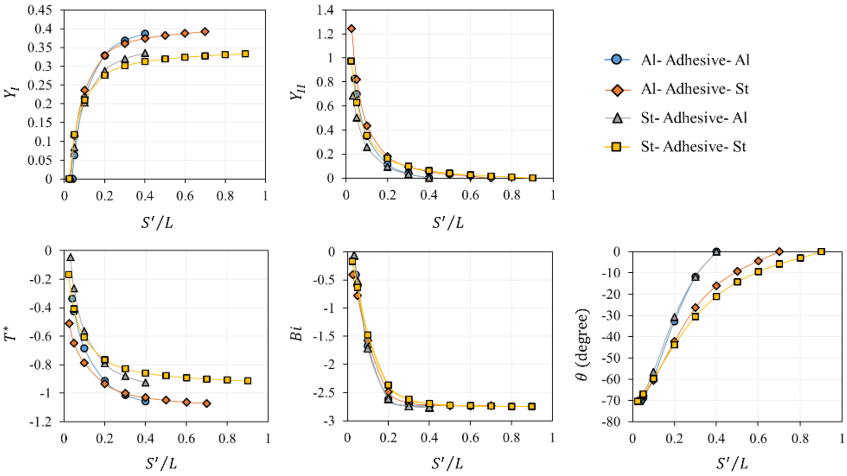

# #287 Data-driven governed material models for complex loading paths

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*Machine Learning* *Material Modelling* *Combined Loading*

**Abstract** In this study, we propose a data-driven approach to characterize the mechanical behaviour of engineering materials. Machine learning approaches are applied to capture the mechanical behaviour and predict the response of material and structures subjected to complex random loading paths. Complex loading simulations are performed under tension-torsion-compression random combined loading. The main objective of this study is to translate the obtained machine learning algorithms into suitable user subroutines to be employed in conjunction with commercial computer-aided engineering software and validate their effectiveness against real loading case scenarios. In this way, data-based machine learning-driven models obtained from arbitrary complex mechanical loadings provide a computationally efficient prediction of the deformation and failure of engineering components during real loading case scenarios.

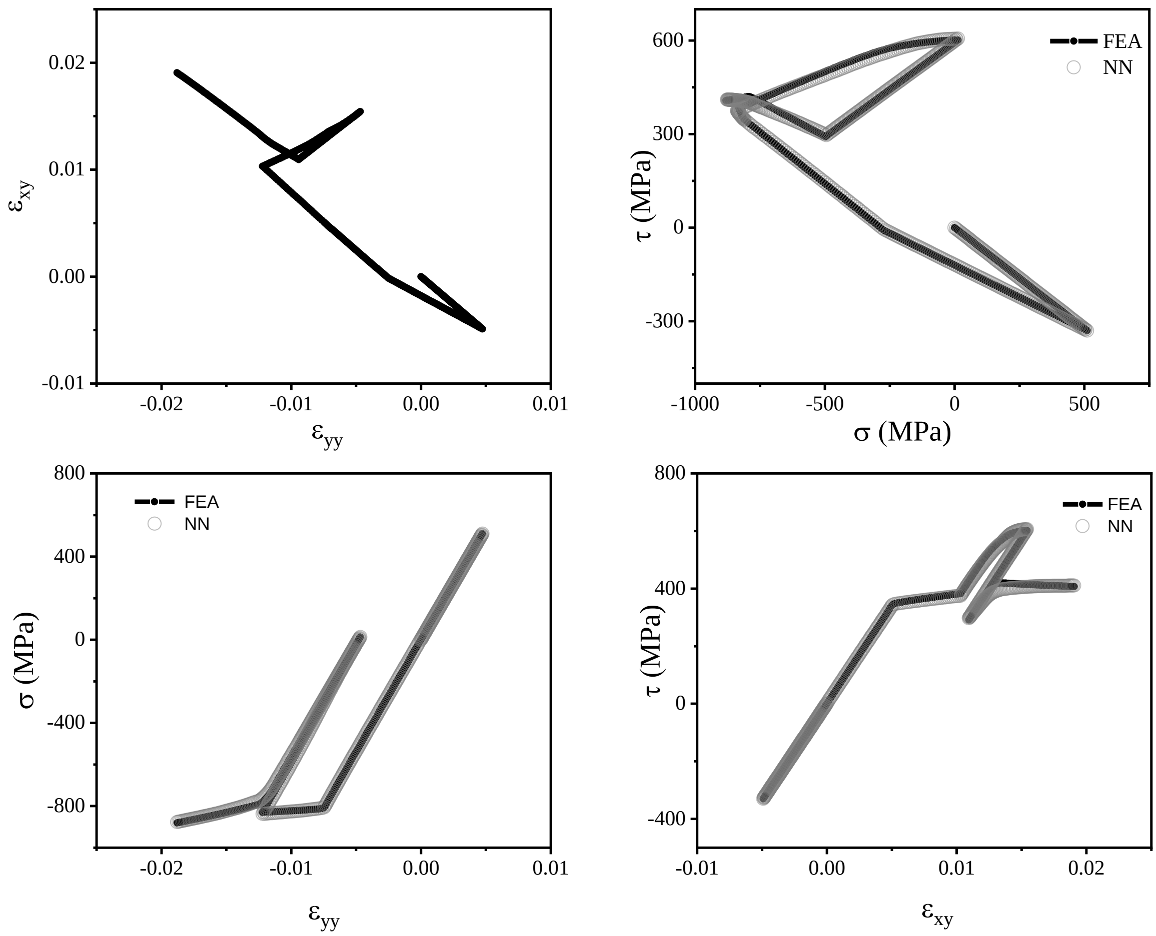


***Figure 1*** *– Stress-strain behaviour of the material during combined complex loading and corresponding neural network predictions*

# #288 Prediction of multiple debonds by an Abaqus implementation of the coupled criterion of FFM and LEBIM

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Finite Fracture Mechanics LEBIM total energy minimization

**Abstract** Interfaces and adhesive bonds are present at macro, meso and micro scales in composite structures. Thus, it is important to have a versatile computational tool able to study their mechanical behavior especially their failure mechanisms.

Crack onset and propagation in adhesive bonds and weak interfaces in composite materials can be modeled by means of a continuous distribution of linear elastic springs whose breakage is governed by a fracture criterion. This approach, usually referred to as Lineal Elastic-perfectly Brittle Interface Model (LEBIM), has some limitations regarding the spring stiffness. The Coupled Criterion of Finite Fracture Mechanics (CCFFM) applied to LEBIM allows an adecuate characterization of stiff interfaces. In previous investigations, this approach was successfully implemented in a BEM code by using the functions given by the stress and energy criteria. However, this procedure can only model crack growth in simple configurations.

In the present investigation, a quite general formulation of the CCFFM + LEBIM based on the Principle of Minimum Total Energy subjected to a Stress Condition (PMTE-SC) is developed. This formulation is implemented in a computational procedure in Python using the commercial FEM code Abaqus®, which solves the total energy minimization problems separately in terms of displacements and an interface-damage variable in each load step.

This novel and quite general computational procedure for predicting onset and propagation of interface-cracks (debonds) is implemented in 2D and is applied to several fracture problems at different scales.

# #289 High temperature mechanical properties of AlMgScZr alloy produced by Laser Powder Bed Fusion

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*Scalmalloy®* *High temperature behavior* *Additive manufacturing*

**Abstract** The present work is focused on the fracture behavior of an AlMgScZr alloy manufactured by laser powder bed fusion (L-PBF) process. This material, commercially known as Scalmalloy®, has gained increasing attention for applications requiring high performances due to its outstanding properties and excellent high temperature behavior. The responsible for the high specific properties of the alloy is its microstructure, characterized by fine grains and the presence of $Al_3(Sc,Zr)$ precipitates. These form during the solidification process and act as nucleation sites for grain refinement. They were also found to commonly exhibit relevant thermal stability.

An increase in strength is achieved from the further formation of smaller $Al_3(Sc,Zr)$ precipitates, characterized by nano-sized dimensions, during the annealing treatment at 325 °C, which is a typical post treatment for this alloy. After the heat treatment, the presence of these precipitates also inside the Al-matrix and the fine-grained structure determine low anisotropic behavior of AlMgScZr alloy. On the contrary, most other additive manufactured alloys are commonly characterized by anisotropy, which represents a strong limitation.

The fracture mechanism of AlMgScZr alloy has rarely been studied so far, especially at high temperature or after high temperature exposure. In the present work, samples were produced by L-PBF process and were subsequently annealed at 325 °C for 4 h. Tensile tests were then performed at different testing temperatures, i.e. 25 °C, 100 °C, 150 °C. Furthermore, samples were tested both under annealed condition and after soaking at 100 °C, 150 °C, 200 °C for 10 h. Mechanical properties were compared to evaluate the high temperature tensile behavior. The damage mechanisms were analyzed by observation of the fracture surface morphology under scanning electron microscope. Differential scanning calorimetry analyses were also performed, in order to verify the thermal stability of the precipitates. The correlation between these results and the mechanical properties allowed the investigation of fracture behavior evolution with temperature. This provided a comprehensive characterization of AlMgScZr alloy, in order to evaluate new applications for components that can be exposed to high temperature during service.

# #291 Side-groove effect on fracture mechanical fatigue testing of PLA material

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*Side-groove* *Fracture mechanical fatigue* *PLA material*

**Abstract** PLA polymer is nowadays probably the most used thermoplastic material in FDM technology. Besides prototyping purposes FDM materials are also considered for functional application use, due to fast fabrication of components, relatively simple workflow and absence of material waste which this technology offers. For functional purposes except static material properties, data concerning expected lifetime and reliability of AM parts under cyclic loading are also necessary. Due to exceptional structural complexity of FDM parts, sometimes minor modifications in material testing must be used. The subject of this paper is the fracture mechanics-based fatigue testing of CT specimens, namely the focus of this research is the effect of side-grooves, placed on CT specimens, on crack growth kinetics according to Paris' law. The main intention of side-groove promotion is to secure a straight crack propagation path, thus imposing a crack to follow the Mode I condition, predominantly. A set of ''regular'' CT and side-grooved specimens are prepared with full infill density interior, with three different layer heights, i.e., 0.1, 0.2 and 0.3 mm. Regular CT specimen bulk dimensions are 62.5x60x10 mm, and side-grooved CT specimens are similar but thicker, designed to have the same thickness at the position of side-grooves as the regular ones. Testing setup with placed CT specimen is shown on Fig. 1. Also, two cameras are used during the testing, one placed at each side of the specimen, to monitor the crack propagation. After the conducted tests, fracture surfaces on CT specimens are examined by means of optical microscopy.

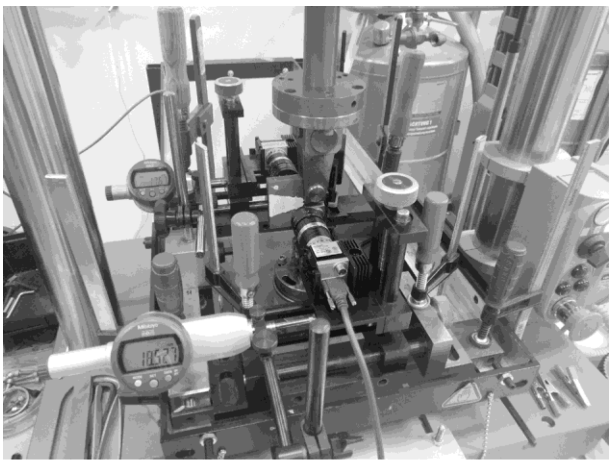

***Figure 1** – Fracture mechanical fatigue testing setup for PLA CT specimen*

# #292 Notch Orientation and Fatigue Strength of As-built L-PBF AlSi10Mg

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*Fatigue notch sensitivity* *Surface quality* *L-PBF AlSi10Mg*

**Abstract** Currently one of the most investigated Al-alloy for AM applications in the aerospace and automotive sectors is AlSi10Mg. It is characterized by good mechanical properties and low density and it is readily processed by commercial powder-bed-fusion (PBF) systems. However, the final surface quality of AM components affects the fatigue strength which critical for load-bearing applications. Geometric complexity associated to notches and unacceptable costs may prevent surface finishing after fabrication. Therefore, the effective fatigue strength in the presence of as-built notches is key for the structural integrity assessment. This study focuses on an experimental investigation of fatigue behavior of L-PBF AlSi10Mg in the presence of geometrical notches with as-built surfaces. An SLM 280$^{HL}$ system (SLM Solutions GmbH, Germany) operated by an established service company (Beam-It, Fornovo Taro, Italy) working with a layer thickness of 50 μm was used for fatigue specimen production. A miniature specimen geometry containing a mild notch with a theoretical stress concentration factor $K_t$ = 1.58 was adopted. Four sets of specimens oriented in four different directions with respect to the build direction were produced and tested in fatigue using a plane bending machine under a load ratio R = 0 with run-out fixed at 2 x $10^6$ cycles.

The notch influence on the fatigue life for the four different notch orientations was experimentally determined in dependence on the as-built surface quality. The significant directionality of the notch fatigue response is demonstrated in Fig. 1, where the data (maximum nominal stress amplitude $S_{max}$ vs. number of cycles to failure, $N_f$) are plotted.

The obtained fatigue test data are interpreted by investigating the actual quality of the as-built surfaces using metallography, image analysis and SEM. The surface characteristics and directional fatigue data are correlated to reach an interpretative framework of the notch fatigue behavior of L-PBF AlSi10Mg in the as-built state.

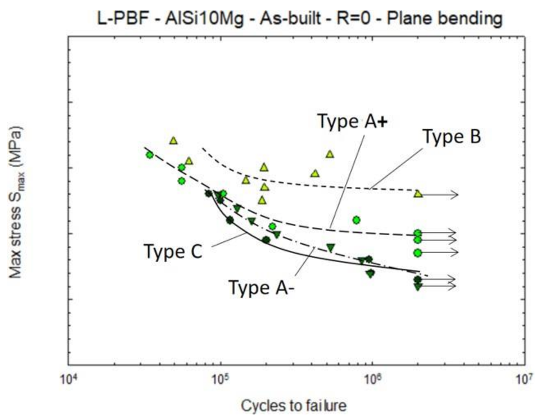


***Figure 1*** – Notch fatigue behavior for $K_t$ = 1.58

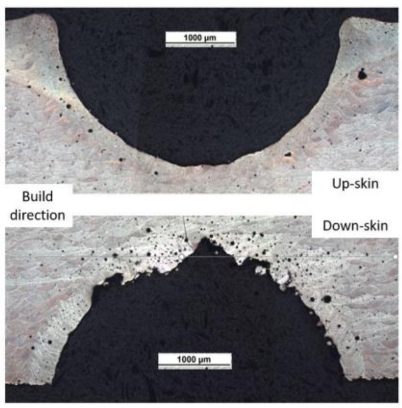


***Figure 2***– Up-skin vs down-skin notch surface quality

# #293 The effect of creep pre-deformation on LCF damage accumulation – model and experimental verification

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*damage accumulation* *low-cycle fatigue* *aluminum alloy*

**Abstract** The paper presents the results of creep rupture, preliminary creep and low- cycle fatigue tests performed on EN-AW 2024 aluminum alloy. Creep rupture tests performed at temperatures 100°C, 200°C and 300°C made it possible to determine the evolution of the material's microstructure as a result of thermo-mechanical loads. The results of creep rupture tests allowed to formulate a model describing damage accumulation in this process [1]. The increase of the material's damage state variable was made dependent on the value of nominal axial stress and growth of axial plastic strain. Values of the model's material parameters were determined, along with the material's damage state resulting from pre-deformation at elevated temperature. Low-cycle fatigue tests [2] made it possible to determine the influence of creep pre-deformation on the fatigue life of the studied alloy. This life is subject to significant improvement due to preliminary creep, but only in the area where ductile strains are dominant. In the case of lower permanent strains, fatigue life is reduced with respect to that of the initial material. In addition, a fatigue damage accumulation model was presented in a form analogous to that of the model proposed for the creep process. In this model, it was assumed that, in every cycle, the increase of the damage state variable is constant. It was accepted that there is no growth of damage in the compressive part of the cycle. This model was adapted for determination of damage accumulation in material with pre-deformation. In such cases, total failure was considered as the sum of damage resulting from preliminary creep and damage accumulated as a result of cyclic loads. At the same time, the need to determine constants present in the model independently for material with differing pre-deformation history was noted.

[1] ReferencesTomczyk A, Seweryn A. Experimental investigation and modeling of damage accumulation of EN-AW 2024 aluminum alloy under creep condition at elevated temperature. *Materials* 2021;14:404.
[2] Tomczyk A, Seweryn A. Fatigue life of EN AW-2024 alloy accounting for creep pre-deformation at elevated temperature. *Int. J. Fatigue*, 2017;103:488–507.

**Acknowledgements:** This research was funded the Ministry of Science and Higher Education of Poland within the framework of research project No 2018/29/B/ST8/00697 (National Science Centre of Poland) and realized in Bialystok University of Technology.

# #294 Topological differences in delamination strength of the human aortic wall

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*Delamination Strength* *Aortic dissection* *Topological differences*

**Abstract** Dissection of the aortic wall is a serious condition, which, even though it is rare, can prove to be quickly fatal to a high number of patients. The underlying biomechanical factors are not yet fully described. The biomechanical response of the human aorta to delamination varies with axial location, showing fluctuations in mechanical stress. The current study presents experimental data, that depict these differences. The role of age and gender is also studied.

In the experimental protocol, sixteen (16) human aortic subjects were used. Each subject considered was divided into nine (9) topological regions and four (4) quadrants. From each region four (4) rectangular strips were cut, two (2) from the right lateral quadrant and two (2) from the left lateral quadrant, each following one of two directions in each quadrant, axial and circumferential. Pictures of the subjects were taken before the strips were cut. Then, a peeling test was conducted with each strip, using a tensile testing device. The subjects were divided into three (3) age groups (young, middle aged, old) and the two genders.

The experimental data indicated lower stress for the old group, higher for the young and somewhere in between for the middle aged. Also, higher stress was found in male subjects. For each subject much lower stress was found in the thoracic aorta, comparing to all other regions. Also, the axial direction showed greater resistance to delamination.

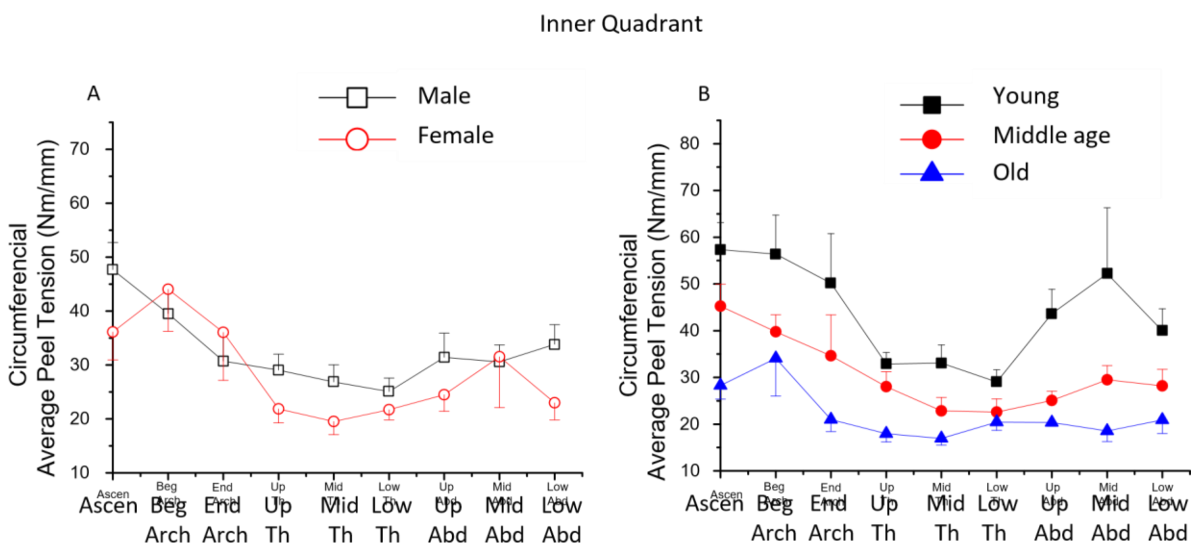


***Figure 1** –Axial variation of the Average Peel Tension along the aortic wall for the left lateral quadrant following the circumferential direction. Subjects grouped by gender (A) and age (B).*

# #295 Mechanical response of connections in stone monuments when various shapes of metallic connectors are used

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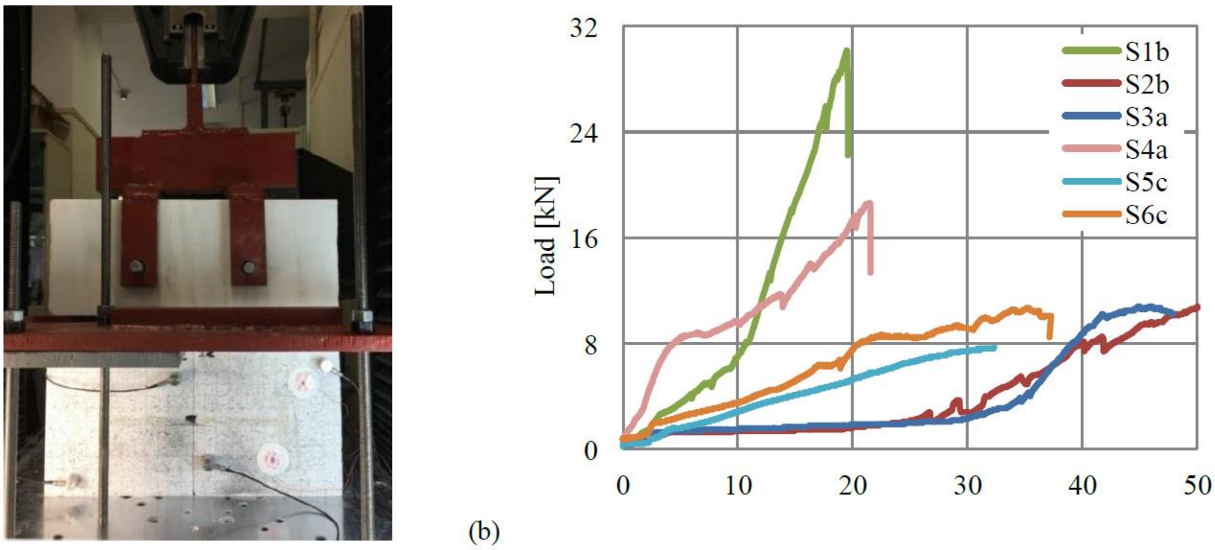
*Stone monuments* *Marble* *Metallic connectors*

**Abstract** The majority of ancient dry-stone monuments are quite often partly destroyed. While restoring such monuments, one of the main problems that must be faced by the scientists and the personnel is the restoration of the connections of their structural elements, taking into account that the safety of these monuments is mainly based on the integrity of their connections. In this context, a series of shear experiments were carried out aiming to study the mechanical response of six different shapes of connections/connectors, i.e., the typical I-shaped, an Ishaped with four rods, an I-shaped with two rods and three types of Π-shaped connectors. The specimens were made of two Dionysos marble blocks. A groove is sculptured on the two blocks, in which the connector is placed and it is then filled with cement paste/mortar.

The experiments were realized using an Instron servo-hydraulic loading frame (of capacity 250 kN) under displacement control mode at a rate equal to 0.8 mm/min. The experimental setup is shown in Fig.1a. The experiments were terminated either when the marble was fractured or when the applied displacement exceeded 40 mm, taking into account that larger relative displacement values have not been met until today in the monuments of the Athenian Acropolis.

Typical load-displacement plots, one for each class of specimens, are presented in Fig.1b. It is clearly seen that classes S1 and S4 are the most “brittle” connections (the specimens failed with the fracture of the marble) contrary to the other classes where the connections failed due to excessive plastic deformation of the connectors. In addition, the specimens of classes S1 and S4, attained the larger load values. The load for the remaining connections did not exceed about half of the previously mentioned values, raising questions about their stiffness and their role in the structural stability of the monuments.

(a)




(b)

Displacement [mm]

***Figure 1** – (a) The experimental set-up. (b) Typical load-displacement curves.*

# #296 XFEM simulation of dislocation in $Si_xGe_{1-x}$ alloy under thermal loads

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*Dislocation* *Semiconductor alloy* *XFEM*

**Abstract** Semiconductors are integral parts of the electronic world, having their application in integrated circuits in the form of diodes and transistors. The size of these devices is at the nanometer scale. The semiconductors are crystalline materials with lattice defects such as dislocations that can result in performance degradation and failure. To restrict the defects in the materials for controlling the properties, the alloying of different semiconductor materials is done. An alloy made of two semiconductor materials from group IV-A of the periodic table is $Si_xGe_{1-x}$ alloy. This alloy is not completely defect-free and possesses some dislocations in it. The dislocations succeeding motion can annihilate and result in cracks; this indicates the necessity to study their behavior. The performance of semiconductors results in higher temperatures due to electric field formation and also they are exposed to elevated atmospheric temperatures. Hence, the problem of an edge dislocation in $Si_xGe_{1-x}$ alloy is considered under thermal loads at different compositions. The numerical modeling of the problem is done using the Extended Finite Element Method (XFEM). An edge dislocation at the center of the semiinfinite $Si_xGe_{1-x}$ domain is considered for which the lattice constant, thermal conductivity, electrical conductivity and thermal expansion coefficient are functions of the amount of Si (x) in the alloy. The Burgers vector of the dislocation is also dependent on the Si concentration as its magnitude is defined in terms of the lattice constant. The size of the domain is around 100 times the size of the lattice constant. The XFEM formulation introduces the Volterra type edge dislocation through the enrichment functions. Firstly, the discrete heat equilibrium equation is solved for obtaining the temperature fields in the problem domain and then considering the thermal strains, the discrete force equilibrium equation is solved. The strains, stresses and heat flux obtained after post-processing, are used to evaluate the Peach-Koehler (P-K) force of the dislocation. The two cases of the heat flux acting normal to the glide plane and along the glide plane of the dislocation are considered for different temperatures, as shown in Fig. 1. The results indicate an increase in the P-K force with the increase in 'x' greater than 0.2 for both the cases of the heat flux application at all temperatures. However, at the lower concentration of Si i.e. below 0.2, the P-K force is affected differently. At a given value of 'x', the applied temperature increases the P-K force for heat flux normal to the glide plane and decreases the P-K force when heat flux is along the glide plane.

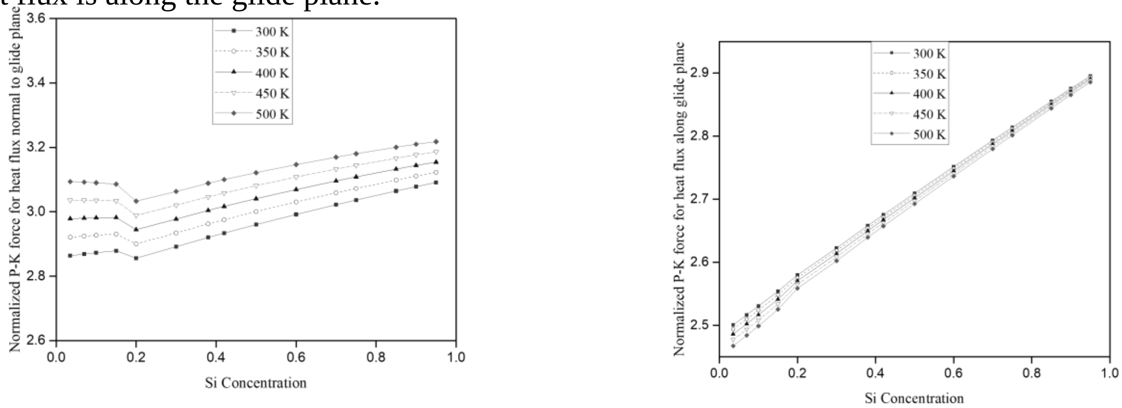


***Figure 1** – The normalized P-K force obtained by dividing the numerical values with the analytical elastic P-K force for* x = 0.5 *is plotted against the Si concentration for heat flux applied normal to the glide plane (left) and heat flux along the glide plane (right).*

# #297 Damage accumulation modeling of structural materials under fatigue loading at elevated temperature

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*low-cycle fatigue* *elevated temperature* *life prediction*

**Abstract** The process of fatigue damage accumulation modeling appears more complicated in the case when construction elements are utilized at elevated temperatures. Mechanical constructions are frequently subject to external loadings connected with the influence of elevated temperatures. Under such work conditions, the mechanical properties of the material undergo changes. Numerous scientists presuppose that the construction material, which has been exposed to elevated temperatures should not be regarded as the same material as it was at room temperature. It should be noted that such material undergoes certain physical–chemical changes, the structure of the material becomes rearranged: its crystal structure changes leaving a constant chemical composition. As a result, this approach can be used known from the literature strength and fatigue models and dependences, taking them material constants determined experimentally for the considered temperature.

The presented test results provide information on the effect of elevated temperature on the mechanical properties and fatigue life of EN AW 2024 T3 aircraft aluminum alloy. They also allowed to predict the fatigue damage accumulation and fracture of this material under fatigue loading at elevated temperature. For this purpose, monotonic and fatigue tests of the analyzed material were performed.

In the first step, the material parameters of the investigated alloy, obtained for different temperature values, such as yield strength $\sigma_{02}$, ultimate tensile strength $\sigma_u$, Young modulus $E$, Poisson ratio $v$, were determined. Therefore, the samples were tested at room temperature and also at elevated temperature (100°C, 200°C, 300°C).

The next step was to perform low-cycle fatigue tests in the range of tensile-compression loads for the adopted temperature values. These were carried out at a constant strain amplitude $\varepsilon_a$ and frequency $f$ of 1 Hz. During the tests, the number of cycles $N_f$, the maximum stress value per load cycle, the hysteresis loops for the first cycles, and for the cycles that illustrate the cyclic strengthening of the material were recorded.

The fatigue breakthroughs of EN AW 2024 T3 aluminum alloy were analyzed in relations of the change in microstructure when tested at elevated temperature. Differences in the formation and development of fatigue micro-damage contributing to failure were observed.

The investigation described in this paper in part of the research Project No. 2018/29/B/ST8/00697 (National Science Centre of Poland) and realized in Bialystok University of Technology.

# #298 Experimental and numerical investigation of the fatigue strength improvement of welded structures submitted to an initial overload.

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*Welded structure* *Fatigue* *Overload*

**Abstract** Welding is an extremely common manufacturing process used for the fabrication of mechanical structures in the automotive, offshore or shipbuilding industries. During their service lives, these structures are generally subject to complex loading conditions, and prior to being put into service, proof tests are often applied, in accordance with the requirements of certain standards. The proof loads can cause local plastic strains at the stress concentrations associated with the weld geometries, which can affect the fatigue resistance of the welded structure. In the literature, different studies have been carried out to investigate the impact of such preloads on the fatigue resistance. For example, Masumoto et al., 1982 experimentally demonstrated a beneficial effect of an initial prestrain on the fatigue resistance of SS41 steel butt-welded joints. The beneficial effect was attributed to an evolution of both the residual stress field and the work hardening.

In this study, the influence of an initial overload on the fatigue resistance of welded longitudinal stiffeners has been experimentally investigated. Numerical simulations have also been conducted in order to evaluate the influence of the principal governing factors. The longitudinal stiffeners are made from 8 mm thick S355 steel plates and are arc welded with the Metal Active Gaz (MAG) process. The structures are preloaded and fatigue tested on a uniaxial testing bench. The influence of both tensile and compressive preloads on the fatigue resistance has been investigated for different loading amplitudes and different loading ratios. In comparison with non-preloaded structures, the results show that a tensile overload higher than 250 MPa improves the fatigue strength while a compressive overload does not alter the fatigue resistance. To better understand the role of residual stresses and work hardening, finite element simulations have been carried out to compute the stress and strain fields resulting from a loading sequence consisting of a preload, followed by cyclic loading. These fields are then used to construct a non-local fatigue criterion that considers the influence of the multiaxial stress state, residual stresses, the stress gradients and work hardening. The comparison between the numerical results and the experimental results indicates that the beneficial impact of a preload is mostly due to the residual stress field generated by the preload. The numerical results also indicate that work hardening contributes to improving the fatigue strength of welded structures.

## References

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# #299 Early Stag Researchers training in the framework of SIRAMM project

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*Early Stage Researchers* *Additive Manufacturing* *Winter School*

**Abstract** The "***Structural Integrity and Reliability of Advanced Materials obtained through additive Manufacturing***" (SIRAMM) project represents a twinning project H2020-WIDESPREAD-2018, Project No. 857124 having five partners: University Politehnica Timisoara (Romania), University of Belgrade (Serbia), Institute of Physics of Materials (Czech Republic), Univerity of Parma (Italy) and Norwegian University of Science and Technology (Norway).

The overall objective of the SIRAMM project is to significantly strengthen research in the field of Additive Manufacturing at the University Politehnica Timisoara (Romania). To achieve this aim, SIRAMM will build upon the existing science and innovation base of UPT, creating a network with two internationally-leading counterparts at EU level: Norwegian University of Science and Technology (Norway) and the University of Parma (Italy). In the long term, the project aims at laying the foundations for creating a pole of excellence on AM in Eastern Europe. For this reason, other two partners from low R&I performing countries, the University of Belgrade (Serbia) and the Institute of Physics of Materials, Academy of Sciences (Czech Republic) will also take part in this Twinning project.

To reach its goals, this 3-year project is focused on the implementation of knowledge transfer activities such as workshops and staff exchange, training events (i.e. summer schools, seminars) for early stage researchers, and dissemination and communication actions (i.e. web site, videos, open access publications, public engagement activities) for different audiences. To keep maintaining the knowledge transfer well beyond the duration

The main activities implemented so far in the project where two Winter Schools (Timisoara 2021, Brno 2022), two Workshops (Timisoara 2021, Brno 2022), the East Europe Conference on AM materials (Belgrade 2021) and seminars for students and for companies. Most of the activities in 2020 and 2021 were organized in hybrid mode (on site and on line).

The staff and PhD mobilities were highly affected by the COVID-19 pandemic, but they started in Summer 2021. As au outcome of the project the Master Course "***Theory and applications of AM materials***" was developed and implemented at the University Politehnica Timisoara and University of Belgrade.

# #301 Numerical and experimental investigation of plasticity induced crack-closure in case of multiaxial fatigue crack growth with constant and component-near loading cases

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*Multiaxial crack-growth* *Simulation of plasticity induced crack-closure* *GPU-DIC Measurements*

**Abstract** Within this study the influence of multiaxial loadings on the fatigue crack-growth behavior is experimentally and numerically examined. The experimental campaign is carried out with cruciform specimen made of the quenched and tempered steel 26NiCrMoV14-5 using a planar biaxial test rig under force-control conditions and sinusoidal loadings with a frequency of 5 Hz. In order to maintain different multiaxial stress states, the T-Stress has been used for characterization and has been varied through different axis-ratios and the initial crack-orientation. Besides HCF-loading scenarios with a constant amplitude, so-called component-near HCF-LCF loading cases were conducted with interspersed super- and sub-load cycles within a fixed ratio. In order to examine the influence of the specimen used, comparative experiments were carried out with Corner-crack specimen.

As a first results of the experimental study, no significant influence of the multiaxial far field loading or T-Stress on the crack-growth behavior nor the resulting plasticity induced crack-closure could be observed. Within a reassessment of the experiments, opportunities on how to improve the Newman model regarding crack-closure could be identified for thin-walled structures. Regarding HCF-LCF loadings, a lasting influence on the crack-closure behavior through super- and sub-level loads could be observed that cannot be adequately described with the model of Newman as well. The results emerge from extensive evaluations of hysteresis data measured with mechanical extensometer and a novel GPU-based Digital Image Correlation system. A deeper analysis about the findings is performed by means of effortful plasticity-induced crack-closure simulations within the FEM-Software Abaqus. The results reveal the potential of such simulations to adequately forecast the resulting crack-closure behavior.

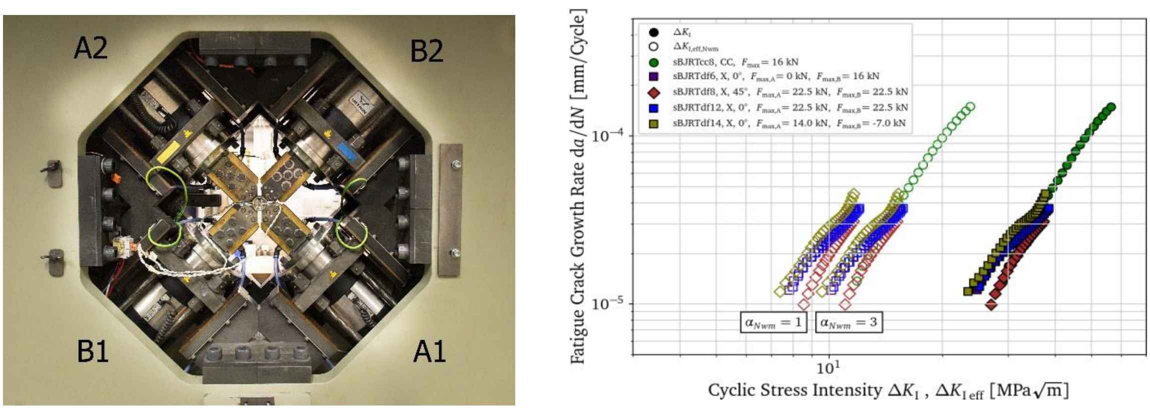


***Figure 1*** *– left: planar biaxial test-rig with a cruciform specimen in the center, right: paris-diagram of experiments using corner-crack and cruciform specimen*

# #302 Numerical Investigation on Impact of Internal Stress Relief Groove on Fatigue Lifetime of Additively Manufactured 316L Stainless Steel

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*Fatigue* *Numerical Modelling* *Additive Manufacturing*

**Abstract** Additive manufacturing is progressively being used for complex structural components, where versatility in design plays a major role. Given the growing popularity of this technique, an increasing amount of research is spent on how the fatigue resistance of additive manufactured parts can be increased. The current study numerically investigates the feasibility of a pre-processing design feature namely, an internal stress relief groove, to improve fatigue lifetime of additively manufactured parts. To do so, first, a numerical sensitivity analysis was performed, using Finite Element Modelling, to monitor the impact of various grooves (with different sizes, shapes and position) on the fatigue resistance of U- and V-notched samples. A multiaxial critical plane fatigue damage parameter was used to estimate the lifetime. According to obtained results, an optimum groove dimension and location could result in a 20% reduction of fatigue damage and a longer life. Furthermore, a practical study was performed on the manufacturability of the calculated optimum internal grooves with suggested dimensions. A demonstrator sample was 3D-printed using Laser Powder Bed Fusion (LPBF) technique. The actual shapes of several grooves were used in the developed model and the obtained results were compared with their respective theoretical shapes in terms of fatigue lifetime, as shown in Figure 1. Based on the observed results, it could be concluded that the internal grooves have a potential to increase the fatigue resistance of additive manufactured parts.

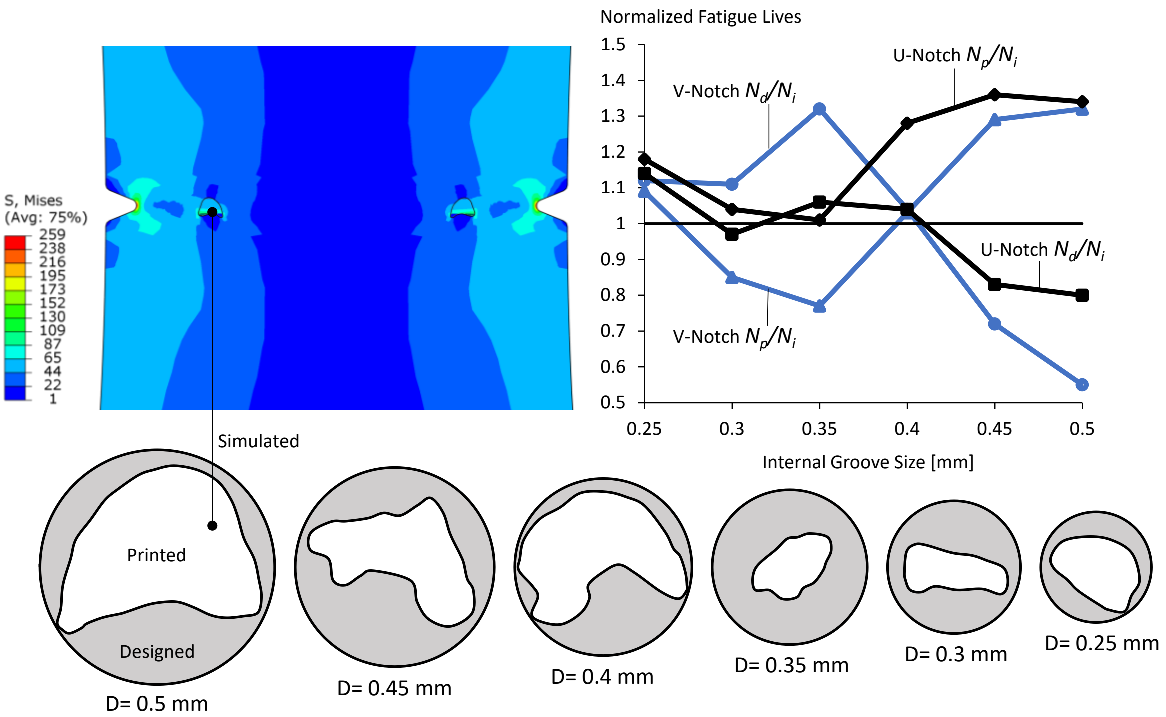


***Figure 1** – Effect of designed (d) and printed (P) internal stress relief groove on fatigue lifetime of V-Notch and U-Notch samples. The lives are normalised using lifetime of initial sample (i) without the groove*

# #303 Finite Element Analysis of Combined Effects of Non-proportional Stressing and Wear Process on Fretting Fatigue Crack Propagation

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*Fretting Wear* *Fretting Fatigue* *Crack Propagation*

**Abstract** Fretting fatigue failures occurs when two parts in contact are subjected to external cyclic loads which lead to a relative micro-slip between these components. This behavior generates a localized high-stress concentration close to the contact surface and accelerates the fatigue crack nucleation process. This research work proposes a new approach covering the main stages involved in the material failure process, i.e. the micro-crack nucleation life considering the fretting wear process and the crack propagation phase until final fracture. For this purpose, the total life is divided into two portions of crack initiation and crack propagation. A combination of a multiaxial fatigue damage parameter (SWT), linear damage accumulation law (Miner's law) and the theory of critical distance (point method, $L_0$) are used to predict the crack initiation life. In parallel, the effect of the fretting wear is considered using Archard's law. The XFEM method is used for predicting the crack propagation path and the crack propagation lifetime. A new method is introduced to predict the crack propagation path under nonproportional loading conditions which is based on calculating the critical plane, based on the SWT damage parameter, at and near the crack tip. Three different values of SWT damage parameters are calculated, i.e. $(SWT_{mean})_{max}$, $SWT_{tip}$, $SWT_{L0}$. The obtained results are compared against the mostly used crack propagation criteria in the literature such as Maximum Tangential Stress (MTS), KII= 0 and Maximum Energy Release Rate (MERR), as shown in Figure 1. Finally, the experimental results are used to validate the estimated numerical simulations. In terms of life assessment and the crack path prediction, the proposed $SWT_{L0}$ criterion has shown a better performance.

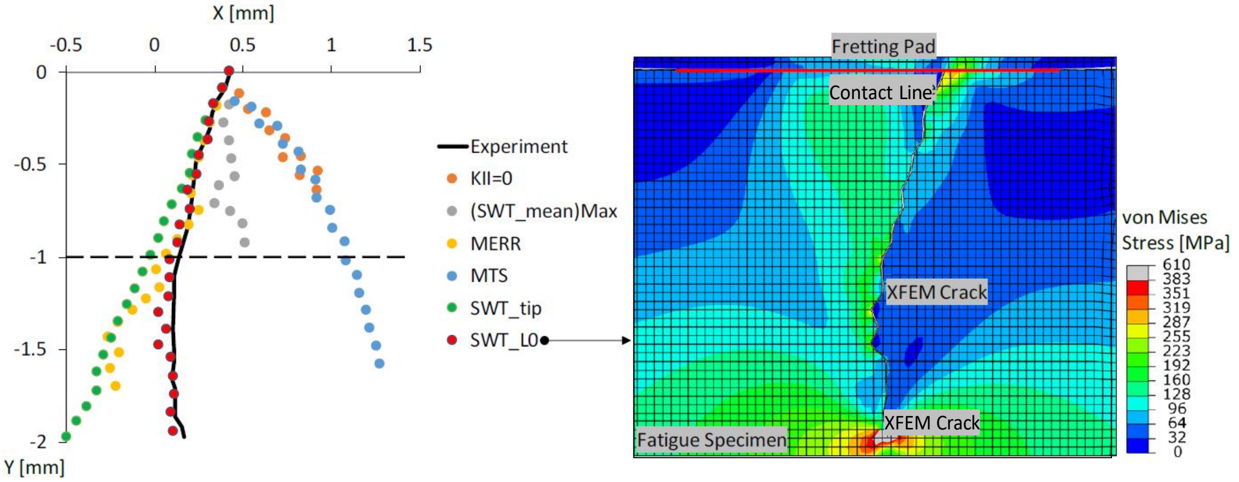


***Figure 1** – Comparing the estimated crack propagation path using different criteria and the experimental observation.*

# #304 The effect of prior austenite grain morphology on hydrogen embrittlement behaviour in as-quenched 500 HBW steels

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*Hydrogen embrittlement* *PAG structure* *Martensitic steel*

**Abstract** The effect of prior austenite grain (PAG) shape and size on hydrogen embrittlement behaviour is investigated with a novel tuning-fork testing method and hydrogen thermal desorption spectroscopy (TDS). Different PAG structures are acquired via reaustenitization (860/960 °C) and rapid quenching of as-received 500 HBW direct-quenched (DQ) steel, which has an auto-tempered lath-martensitic microstructure and elongated/pancaked PAG morphology. Average PAG size of the as-received material is 10 µm. The reaustenitized steels, A860 and A960, have similar hardness and tensile strength but different equiaxed PAG sizes of 10 µm and 40 µm, respectively. These differences allow the comparison of the effects of the shape and size of the PAG structure on hydrogen embrittlement with the same alloy composition.

Constant-displacement tuning-fork tests were conducted with notched specimens locally stressed beyond the yield point. Crack initiation and propagation was monitored via relaxation measured with a load-cell clamping system. Stressed specimens were tested using in-situ charging until failure in a 3% NaCl + 3 g/l $NH_4SCN$ solution at -1.2 $V_{Hg/Hg2SO4}$ electrochemical potential. During hydrogen charging, a crack initiates at the tensile stress concentration site and propagates through the specimen. The obtained time-force data from each test is used to calculate the crack initiation time ($t_i$) and time-to-fracture ($t_f$). The same hydrogen charging conditions were utilised in 2.5 h pre-charging of 10 x 5 x 1 mm TDS specimens, which is considered to provide a homogeneous distribution of hydrogen in the specimens. After electrochemical hydrogen charging, hydrogen contents were measured with TDS.

Both $t_i$ and $t_f$ times are significantly longer for the elongated PAG structure in comparison to the equiaxed PAG structures, which suggest that the elongated PAG structure has a better resistance against hydrogen embrittlement. At the same time, different grain sizes of the equiaxed PAG structures show similar performance with each other, indicating that the PAG size in the range of 10 – 40 µm does not affect hydrogen embrittlement susceptibility. Fractography revealed different crack propagation modes depending on the PAG shape and/or heat treatment. With the elongated PAG structure, the hydrogen-induced crack propagation mode was transgranular quasi-cleavage, and with the equiaxed PAG structures it was partially intergranular. The TDS results show that there are no significant differences between the total hydrogen contents, even though the PAG boundary surface area is 5 – 6 times smaller for A960 steel. This indicates that the PAG boundaries are not the dominant hydrogen traps, and the different crack propagation modes are rather linked to the geometrical shape of the grain structure and grain growth mechanisms

# #305 Prospects of Configurational Forces in 3D Finite Element Crack Growth Analyses

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*Configurational Forces* *Finite Element Method* *Crack Growth*

**Abstract** The evaluation of cracks in three-dimensional (3D) specimens requires an accurate calculation of loading quantities, based on stress and strain in the vicinity of the crack front. One of these loading quantities is the J-integral, which is strongly related to the configurational forces in material space.

In the context of 3D finite element analyses, it is often calculated as an equivalent domain integral, providing both loading quantity and crack propagation direction along the crack front in terms of the J-vector. However, in the presence of mixed-mode-loading or curved crack faces, additional integration over the crack surfaces is required to ensure domain independency, lacking accuracy due to poor representation of the involved singular mechanical fields in the finite element method. In contrast, the computation of configurational forces enables the calculation of a driving force vector by employing stress and strain in the vicinity of the crack front. The calculation of crack surface integrals is thus circumvented, however, the procedure lacks accuracy due to the same reasons as mentioned above, unless appropriate measures are taken. Furthermore, the coordinate $J_2$ is obtained straightforwardly, and a virtual crack extension area does not have to be introduced.

This work focuses on the computation of configurational force vectors in 3D finite element crack analyses. Methods to improve the accuracy of the calculations are developed and implemented into a commercial finite element code. Loading analyses for common crack problems are investigated and compared to analytical results if available. The efficiency of the approach is demonstrated by 3D crack growth simulations.

# #307 Investigation of Failure Criteria for Tungsten Carbide-Cobalt Hard Metals

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*Failure criteria* *WC-Co hard metals* *Metal-ceramic composite materials*

**Abstract** Predicting failure by a single universal failure theory covering all material types and loading conditions has not been demonstrated yet. Therefore, it is very crucial to choose a suitable failure criterion depending on material and application. In this study, various failure criteria were questioned for tungsten carbide cobalt (WC-Co) hard metals, used in cold forging dies. As known for WC-Co hard metals, the ratio of uniaxial tensile and compressive strengths of WC-Co materials is less than unity and the materials behavior under tensile loading is more close to brittle and defect-controlled. Considering the underlined nature of this type of materials, failure criteria such as Von Mises, Tresca, Coulomb-Mohr and Drucker–Prager were investigated to be employed for stress levels obtained by analytical or numerical methods. Von Mises (maximum distortion energy theory) and Tresca (maximum shear stress theory) failure criteria are widely employed particularly for ductile materials. Being independent of hydrostatic stresses, which is proven to be not contributing yielding for ductile materials and easy calculation for known stress state make these methods attractive. On the other hand, Coulomb-Mohr failure criterion accounts for hydrostatic stresses for failure and difference in yield strength of materials under tension and compression. Therefore, this criterion is preferred for brittle materials including rock and granular materials. However, being independent of the intermediate principal stress component and having sharp corners in yield surface are declared as the two disadvantages of this failure criterion. Drucker– Prager is one of the smooth alternatives of Coulomb-Mohr theory. Based on investigations carried out in this study, it was revealed that Coulomb-Mohr and Drucker Prager failure criteria were more realistic compared to Von Mises and Tresca. However, due to nature of WC-Co materials, it is very challenging to obtain tensile properties, affecting the degree of approximation.

# #308 Fracture mechanical investigation of preformed metal sheets using a novel CC-specimen

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*clinching* *fatigue crack growth rate* *metal sheet*

**Abstract** Joining is used in many areas of manufacturing where components are formed from individual parts or sheets into complex structures. A simple and common method used in industry to join dissimilar and coated materials is clinching. This joining process does not require additional joining parts, which save weight to reduce energy requirements and harmful emissions from moving masses. In addition, the joining process is carried out without pre-punching and is therefore time-efficient. Damage caused by the joining process or by operational loading can lead to cracks near the joint, crack propagation due to time-varying loading and subsequently complete failure of the component. To avoid these damage cases, knowledge about the fracture mechanical behavior of the clinched connection is required.

Within the scope of this paper, a novel CC-specimen for fracture mechanical investigation of preformed metal sheets is developed and investigated. The new specimen geometry is taken directly from a clinched joint in order to identify a possible influence of the outer forming area of the clinched joint on the fatigue crack growth rate (figure 1a). The clinched joint is placed at three different positions and is moved from the radius to the center of the C-shape at 3 mm intervals (figure 1b). In order to investigate the crack growth rate of this new specimen, it is necessary to determine the geometry factor function as well as the calibration curve numerically beforehand. Finally, the results of the crack growth rate tests using the CC-specimen with different positions of the clinched joint are compared with the results of the base material.

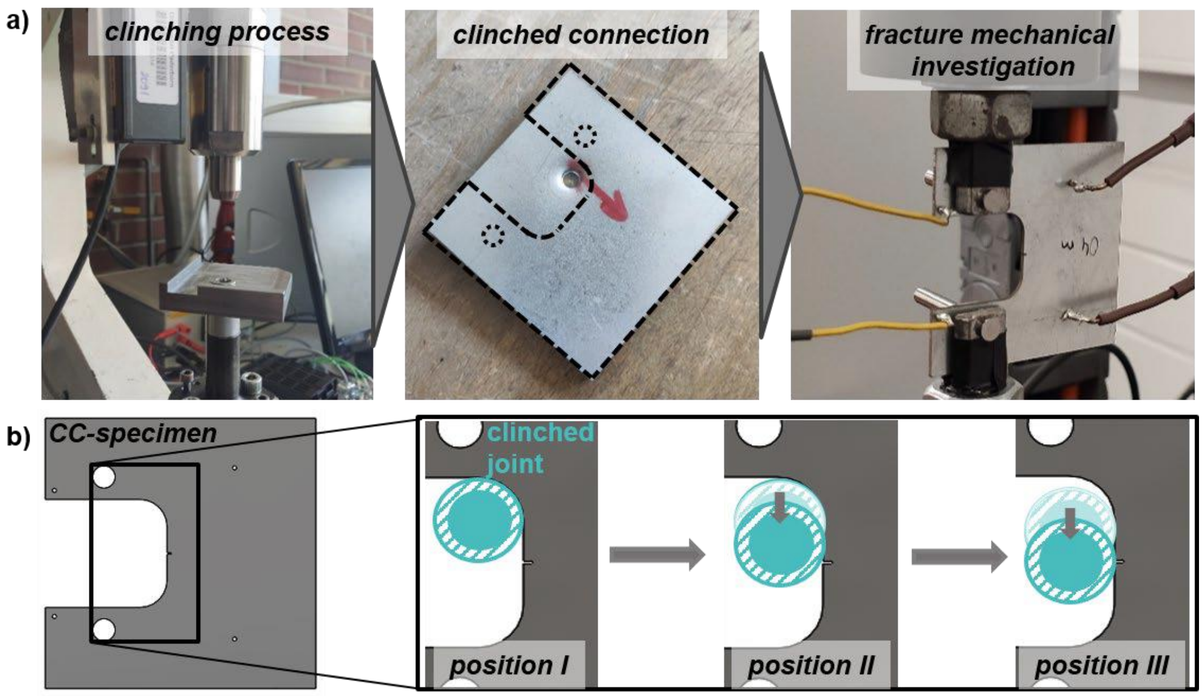


***Figure 1*** *– Illustration of the clinching process, the clinched connection and the fracture mechanical investigation (a), different positions of the clinched joint (b)*

# #309 Impact of heat treatment on the impact toughness and brittle fracture initiation mechanism of a quenched and tempered nuclear Pressure Vessel Steel

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*Low alloy steel* *Fracture Mechanisms* *Microstructure*

**Abstract** In nuclear pressurized water reactors, components, such as pressurizers and steam generators, are made of thick forgings of low alloy steel. The final heat treatment aims at obtaining a bainitic microstructure with as little proeutectoid ferrite content as possible. This ensures a suitable balance between strength and toughness. However, the large thickness of these components (several hundreds of mm) induces a large range of microstructures after quenching, containing different amounts of bainite and ferrite. Even after tempering, this could induce local variations in mechanical properties, especially, in toughness. Although many studies reported about relationships between the microstructure and the fracture properties, there is no systematic investigation in the case of low alloy steels, starting from a unique and homogenous material. The present research aims at filling this gap, focusing on brittle fracture initiation mechanisms. To tackle with this, several microstructures have been created from the same industrial low alloy bainitic steel. Two different cooling rates have been studied: 150°C/h to give a mixture of 50% proeutectoid ferrite and 50% bainite and 10000°C/h to give a 100% bainitic microstructure. For both cooling rates, four tempering conditions have been used: 610°C, 640°C and 660°C for 6h and 640°C for 20h. All microstructures have been characterized by optical and scanning electron microscopy. The Charpy ductile-to brittle transitions and tensile properties of these microstructures have then been determined (Fig. 1a,b). A comprehensive fractographic study of the Charpy specimens broken in the transition regime has been conducted (Fig. 1c,d). The results reveal three different types of initiation sites: on large precipitates such as TiN mostly at low energy and on carbide cluster as tempering increases However, in several cases, no visible particle can be detected (in the center of a facet or near a boundary) mostly for high energy at low temper and for low energy at high temper. Proposals on fracture modelling by local approach accounting for these observations are presented.

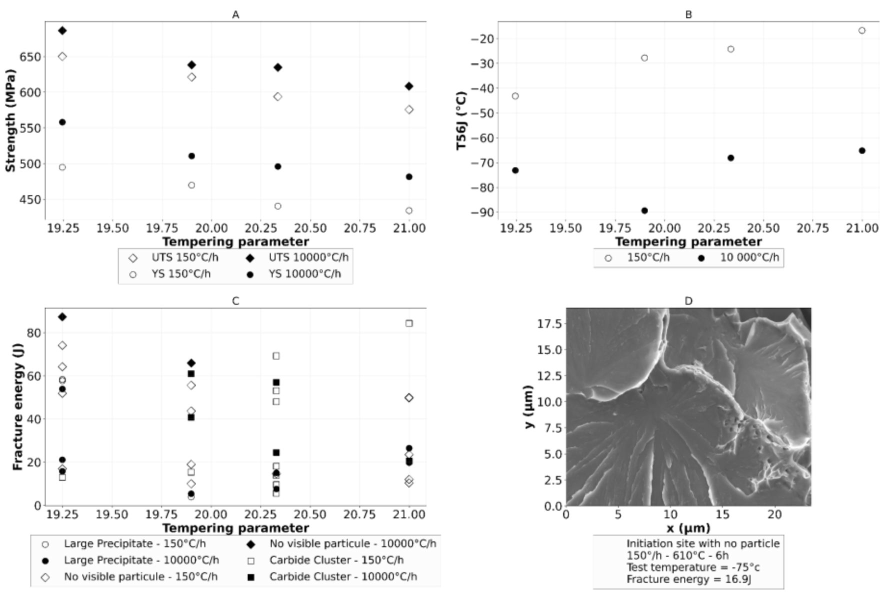


***Figure 12** – a) Ultimate Tensile Strength (UTS) and Yield Strength (YS) at 20°C (b) T56J transition temperature (c) Initiations sites of rupture by cooling rate and tempering parameter. (d) Example of a typical cleavage initiation site with no particle. Tempering parameter* $=\frac{T_{tempering}}{1000}(20+ln(t_{tempering}))$

# #311 Fracture toughness of Zircaloy cladding in case of Delayed Hydride Cracking

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*Fracture toughness* *Hydrogen* *Diffusion and precipitation*

**Abstract** Delayed Hydride Cracking (DHC) is investigated as a potential failure mechanism during dry storage of zirconium alloys fuel cladding. This chemical-mechanical phenomenon is composed of two steps: (i) stress-induced diffusion of hydrogen in solid solution caused by a pre-existing crack, so that hydrogen concentration increases until it reaches the Terminal Solid Solubility in Precipitation (TSSP) and precipitates into hydrides; (ii) hydrides growth at the crack tip so that local brittle fracture can occur when a critical hydride size and a critical stress intensity factor $KK_{IIII}$ are reached. The repetition of these two steps leads to a constant rate crack propagation, until the stress intensity factor reaches the material critical value $KK_{IIII}$. Therefore

$KK_{IIII}$ is a criterion to prevent DHC crack growth. This study presents a combined experimental-numerical approach to provide a quantitative cracking model, allowing the evaluation of fracture toughness in case of DHC (as a function of thermomechanical history and irradiation). The experimental procedure uses a new specimen geometry ("notched C-ring") designed to create a favorable zone for hydrogen diffusion and precipitation due to the presence of a stress gradient. The setup avoids friction between the assembly and the specimen. An inner pre-machined notch is used to trigger controlled crack propagation. The influences of temperature, hydrogen concentration, load, and time were investigated. These mechanical tests, combined with fractography and metallography, showed a slow quasi-brittle failure followed by unstable ductile crack growth, thus demonstrating that the setup can reproduce DHC. A model coupling mechanical behavior, hydrogen stress-induced diffusion and hydride precipitation was developed. Within this framework, cohesive zones were used to model crack growth in both quasi-brittle and ductile regimes.

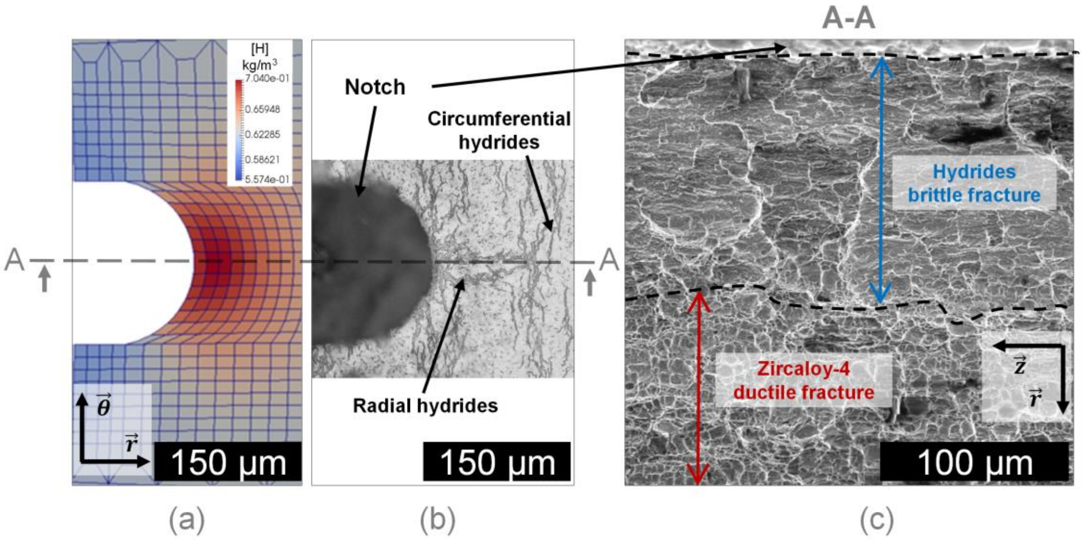


*Figure 1 – (a) Finite element simulation of stress-induced diffusion of hydrogen at the initial machined notch tip; (b) Optical microscope observation of hydrides for $KK < KK_{IIII}$; (c) MEB fractography after DHC fracture.*

# #312 Robust Determination of Fatigue Crack Propagation Thresholds from Crack Growth Data

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*Fatigue Crack Propagation Threshold*     *Data evaluation methods*     *Experimental Determination*

**Abstract** To assess the ability of cracks to grow, a robust determination of the threshold against fatigue crack propagation $\Delta K_{\mathrm{th}}$ is of paramount importance. The standards ASTM E647 and ISO 12108 introduce operational definitions of $\Delta K_{\mathrm{th}}$ based on the crack propagation rate $\mathrm{d}a/\mathrm{d}N$. For evaluating $\Delta K_{\mathrm{th}}$, both suggest fitting a linear function to a defined subset of the logarithmic $\Delta K - \mathrm{d}a/\mathrm{d}N$ test data, where $\Delta K_{\mathrm{th}}$ follows by evaluating the linear function at $\mathrm{d}a/\mathrm{d}N = 10^{-7}$ mm/cycle and $\mathrm{d}a/\mathrm{d}N = 10^{-8}$ mm/cycle, respectively.

In general, this kind of fit suffers from a bad representation of the actual curvature of the crack propagation curve. Therefore, we propose a robust method for evaluating $\Delta K_{\mathrm{th}}$ using a non-linear function that reduces the artificial conservativeness induced by the evaluation method as well as the susceptibility to scatter in test data and the influence of test data density. The method is calibrated against a large set of S690QL crack growth data obtained from a total of 48 specimens, and validated against a set of S355NL and S960QL data (3 specimens each), obtained as a part the IBESS (integral fracture mechanics determination of the fatigue strength of welds) project.

**Acknowledgements**

This work is part of the research project IFG 20530 N/1263 "Ermittlung des intrinsischen Schwellenwerts und dessen Validierung als Werkstoffparameter" from the Research Association for steel Application (FOSTA), Düsseldorf, which is supported by the Federal Ministry of Economic Affairs and Climate Action through the German Federation of Industrial Research Associations (AiF) as part of the program for promoting industrial cooperative research (IGF) on the basis of a decision by the German Bundestag. The project is carried out at BAM Berlin and MPA−IfW Darmstadt.

# #314 Influence of cold rolling on the fracture toughness and fatigue crack growth behavior of pure tungsten

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*Tungsten* *Fracture toughness* *Fatigue crack growth*

**Abstract** The inherent brittleness of tungsten below the ductile-to-brittle transition (DBT) represents a well-known drawback of tungsten regarding application areas such as in future fusion reactors. Among different strategies to overcome this issue, such as alloying, the strategy of intense plastic deformation by cold rolling is in the focus of this contribution.

Selected microstructural states of pure tungsten sheets with varying thickness between 2 and 0.1 mm were investigated at different temperatures regarding the fracture behavior in terms of the occurrence of an R-curve behavior. In addition, the fatigue crack growth behavior was characterized with focus on the cyclic R-Curve, the threshold of stress intensity factor range and the influence of the specimen orientation.

The rolling process induces a continuous refinement of the microstructure along with an extreme grain elongation parallel to the rolling direction. The room-temperature (RT) fracture behavior changes from brittle to fully ductile with increasing pre-deformation which is equivalent to a shift of the DBT to RT. As a main reason for the toughness enhancement the formation of delmaination cracks has been indentified that leads to stable crack growth and a rising R-curve. The fatigue crack growth behavior exhibits a pronounced anisotropy of the fatigue crack growth rates and the threshold of stress intensity factor range. Both trends seem to be a result of the elongated grain shape.

# #315 Toughness of an electron-beam welded 0.2C quenched and partitioned steel

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*Quenching & partitioning* *Electron-beam welding* *Impact toughness*

**Abstract** Third generation advanced high-strength steels, e.g., quenched and partitioned steels, are industrially relevant forthcoming structural materials, which consist of a hard ferritic/martensitic matrix and a substantial amount of stabilised residual austenite for improved deformability. A novel processing route of direct-quenching and partitioning aims to improve this concept by facilitating carbon partitioning to untransformed austenite directly from the quench-stop temperature, making production less energy-intensive. However, a major challenge also with these steels is how to maintain structural integrity in the welded end-products after additional heat-input reaching above the elevated partitioning/tempering temperature, i.e., where the given microstructure should still be stable. One heat-input limiting solution to this are beam welding processes, which can minimize degradation of the heat-affected zone (HAZ) and produce even-strength welded joints for S1100 and above.

In this study, we tested toughness properties of an electron-beam welded low-alloyed direct-quenched and partitioned steel (DQP) having a nominal composition of 0.22C-1.50Mn-0.53Si-0.83Al-1.10Cr-0.75Ni (wt.%) and yield strength of ~1100 MPa. The steel plates were produced by laboratory hot-rolling to 11 mm thickness and directly quenching in water to a quench-stop temperature of 275 °C, at which the plates were transferred to a slowly cooling oven preheated to the same temperature, facilitating simulation of cooling of a coiled strip. The resulting microstructure consists of elongated prior austenite grain structure, lath-martensitic matrix and fine film-like residual austenite. Essentially lath-martensitic plates direct-quenched to room temperature (DQ, yield strength ~1350 MPa) are used in comparison to investigate the effect of residual austenite content. The plates were electron-beam welded transverse to the rolling direction, and a low-temperature post-weld heat treatment (PWHT) is compared to the as-welded state. Weld seam, coarse-grained HAZ, and the base materials are tested for toughness both at room temperature and at sub-zero temperatures.

Both the DQ and DQP base materials have excellent estimated impact toughness transition temperature $T_{28J}$ below -90 °C. The weld seam has very good low-temperature toughness also already with the non-optimised welding process with $T_{28J}$ of -60 °C, which shows robustness of the chosen alloy. Furthermore, both the DQ and DQP HAZs have $T_{28J}$ below -70 °C, indicating that the weld seam would be the weakest link. However, the conducted PWHT reduced low-temperature impact toughness in all cases, clearly demanding reassessment of it. More surprisingly, clearly increased residual austenite content doesn't provide improved low-temperature toughness over the respective DQ conditions, which has been reported in medium-carbon DQPs. Detailed microstructural characterization and conducted fractography aim at explaining these results. Also tested promising fracture toughness results will be discussed, too.

# #316 Mechanical performance of 3D printed prosthetic sockets: An experimental and numerical study

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*Mechanical Performance* *Prosthetic Socket* *Additive Manufacturing*

**Abstract** The prosthetic socket is a bespoke product tailored to the needs of each user and its conventional manufacturing process can be very long until the desired and comfortable shape is achieved. Modern technologies such as additive manufacturing provide a time-efficient alternative. Still, production of such products is quite limited and their mechanical compliance to safety regulations remains unproved. In this study, the mechanical performance of various 3D printed above-knee prosthetic socket designs was assessed experimentally according to BS EN ISO 10328:2006 test guidelines for ultimate strength (Figure 1A). A plaster residual-limb phantom was used to apply the load. Sockets of all in-house designs successfully passed the requirements. Still, significant variance was observed in the maximum load-bearing capacity between sockets with the same design but different materials (Figure 1B). All the sockets exhibited a brittle fracture at their posterior distal end, with a crack spanning along the printing direction laterally to the socket. This study also used FEA to investigate the stress distribution within the 3D printed sockets and identify the sites with higher local loads for performance improvement.

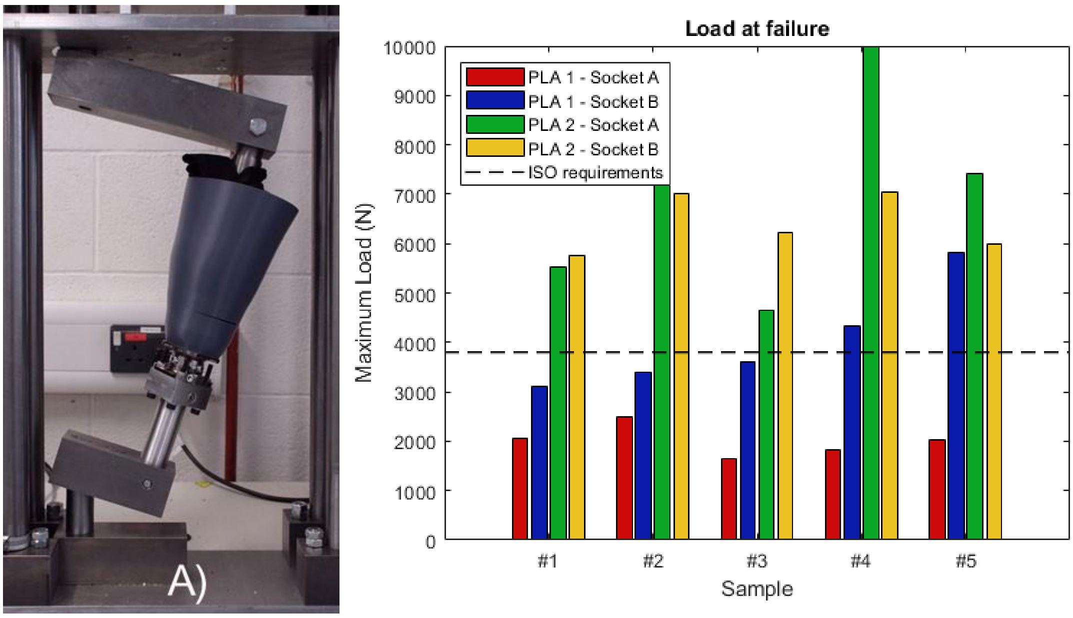


***Figure 1** – A) Ultimate-strength testing configuration. B) Maximum load at failure for two different socket designs printed with two different materials.*

# #317 Comparison of crack closure estimated by 3D finite element modelling and by strip-yield model

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*Crack closure* *Numerical modelling* *Steel*

**Abstract** Crack closure is a process that slows down propagation of fatigue cracks. In fact, the crack can be closed at non-zero external tensile loads. Wolf Elber who firstly described the mechanism noticed that the change of stiffness associated with early crack closure during unloading resulted in reduced crack propagation rate in an aluminum CCT specimen. The corresponding effective stress intensity factor range $\Delta K_{\mathrm{eff}}$ started to be used to describe fatigue crack propagation rate more accurately. One of the mechanisms of crack closure is plastic deformation, which is left at the fracture surfaces after crack propagartion. Today more mechanisms of crack closure are known, however, in order to study them, the 3D distribution of plasticity-induced crack closure in the specimen needs to be investigated.

The first type of modelling was finite element simulation of a CT specimen in 3D, where contact between fracture surfaces was defined, and elastoplastic material behaviour was considered. Two types of steels were considered: a low-alloy bainitic steel and a high-strength steel with 75% of perlite. The specimen was loaded by constant $\Delta K$ at the load ratio $R$ = 0.1. The crack propagation was simulated by gradual release of the nodes in a pre-specified procedure, see Figure 1. Twenty growth steps were simulated in the Load-Debond-Unload (LDU) strategy. After this procedure 15 load-unload blocks were added to simulate a saturated state during fatigue loading. Various crack front curvatures were modelled in order to reach more realistic result than for a straight crack front.

The second used method was evaluation of crack closure using the code for simulation of crack propagation developed by J. C. Newman Jr., which is based on the strip-yield model and the modified Dugdale model. The most important inputs influencing crack closure are the yield stress and the out-of-plane constraint factors in tension ($\alpha$) and compression ($\beta$). Some guidelines are available for the values of $\alpha$ but not for $\beta$. The value $\beta$ = 1 has been used by all authors until now. However, this value was not explained and it has an effect on crack closure. Both constraint factors were computed by 3D finite element analysis of the CT specimen, which provided more accurate results of the strip-yield model. They were compared with those obtained by finite element modelling.

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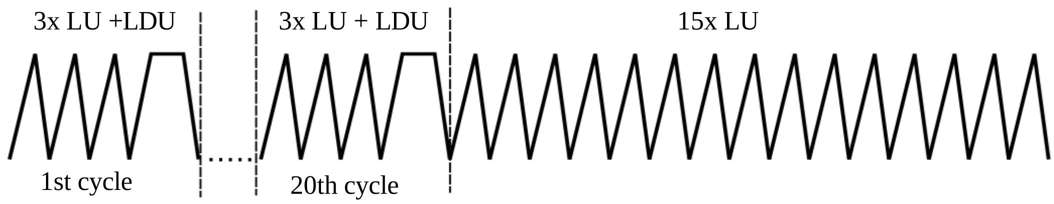


***Figure 1*** *– Loading procedure of specimen*

# #318 Active Learning of Gaussian Approximation Potential: Application to Fracture in Iron

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*Fracture Mechanics* *Molecular Dynamics* *Active Learning*

**Abstract** Fracture ultimately originates from the atomic scale, by involving processes that lead to bond rupture and dislocation activity. A clear understanding of these processes is often lacking, because classical interatomic potentials (IAPs) for Molecular Dynamics simulations yield contradicting results, only in partial agreement with experiments [1]. This is also due to the limited flexibility of their functional form, which is inadequate to describe the complex potential energy surface associated with fracture processes. Emerging machine learning (ML) IAPs allow near-quantum accuracy, based on density functional theory (DFT), but are orders of magnitude faster than DFT [2]. In this work, we develop an active learning algorithm that enables the prediction of atomistic fracture mechanisms via the Gaussian Approximation Potential (GAP) approach. An existing DFT database for ferromagnetic bcc iron is first enriched with configurations that are relevant for the fracture process. Next, the active learning approach is applied to four crack systems, in which the maximum predicted per-atom error is reduced to 10 *meV*. The predicted critical stress intensity factors are compared with theory estimates, and the learning efficiency of the approach is analysed. Our work provides an active learning strategy for improving ML-IAPs for fracture, while revealing for the first time the atomic scale mechanisms that initiate fracture in iron with quantum accuracy.

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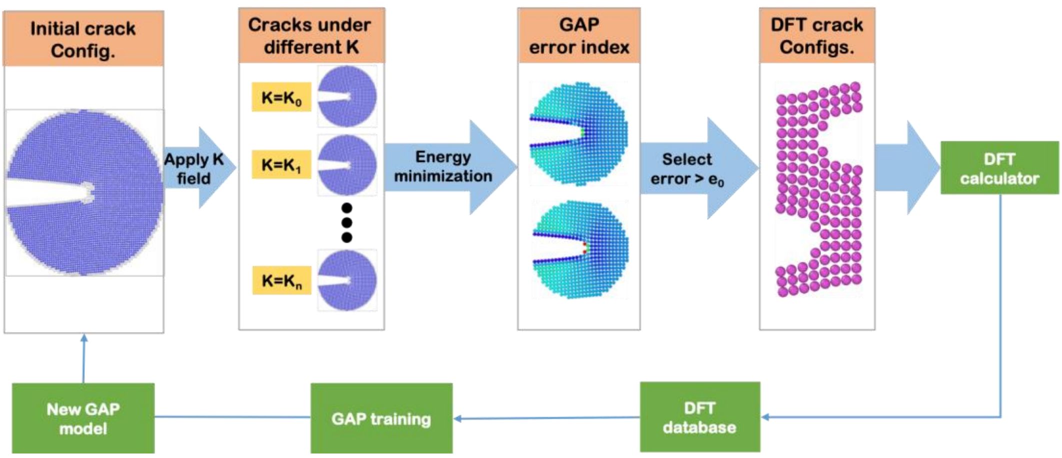


***Figure 1** – Schematics of the active learning algorithm*

# #319 Micromechanism associated with very high cycle fatigue crack initiation of advanced DQ&P processed steel

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*Quenching & partitioning* *Fatigue limit* *Failure micromechanisms*

**Abstract** Very high cycle fatigue (VHCF) failure of high/ultrahigh-strength steels has become a key issue because of their lower defect tolerance. In these steels, cracks tend to initiate in VHCF regime at interior inclusions even at a stress level below the conventional endurance limit. Hence, to ensure the long-term stability and safety of many engineering components and structures made of advanced ultrahigh strength steels, a thorough evaluation of VHCF property is very important. Moreover, the fracture surface of a VHCF failed sample often shows a unique fish-eye type of failure region around the interior inclusion. Such a unique feature has attracted the attention of many researchers to investigate the associated VHCF failure micro-mechanism/s.

Direct quenching and partitioning (DQ&P) process is well established as a novel processing route to improve the strength and ductility balance of advanced high-strength steels, besides imparting excellent low temperature toughness. In this process, austenite is often finely divided as thin interlath films and/or smalls pools between the martensite blocks, and partially or fully stabilized down to room temperature. Whilst the martensitic matrix has the potential to provide the required high strength, a small fraction of finely divided austenite stabilized between the martensitic laths is expected to provide the high uniform elongation and work hardening characteristics via the transformation induced plasticity effect.
In the present study, VHCF properties of a DQ&P processed 0.4C steel (UTS = 2086 MPa) was investigated using the ultrasonic-fatigue testing technique (~20 kHz frequency) up to >$10^{10}$ cycles. The occurrence of crack initiation was observed from interior nonmetallic inclusions in the VHCF regime. The microstructural changes occurring under the fracture surfaces near to crack initiation sites after VHCF failure of the DQ&P steel were further investigated through transmission electron microscopy. A clear nanograined subsurface layer adjacent to the interior inclusion was observed. The variation of average grain size and the thickness of nanograin layer at different stress amplitude level were measured in details. Possible mechanisms behind the significant microstructure refinement of the 2GPa ultrahigh-strength steel have been presented in the paper.

# #321 Fracture mechanical concept to predict crack nucleation in elastic adhesive joints

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*Hyperelastic adhesive* *Energy release rate* *Representative volume element*

**Abstract** Adhesive bonding technologies enable both the automated, economical joining of different types of materials and the mechanical properties of the joint to be modified by the choice of a suitable adhesive. If, in addition to transmitting forces and moments, different thermal expansions of the joining partners need to be compensated for or component tolerances are to be evened out, then elastic adhesive bonds on a polyurethane and silicone basis are established in the assembly process of vehicle, marine and construction industries. Due to the elastomeric, hyperelastic material properties, these adhesives have the potential to ensure adhesion between adherends without damage, even in the case of relatively large distortions in the adhesive layer. To exploit this potential, adhesive layer dimensioning is crucial. While oversizing is economically and resource-wise against the idea of lightweight designs, undersizing may cause adhesive layer failure, which compromises the integrity of the entire structure. In the latter case, the origins for adhesive layer failure are natural imperfections in the sense of cavities and filler agglomerates, which favor the initiation of small, macroscopic cracks. If such cracks initiate due to a quasi-static overload event not only the static load-bearing capacity is reduced but also considerably accelerated fatigue failure by subsequent operationally induced fatigue loads is to be expected. To address this issue, a fracture mechanical concept for predicting crack initiation within the framework of the finite element method (FEM) is presented, which allows for quasi- static load cases the load-appropriate dimensioning of elastic adhesive joints in the virtual product development process.

The approach is based on the idealized consideration of small circular cracks within an extended adhesive continuum. For this crack configuration crack growth potentials, in terms of the energy release rate, are investigated as a function of the surrounding general stress state using FEM simulations on representative volume elements (RVE). An empirical function is derived from the numerical results, which can be used to evaluate the stress on the hyperelastic adhesive layers in terms of the crack growth potential of small circular cracks that may nucleate and propagate at any point in the adhesive layer. With this type of stress evaluation, the quasi-static load-bearing capacity of the adhesive layer can be regarded as the limit to a material specific, critical crack growth potential where initial crack propagation is possible and, hence, a crack is initiated. By identifying this material parameter with a suitable adhesive layer test specimen, a fracture mechanical failure criterion is defined. This failure criterion is validated on the basis of various adhesive layer test specimens by comparing the numerical load predictions for initial crack growth with quasi-static test results. The validation process shows a satisfactory agreement between prediction and experiment, so that the fracture mechanical concept enables load-compliant dimensioning of elastic adhesive joints.

# #323 Matrix and Interface Cracks in Multiferroics

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*Multiferroics* *Cohesive Zone Model* *Maxwell Stresses*

**Abstract** The efficiency in converting magnetic into electric energy and vice versa makes multiferroic composites promising candidates for many technical applications. The ferroelectric matrix as well as the magnetostrictive inclusions of particle composites and the layers of laminates are mostly ceramics or other brittle materials, thus being prone to cracking. Independent from the kind of composite, the transmission of stresses and strains via the interfaces between the constituents plays the key role in its functionality. Therefore, the investigation of delamination processes is of great interest for the prediction of durability and coupling factors. In order to investigate delamination processes in multiferroic composites, cohesive elements are being developed and applied in combination with nonlinear magnetoelectric (ME) finite elements introduced in [1] and [2]. The mechanical behavior of the cohesive zone is classically prescribed by a traction-separation-law. Magnetic and electric fluxes as well as electrostatic stresses in cracks and the fracture process zones are approximated by an extended capacitor analogy, constituting a multi-field generalization of the traction-separation-law. Piezoelectric and piezomagnetic properties of the fracture process and cohesive zones are taken into account, introducing an appropriate thermodynamical potential. Electric and magnetic properties change during damaging processes, being controlled by damage variables, which in turn are determined by the separation between the boundaries. The cohesive zone approach and associated crack tip opening displacements are related to other electromagnetomechanical fracture quantities such as energy release rates or the J-Integral. Based on simulations influence factors on delamination like the arrangement of the composites, the ME poling processes or loading regimes are investigated, finally with regard to improving ME coupling coefficients. Furthermore the influence of electromagnetic volume forces (Maxwell stresses) on crack propagation in dielectric media is investigated numerically, showing that a $r^{-1/2}$-singularity is no longer valid under ME loading.

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# #324 Damage-Preserving Transformation from Continuum to Embedded Discrete Microstructure

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*Multiscaling* *Dynamic Coupling* *FEM, DEM*

**Abstract** The fracture process of heterogeneous microstructured materials, such as concrete, is highly influenced by its microstructure. However, to accurately simulate the fracture process of such materials fullscale simulations are needed. Multiscale simulations are one way of lowering the computational costs of such simulations. A particular class of them uses domain decomposition approaches, *i.e.* splitting the computational domain into several regions. Inside each region a different computational method is used. For instances a high resolution method is selected for regions where a fracture will appear, while for predominantly static regions methods with less resolution can be employed. The different regions are then coupled together at their junctions, resulting in one large system. The drawback of these methods is, that they usually require the decomposition of the domain to be known in advance. To overcome this problem, adaptive schemes, which are able to dynamically refine certain regions on demand, have been proposed. One of the main challenges in using them is the consistent creation of the refined discrete representations, which should be inserted. The main reason for this is, that the coarse representation, that was previously active in the region, has already accumulated damage, which influences its mechanical behaviour, for example weakening the material. Thus, if an unimpaired discrete representation would be inserted, inconsistency would be created by this. Instead the discrete representation has to be artificially damaged, in a way that is compatible to the damage that was incurred by the original coarse grain representation, before it is inserted into the region. Here, we propose a method for initializing these new fine scale representations. The proposed method employs FEM for the coarse and a network composed of Bernoulli beams on the fine scale, the different regions will be coupled together through the Arlequin method. Inside the continuum scale a continuum damage model (CDM) is used to model the degradation of the material and the progression of damage. Once the damage inside a (coarse) region has surpasses a certain damage threshold, the continuum representation will be replaced by its discrete counterpart. These representations, will be initialized based on the accumulated damage, which was monitored by the CDM, to match the degraded state of the continuum scale.

# #325 Mechanical behaviour of specimens made via fused deposition modelling under three-point bending

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*Fracture* *Material extrusion* *Polylactic acid*

**Abstract** Presenting fused deposition modelling (FDM) as a cost-efficient alternative to produce prototypes and customized components, the mechanical behaviour of FDM parts is not totally known yet due to the large number of variables involved during the manufacturing process. In order to provide additional knowledge on this topic, several prismatic specimens were manufactured via material extrusion using polylactic acid to analyse the influence of some key printing parameters (such as infill density and raster orientation) on their failure mechanism under quasi-static conditions. Three non-solid (under 100% infill density) and four solid designs were tested under three-point bending at a low strain rate and monotonic loading. Three-dimensional digital image correlation technique was implemented to track the displacement and strain distributions on the sample surface. Additionally, finite element method-based numerical models were created to simulate these tests and predict failure through the theory of critical distances application. Experimental results were analysed in terms of flexural strength and fracture morphology, identifying their correlation with specific parameters and designs. The impact of the printing defects was also assessed by comparing the numerical estimations and the experimental results, considering data collected from a micro-CT scan of post-mortem samples. This work shows the significant effect of process parameters in the mechanical behaviour and failure mechanisms of polymeric components manufactured via material extrusion.

# #326 A quasi-static computational model for interface and phase-field fracture in domains with inclusions

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Phase-field fracture Quadratic programming *Staggered approach*

**Abstract** A computational model for dealing with fracture in materials with inclusions is considered in the present contribution. The proposed model allows to predict crack initiation and growth in quasi-brittle materials. The inclusions cause that cracks may appear inside the matrix materials or along matrix-inclusion interfaces. The presented model can treat them both using two internal variables in a form considered in damage mechanics so that crack formation process is a consequence of a material degradation. The first of the damage variables is defined at matrix-inclusion interfaces and it is represented by a thin degradable adhesive layer so that an adequate stress-strain relation is rendered as in common cohesive zone models. The second variable is defined in the structural domains, matrix plus inclusions, as a phase-field fracture variable which causes domain elastic properties degradation in a narrow material strip that results in a diffuse form of a crack. Both these damaging schemes are expressed in a unique quasi-static energy evolution process. The numerical solution approach is thus rendered from a variational form obtained by a staggered time-stepping procedure related to a separation of deformation variables from the damage ones and using sequential quadratic programming algorithms implemented together within a MATLAB finite element code. The numerical simulations with the model include simplified structural and material elements containing one or more inclusions as shown in Fig. 1. The cracks appeared both along interface and inside the material of the matrix when an increasing in magnitude displacement loading $g_2$ had been applied.

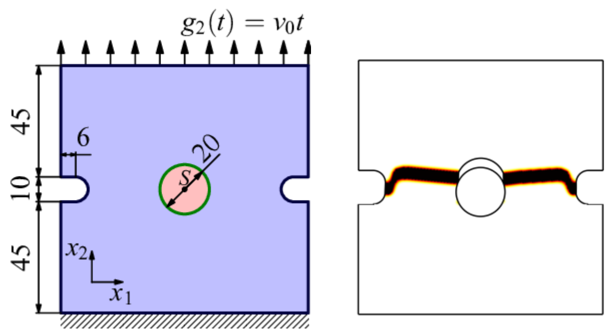


***Figure 1*** *– interface and bulk cracks.*

# #327 Phase Field Fracture models for Viscoelastic Materials

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*Prony series model* *Fractional calculus* *Phase-field method*

**Abstract** Fracture of viscoelastic solids plays an essential role in many areas of science and technology, including biological attachments, adhesives, polymers, and soft robotics. Nearly all properties of these materials are time-dependent and may tremendously affect their failure behavior. Since time appears in the stress strain relations, viscoelastic problems differ from the corresponding elastic ones. Compared with elastic or elastic- plastic materials, viscoelastic fracture received far less attention in the literature, and it is not yet well understood. This work focus on the Phase Field (PF) method for modeling fracture in viscoelastic materials. Due to the ability to model complex crack propagation, including branching, PF has significant relevance in fracture studies. Various mathematical models have been developed and used to represent the viscoelastic material functions. The most versatile model is obtained by connecting the number of Maxwell's arms in the Generalized Maxwell model (GMM) through standard Prony series type expansion. The material properties are determined by fitting the Prony series in the real data. Alternatively, fractional calculus has proved to be very effective in modeling the power-law time dependency of relaxation behavior of polymers. Recent work of Lenarda and Paggi (2022) shows that Fractional calculus offers the easiest way to estimate the model parameters compared to other models. The present work proposes a PF formulation for crack propagation in viscoelastic materials using material models based on GMM and on fractional calculus. A comparative study is performed with several benchmark problems to determine the effectiveness of the above models. Further, the proposed framework is exploited to numerically solve some test cases related to fracture tests conducted on samples of viscoelastic materials used in photovoltaics.

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# #328 Hydrogen Embrittlement Assessment of Pipeline Materials Through in situ Slow Strain Rate Tensile Testing

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*Pipeline steels* *Hydrogen embrittlement* *Tensile Testing*

**Abstract** The use of hydrogen as an energy carrier plays a key role the transition from fossil fuel to renewable energy. Norway may contribute to this shift by using its already existing vast natural gas subsea pipeline network for large scale transport of hydrogen gas to the European countries. However, safe operating limits and countermeasures for hydrogen embrittlement need to be established to safely enable hydrogen transport. The knowledge basis for safe operation limits is being built within a research project funded by the Research Council of Norway and an international industry consortium. This paper presents the results from an initial materials screening program from three vintage pipelines and one new pipeline. Both base metal and weld simulated heat affected zone materials have been investigated. Results from microstructural characterization, slow strain rate tensile testing in air and in situ hydrogen charging conditions and electrochemical diffusion measurements are presented and discussed. The degree of embrittlement for the different pipeline materials is quantified by the Embrittlement Index (EI). Post-mortem analysis of the fracture surfaces morphologies is also carried out to relate the overall degree of hydrogen embrittlement susceptibility of the materials with respect to their characteristic metallurgical features. There was no discernable degradation of strength for any material in hydrogen, while there was significant ductility loss in terms of EI. Surface cracking was observed both in and outside the neck. Quasi-cleavage and secondary cracks were typical fracture features, however, the center of the specimens still showed dimpled rupture. Based on the EI, the new pipe material was the least susceptible to hydrogen embrittlement.

# #330 Effect of hydrogen on nanomechanical properties of Inconel 625 revealed by in situ electrochemical nanoindentation

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*Hydrogen embrittlement* *Electrochemical nanoindentation* *Dislocation patterns*

**Abstract.** In situ electrochemical nanoindentation experiment is performed to probe the nanomechanical properties of nickel based super alloy under hydrogen environment. Simple diffusion absorption desorption model is used to relate the nano hardness increase and decrease during different polarization sequence. The slip traces observed at high cathodic potential are correlated with the absorbed hydrogen induced internal stress. Furthermore, the electron channeling contrast imaging technique is used to study the dislocation patterns around the indents in air and in hydrogen environment to shed light on the difference in plastic behavior. The pop-in load which indicates the onset of homogenous dislocation nucleation event is increased with hydrogen charging. This is in contrasts with “Defactant model” which states that hydrogen segregation to defects reduces their respective formation energy. The reason for observed difference is systematically evaluated and the role of microstructural features in influencing the pop-in behavior is discussed in detail.

# #331 Compressive fatigue behaviour of pure Ti scaffolds with compact and porous strands produced by material extrusion additive manufacturing

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*Tissue engineering scaffold*    *Direct ink writing*    *Fatigue*

**Abstract** Metallic porous structures (scaffolds) produced by additive manufacturing represent an important class of personalised implants used in load-bearing orthopaedic applications. As such, their fatigue performance has to be excellent to prevent the need of revision surgery. In comparison with predominantly used powder bed fusion (PBF), material extrusion is more cost-effective and offers the possibility to design the intrastrand porosity by controlling the sintering conditions, resulting in scaffolds with hierarchical porosity. However, because the preparation of metallic porous structures by material extrusion is novel itself, there are no studies yet addressing their fatigue behaviour. Therefore, the present work reports on the cyclic compression fatigue behaviour of pure titanium extruded scaffolds with compact and porous strands. Interestingly, the results showed that, due to crack growth shielding effects, scaffolds with porous strands endured an order of magnitude more than scaffolds with dense strands, which in terms of normalized fatigue strength was at the upper limits of structures produced by PBF.

# #332 Deep learning algorithm for prestressed railway bridge structural safety

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*Data mining* *Deep learning* *Structural health monitoring*

**Abstract** Continuous monitoring, with automatic acquisition and data processing from remote locations, is one of the most successful approaches for controlling huge infrastructure assets. The recorded data, online and in real time managed, must be processed to highlight the presence of damages and degradation phenomena that may affect structural performance.

For the development of effective and timely maintenance plans, a correct interpretation of structural response evolution is critical. The presence of time-delayed phenomena (e.g., fluage), to which structural materials are subjected, requires the combination of transversal engineering skills for data trends interpretations and for the research of data processing suitable solutions. This paper investigates the combined use of data pre-processing techniques and deep learning algorithms (e.g., Random Forest and Multi-Layer Perceptron) to address some critical issues in the development of structural control strategies for prestressed bridges. The proposed unsupervised approach has been validated using data recorded on a simply supported prestressed concrete railway bridge, located in northern Italy. It is part of an economic and managing optimization of hierarchically articulated monitoring systems. The robust architecture of the system, the use of parameters recorded with low frequency, and the automatic data analysis process ensures that the system is both effective and cost-efficient. The analyzed viaduct turned out to be a very important case study as it is representative of a common static structural typology. As a result, the gained know-how and the prospect of generalizing the method to other bridges of the same type are of great importance. The results in terms of damage identification capacity are promising and encourage further developments.

# #333 Modelling of an indentation induced ring crack using the coupled criterion

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*Sphere indentation* *Ring crack* *Coupled criterion*

**Abstract** Study of indentation-induced fracture of brittle ceramics has been motivated by characterization of material hardness, indentation strength and specific fracture energy. When a hard spherical indenter (a ball) is pushed onto a flat surface of brittle ceramic material, a ring crack develops, which can further extend into a cone crack. Empirical observation is that the fracture force required for crack initiation is linearly or quadratically proportional to the small or large ball radius respective. This size effect is commonly explained by two approaches: the flaw statistics or the energy balance.

Classical linear elastic fracture mechanics assumes that a crack is present in the material and unstably propagates when the Griffith's criterion is fulfilled. However, it does not allow prediction of crack initiation or to determine the critical force and the location of macroscopic crack. An alternative approach, called the finite fracture mechanics (FFM), does not require presence of a crack. Instead, FFM can predict the formation of a new crack of finite length $a_0$, which initiates when both stress and energy conditions (a coupled criterion) are simultaneously fulfilled.

We developed a computational model to predict fracture forces and crack locations based on elastic properties, fracture toughness and strength of a brittle material without any further assumptions about the flaw distribution on the surface. Predictive ability of the model is demonstrated by comparing calculations results with experimental data available in the literature and our own experiments. Additionally, we can explain the cause of discrepancy between predictions of coupled criterion with experiments observed by Hahn and Becker.

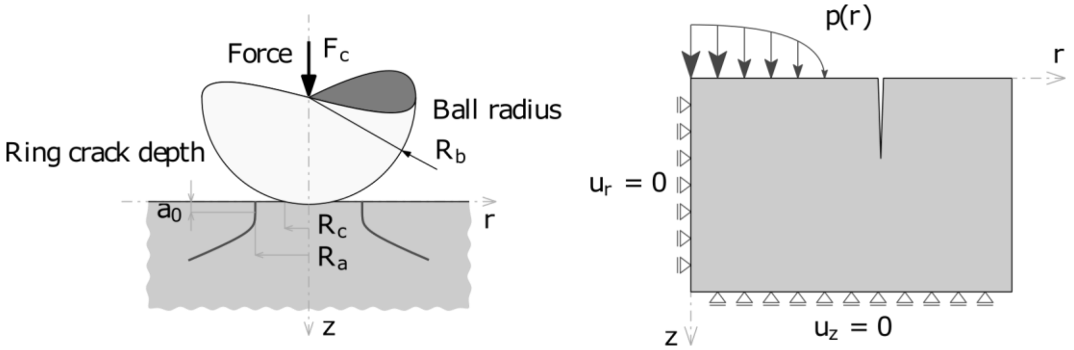


***Figure 1*** *– Geometry and parameters governing the crack initiation problem (left) and boundary conditions used in the computational model (right).*

# #334 Correlating electrochemical and gaseous hydrogen charging of a X65 pipeline steel by the permeation technique


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*Hydrogen permeation* *Low alloy steel* *Hydrogen embrittlement*



**Abstract** Hydrogen is promoted, as a clean energy carrier, to play an important role in achieving carbon neutrality. A possible mode of transportation for hydrogen gas are steel pipelines. However, hydrogen may cause degradation of mechanical properties in the form of hydrogen embrittlement. As hydrogen embrittlement can be affected by the hydrogen uptake and diffusivity, it is important simulate operating conditions during experiments. Charging with hydrogen gas comes with safety concerns and lab infrastructure for gas charging is often limited. As a result, hydrogen charging is often performed by electrochemical charging. Establishing a relation between electrochemical and gaseous charging conditions would enable interpretation of the large amount of data obtained with electrochemical charging.

In this work, the hydrogen permeation technique was used investigate hydrogen uptake and diffusivity in a X65 pipeline steel. Both hydrogen gas charging and electrochemical charging were performed. The sub-surface lattice hydrogen concentration was used to compare and relate the severity of the different charging conditions. The effect of gas pressure and charging current density on the sub-surface lattice hydrogen concentration and the effective hydrogen diffusivity were also investigated. The lattice diffusivity was estimated by partial transients. The sub-surface lattice hydrogen concentration increased with increasing hydrogen gas pressure and increasing charging current density. An increase in the effective diffusivity with increasing hydrogen content was observed and attributed to the effect of reversible trapping.

# #335 Application of Deep Learning models to characterize porosity defects in additive manufactured components

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*Additive manufacturing* *Deep learning* *Porosity*

**Abstract** This work is part of a large package of work investigating the structural integrity of additively manufactured components in nuclear applications. Components manufactured using additive manufacturing (AM) often contain high degree of manufacturing defects which may lead to pre-mature failure in service conditions, for example, during fatigue loading. The aim of this work is to automate the detection and analysis of various types of manufacturing defects in AM using image segmentation techniques such that, robust predictive models can be built to correlate the defects with material deformation. The types of defects considered in this work are lack of fusion, micro-crack, spherical porosity, and unmelted particles.

Four rectangular blocks of 316L stainless steel were fabricated using Selective Laser Melting (SLM) and Direct Lased Deposition (DED) techniques. The blocks were cut longitudinally, and the surfaces were metallographically polished and imaged using Scanning Electron Microscope (SEM). Deep neural network models were constructed based on three architectures: Fast Fully Convolutional Network (FCN), SegNet and UNet. The models were then trained using a set of micrographs utilizing various sets of hyperparameters. Model testing and validation were conducted using new and unseen images. Performance of the models were assessed based on training run times, testing run times and accuracy of detecting the correct locations, types, and sizes of the defects in the validation datasets.

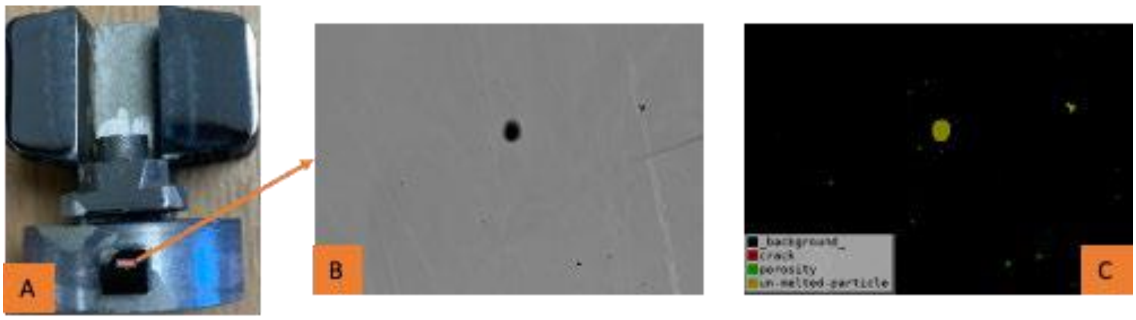


***Figure 1*** *– A) Metallographically polished 316L steel SLM and DED samples B) Example micrographs with different types of defects C) Masked micrographs used for training the neural network models*

# #336 Phase Field Fracture Analysis of Periodically Heterogeneous Material under thermo-mechanical loading

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*Phase Field Method* *Thermo-mechanical* *Crack*

**Abstract** The phase field method (PFM) has been implemented to fracture problems to simulate complex crack growth behavior. That includes crack nucleation, crack branching, crack coalescence and crack growth along complex trajectories. In the last decade, the PFM was widely used to solve various complex fracture problems such as fracture of heterogeneous materials, composites, ductile materials, polymers, smart materials etc., under different loading conditions (mechanical, thermal, thermo-mechanical, electro-mechanical, thermo-electro-mechanical, etc.).

Recently author had developed an adaptive multiscale phase field method (AMPFM) to simulate fracture in heterogeneous and composite material. The AMPFM provides a adaptively refined mesh for crack growth and during crack growth adaptively refined region at the crack tip converted into coarse mesh region after crack growth. Moreover, AMPFM takes very little computation time as compared to standard PFM.

In the present study, AMPFM is implemented to simulate fracture in periodically heterogeneous material subjected to thermal and thermo-mechanical load. A composite made such that the thermal conductivity and thermal coefficient of expansion of heterogeneity (square shape inclusion) and matrix material have different values. Various numerical experiments are conducted for different geometrical configurations, spacing, size, and material properties of the periodic heterogeneities. The simulated results of AMPFM under thermal and thermo-mechanical load are compared with body subjected pure mechanical load for the same crack configuration. The pre-existing crack in the body is considered as an adiabatic crack.

From the obtained result, it has been observed that the thermal and thermo-mechanical load significantly affect the crack growth path and crack nucleation sites in the chosen crack configuration as compared to pure mechanical load.

# #337 Structural Integrity of Skin: Effect of Thickness

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*Skin* *DIC* *ABAQUS*

**Abstract** Skin is susceptible to tears, abrasions and lacerations, some of which require extensive long-term care. These wounds are a result of mechanical forces such as shear stress, blunt trauma and friction, which can cause full or partial separation of the skin layers. Lower structural integrity of the skin is one of the factors that increases the prevalence of tears, abrasions and lacerations in it. As the thickness of skin varies in different locations of the body, knowledge of the effect of skin thickness on its mechanical properties can give an insight into location with higher probability of occurrence of such body wounds.

Skin is the largest organ of the body with a multi-layered structure. It consists of the epidermis, which is broken down into four stratum layers (Figure 1), the dermis, and the hypodermis. Each of these layers is formed by a variety of cells with independent mechanical and structural properties, resulting in unique properties of the layers. As a result of fluctuation of skin thickness throughout the body, in some locations, the frequency of certain skin cells is higher than others.

This research focusses on the skin tissue at macroscale, using silicone rubber as a synthetic skin substitute. Tensile testing was used to determine the effect of thickness on mechanical and structural properties of the material, with results validated using Digital Image Correlation (DIC). This was achieved by applying a speckle pattern to the samples and completing the tensile tests, with images taken before and after the experiment. GOM software was used to analyse these two images to measure the strains on the surface of the material and comparison with the experimental results.

These experimental results were used for development of a finite-element numerical model with ABAQUS software. Numerical simulations demonstrated the effect on the sample's thickness for different stresses and strains applied to the surface. This knowledge can be used to understand, which locations of the body are more susceptible to injury and can be expanded to assess the effect of presence of certain skin cells on the structural integrity of each layer of skin.

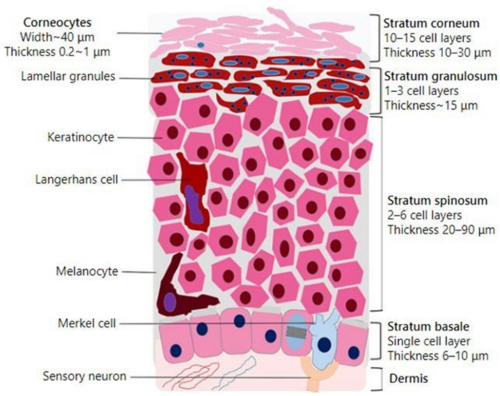


***Figure 1*** *– Cell composition of epidermis*

# #338 Atomistic interactions of H at dislocations in iron

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*hydrogen embrittlement* *dislocation plasticity* *iron*

Hydrogen (H) has the potential to lead the energy transition due to its clean and sustainable makeup. However, one of the major obstacles for an efficient hydrogen economy is material compatibility since it leads to metal embrittlement. In the past decade, following experimental and numerical investigations at different time and length scales, several embrittlement mechanisms have been proposed [1]. Nonetheless, the proposed mechanisms are often in contradiction with each other, and there is no broad consensus on the role of hydrogen, as a function of concentration, on the motion of the dislocations, which is crucial for plasticity and hence fracture toughness.

In this work, we investigate the hypothesis of hydrogen enhanced localized plasticity (HELP) by studying the nano/macro-scale interaction of hydrogen atoms with dislocations in iron and how this interplay ultimately dictates the glide behaviour. To this purpose, we perform molecular statics and dynamics simulations of bcc edge dislocations using an empirical EAM potential [2] that captures the correct lattice parameter, elastic constants and Fe-H interactions. These simulations are performed using the open-source LAMMPS code [3]. The influence of edge dislocation line length, and varying distribution and concentration of H atoms around the dislocation core is systematically investigated.

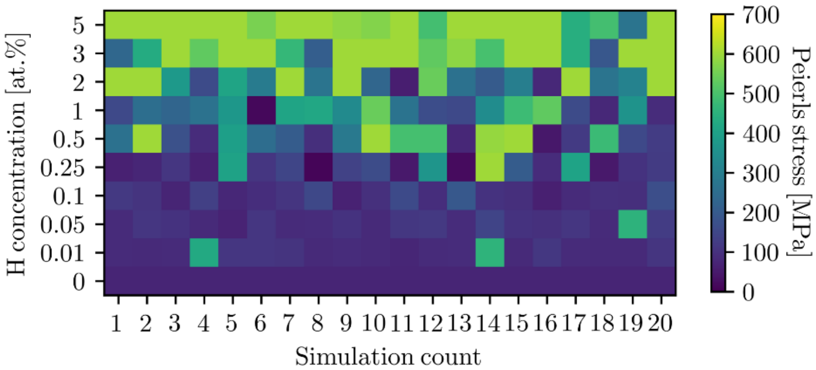


***Figure 1*** *– Heat map schematically showing the Peierls stress required to glide an edge dislocation as a function of varying H concentration. The Peierls stress increases with H concentration, thereby revealing H enhanced dislocation pinning; the magnitude of pinning for a given concentration shows a significant dependence on the local distribution of H atoms around the dislocation.*

The critical Peierls stress for the glide of dislocation in presence of H is computed and compared with the reference case i.e., the one of pure iron, revealing H assisted pinning of dislocation glide, as shown in Figure 1. This finding is in contradiction with the well-established theory of hydrogen enhanced localized plasticity (implying hydrogen enhanced dislocation mobility) and is supported by the observation that the H-dislocation interaction energy is caused by strong elastic interaction of H with the dislocation core, ultimately increasing the Peierls stress. Furthermore, considering the physical mechanism of dislocation pinning, an analytical model to predict the finite temperature critical resolved shear stress for varying local H concentration is developed and used to make predictions corresponding to experimental conditions.

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# #339 Dynamic Finite Fracture Mechanics

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*Finite Fracture Mechanics* *Dynamic Fracture* *Loading rate*

**Abstract** The development of robust failure criteria applicable to both quasi-static and dynamic loading conditions arouses interest in the scientific community as for the impact it poses in the reliability of failure predictions for critical structural applications. Consequently, different quasi-static failure criteria have already been modified to account for the effect of non-negligible loading rates, although limitations in their applicability and physical soundness still remain.

The extension of the well-established Finite Fracture Mechanics failure criterion to the dynamic loading regime is herein addressed. To that end, some general requirements to be fulfilled by any proper dynamic failure criterion are first shortlisted. Upon these, the definition of the Dynamic Finite Fracture Mechanics (DFFM) is proposed, compared against the main existent failure criteria, and proven to be more robust. Finally, the introduced DFFM approach is validated with suitable experiments from the literature, which were performed on rock specimens that contained three differentiated stress distributions, namely constant, stress concentration (non-singular) and stress intensification (singular). In all of them, DFFM is able to capture the rate dependence of the failure load with reasonable accuracy.

# #340 Computational semi-analytic code for stress singularity analysis

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*Stress singularities* *Anisotropic materials* *Frictional contact*

**Abstract** Problems of stress singularities in single or multi-material corners have been addressed by many authors over the years. Most of the authors presented closed-form corner-eigenequations for special cases, and often there is not an easy way to check if the solution is correct. In this work, we present a general computational tool that can solve many different cases of stress singularity problems for multi-material corners under generalized plane strain. The semi-analytic code is based on the matrix formalism presented in [1,2,3] and is developed in MATLAB. The following boundary conditions are implemented: stress free, fixed, some restricted or allowed direction of displacements (defined either in the reference frame aligned with the cylindrical coordinate system or in an inclined reference frame), or frictional sliding. The following interface condition between two consecutive materials are implemented: perfectly bonded, and frictionless or frictional sliding. The code can analyze both open and closed (periodic) corners, composed of one or multiple materials with isotropic, and transversely isotropic or orthotropic (with any orientation) constitutive laws. The code has proven to be a reliable, very accurate, robust, and easy-to-use tool, which has been verified by comparing the results computed with those obtained by other authors. A summary of the corner singularity problems solved is presented. The results of the corner singularity analysis obtained by the code can be further used for prediction of crack onset at the corner tip by the Coupled Criterion of Finite Fracture Mechanics and FEM, see [4] and references therein.

## Acknowledgements

The research was conducted with the support of Spanish Ministry of Science, Innovation and Universities: PGC2018-099197-B-I00. Consejería de Transformación Económica, Industria, Conocimiento y Universidades, Junta de Andalucía: P18-FR-1928, US- 1266016. European Regional Development Fund: PGC2018-099197-B-I00, P18-FR-1928, US- 1266016

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# #341 Extended back-face strain compliance solution for physically short crack regime in SENB-4P specimen

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*Cracks* *FEM* *Back face strain*

**Abstract** Compliance equations based on back face strain, crack mouth opening displacement and potential drop techniques are widely used to calculate fatigue crack growth rate. The ASTM E 647 standard does not include compliance based techniques for single edge notched four-point bending (SENB-4P) specimens [1]. A compliance expression for SENB-4P developed based on FEM has been reported in literature; it has a limited validity criterion based on relative crack depth (a/W) ($0.2 \leq a/W \leq 0.6$) [2]. It is therefore only applicable to long crack propagation. For crack growth in the physically short crack regime, no compliance solutions for SENB-4P specimen were found in literature. This work investigates the calibration of back-face strain compliance for calculation of relative crack depth a/W ratios ($0.05 \leq a/W \leq 0.5$) of an SENB-4P specimen. Two methods are used: finite element analysis (FEA) and fatigue testing of SENB specimens extracted from thick steel plates of grade S355. Along with back face strain compliance, Direct Current Potential Drop (DCPD) was used for crack monitoring. The developed compliance expression offers good agreement with expressions found in literature and has been validated with fractography of fatigue tested specimens.

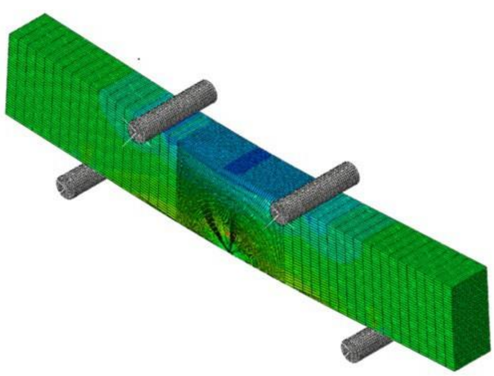

***Figure 1*** *– FEM simulations for extracting strain.*


***Figure 2*** *– Test setup for fatigue four point bending.*

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# #342 Tough and damage tolerant composites for bi-axial loading

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*Composite materials* *Configurational force* *Ductile damage*

**Abstract** The insertion of material inhomogeneities can greatly change the fracture toughness and the crack path in inherently brittle materials. The main reason is that spatial variations of material properties, i.e. Young's modulus $E$ and yield stress $\sigma_y$, influence the magnitude and the direction of the crack driving force vector [1]. Investigations have been carried out that show the effectiveness of layered composites to arrest cracks in the interlayer under uniaxial loading conditions [2]. However, such layered composites are not applicable for bi-axial loading conditions, since they would easily fracture along the soft interlayer. The topic of the current presentation is to investigate design concepts for new, tough composites that sustain biaxial loading conditions. The first idea has been to insert circular voids into the brittle matrix material in order to deviate and arrest the cracks by forcing them to grow into a void [3]. Based on the configurational force concept [1,4], a computationally efficient crack trajectory interpolation (CTI) method has been developed, which evaluates the trapping zone size of circular voids in terms of the biaxiality factor $\beta$ [3]. The trapping zone is the area around a void where approaching cracks run into the void and get trapped. In the current investigation, it is tried to estimate the optimum shape of elliptic voids as a function of the load biaxiality ratio. The trapping zone sizes are determined by the CTI method and the improvement of the fracture toughness is evaluated by a damage-based approach [5]. Hereby perfect and pre-damaged void surfaces are assumed. Since new manufacturing processes, such as additive manufacturing, have almost no restrictions to the composite architecture, it is also studied whether and how the insertion of stiff particles can help to increase the trapping distances of voids, as well as the stiffness of the material. An extension of the CTI method to multi-void arrays aims to find a composite architecture with an optimum arrangement of voids so that all possible cracks are arrested and the fracture toughness of the composite is substantially increased.

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# #344 New view on crack closure determination from compliance data

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*crack closure* *crack propagation* *fatigue crack*

**Abstract** It is believed that crack propagation rate is controlled by effective value of stress intensity factor range $\Delta K_{eff}$, where $\Delta K_{eff} = K_{max} - K_{cl}$. Whilst the maximal stress intensity factor $K_{max}$ in a load cycle can be easily determined, the stress intensity factor related to the crack closure $K_{cl}$ cannot be simply determined. This work provides a new view on procedure for determination of crack closure level from experimental tests. The experimental tests were carried out on C(T) and M(T) specimens. Most of the crack closure data was determined by using of crack mouth opening displacement (CMOD) gauge. Based on recorded dependence between applied force and CMOD data (strain/displacement) the force-compliance dependence was determined according to the standard ASTM E647. A typical problem of these results is a large scatter of data, which reduces clearness of crack closure level. Therefore, ASTM E647 recommends the offset of compliance data 1%, 2% or 4% to determine clearly the crack closure level. Even when enough data points were recorded and statistically evaluated it seems that the ASTM offset criteria can underestimate crack closure level. Figure 1 shows that for some force-compliance records there is another source of non- linearity besides crack closure. This extra non-linearity leads to underestimation of crack closure level. Consideration of all sources of non-linearity in the load-compliance data leads to better estimation of crack closure level than in the case where other sources of non-linearity are neglected. This new view on crack closure determination can improve current approaches to crack closure investigation. Consequently, the effective stress intensity factor range can be determined more accurately than before.

**Acknowledgement:** This work was financially supported by Czech Science Foundation in frame of the project 22-28283S.

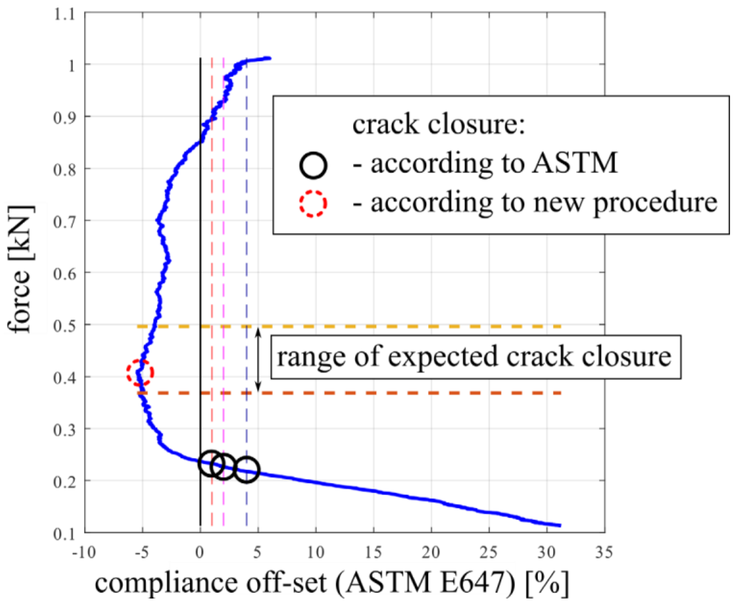


***Figure 1** – force-compliance record for evaluation of crack closure, herein standard ASTM E647 leads to underestimation of crack closure level*

# #346 Effect of hydrogen charging on Charpy impact toughness of two pipeline steels

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*Hydrogen embrittlement* *Pipeline steels* *Charpy V-notch*

**Abstract** Hydrogen uptake in steel structures can cause a degradation in mechanical properties such as a decreased toughness, and can induce cracks. This phenomenon is widely known as hydrogen embrittlement. For structural steels subjected to cathodic protection or pipelines transporting high-pressure hydrogen gas, hydrogen embrittlement represents an important challenge. Charpy V-notch testing provides a fast and inexpensive method for quantifying the fracture toughness of a steel. In this work, the influence of hydrogen uptake on the impact toughness of two pipeline steels, a 'vintage' API 5L X56 and a 'contemporary' API 5L X70, is investigated. Charpy V-notch impact tests are performed for both materials in air, both in uncharged condition and after electrochemical hydrogen pre-charging. Different charging times and solutions are used to study the influence of the hydrogen concentration. The tested temperature range is between -80 °C and +20 °C. For the X56 steel, there is little effect of hydrogen and the ductile-to-brittle transition is in the same temperature range. For the X70 steel, on the other hand, a rising upper shelf phenomenon is observed in the uncharged specimens and the DBTT is not reached for the tested temperatures. For this material, hydrogen uptake causes a reduction in Charpy impact energy at the higher temperatures, with the highest reduction measured at room temperature. A post-mortem analysis of the fracture surfaces suggests that the presence of hydrogen in the lattice aids the formation of separations during fracture, lowering the absorbed energy. As such, the Charpy V-notch impact test is not deemed fully adequate for analyzing toughness reduction due to hydrogen in the tested materials, as the presence/absence and nature of observed effects are material-specific.

# #348 Multiaxial fatigue assessment of arc-welded steel joints with weld ends for automotive application according to the peak stress method

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*Multiaxial fatigue* *Weld ends* *Peak stress method*

**Abstract** The Peak Stress Method (PSM) [1] is a rapid FE-oriented application of the approach based on the Notch Stress Intensity Factors (NSIFs) for the fatigue strength assessment of welded structures. More precisely, the PSM allows to estimate the NSIFs based on the singular, linear elastic peak stresses calculated at the weld toe or at the weld root locations of a welded structure using coarse FE meshes. In this work, steel welded joints with weld ends, of automotive interest, have been fatigue tested under uniaxial external loading, which generates a multiaxial stress state both at the weld toe (mode I+II+III) and at the weld root (mode I+II+III) locations. Two different joint geometries were tested, i.e. with welds located either along (lateral joints) or perpendicular (frontal joints) to the load axis, both in the as-welded and stress relieved conditions. An idealized geometry of the weld ends has been proposed and introduced in the FE models. The PSM has been applied to the tested joints by taking advantage of an automated application [2] (Fig.1a), providing a proper estimation of the crack initiation location, which experimentally occurred at the weld ends (Fig.1b). The theoretical estimations based on the PSM resulted on the safe side as compared to the experimental results generated by the frontal joints, while estimations were in good agreement with experimental results relevant to lateral joints. Finally, the results obtained by a FE model including the actual geometry of the weld ends, as virtualized using a 3D scanning technique, have been compared with those derived by the FE model including the idealized weld end geometry.

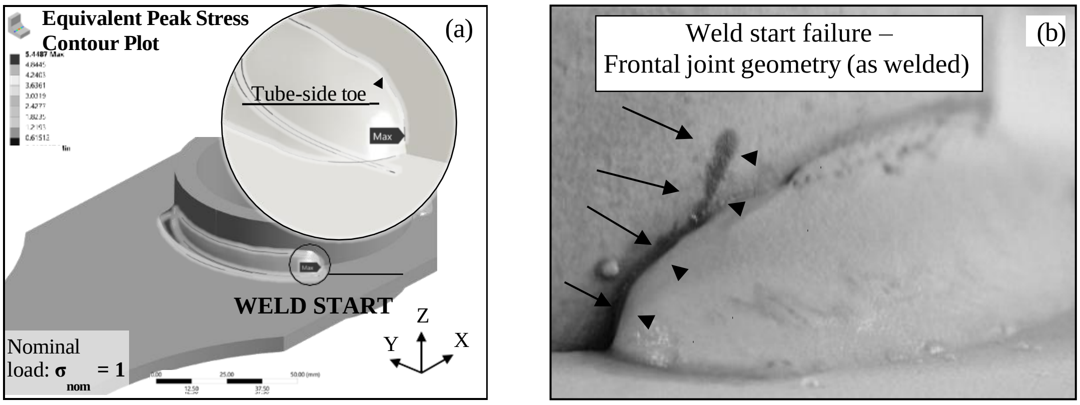


***Figure 1*** *– (a) Fatigue assessment of the frontal joints with the 3D scanned geometry of the weld ends according to the PSM. (b) Example of failure analysis of the frontal joints.*

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# #350 Structural integrity of welded joints with different defect combinations – previous studies

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*Welded joint defects* *Structural Integrity* *Low-alloyed low-carbon steels*

**Abstract** This paper presents the overview of extensive research about the effects of multiple different welded joint defects on the structural integrity of welds typically used in pipelines, made of steels S235 and S275. This research involved the preparation and welding of plates (with several different combinations of defects), cutting of specimens with “defective” geometries, experimental tests (such as tensile tests and hardness), measuring of strain using digital image correlation and numerical simulations. Initial tests and analyses were performed on plates made of S235 steels, and will be used as the base for investigating a higher quality steel, in this case S275. During the research, numerous adjustments and improvements to the welding technologies and numerical methods were made, in accordance with the obtained results, in order to develop a methodology for accurately describing and predicting the behaviour of welded joints in the presence of multiple defects, which is a topic that still remains largely unexplored, even by state-of-the-art relevant standards.

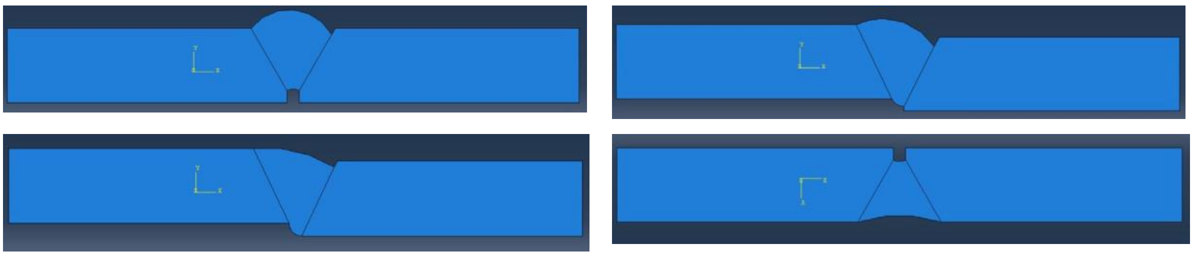

Figure 1. Numerical models used throughout the various stages of research

# #351 Optimisation of numerical models of welded joints with multiple defect combinations

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*Welded joint defects* *Finite element method* *Steel S275*

**Abstract** This paper presents the continued efforts in investigating the behaviour of low-alloyed low-carbon steel welded joints in the presence of different combinations of multiple defects which can occur during welding (such as undercuts, incomplete root penetration, misalignments…). Since these defect combinations can greatly affect the integrity of welded joints, due to significant changes in geometry which are induced by their presence. For this reason, a total of 8 numerical models were made, including four different defect combinations (2 models for each group). This number of models was equal to the number of actual test specimens that were used for tensile test experiments, which also provided the necessary input data (mechanical properties) for each model. The goal was to determine if the two models from each group were sufficiently similar to each other, so that in the future research, they could be replaced by a single, unified model for each defect combination. Comparison was made in terms of stress and strain distribution, and it was determined that three out of four models have nearly identical values, whereas the first group specimens had shown slightly bigger differences, which were still acceptable. Thus it was concluded that a single representative model could be made for each defect combination group.

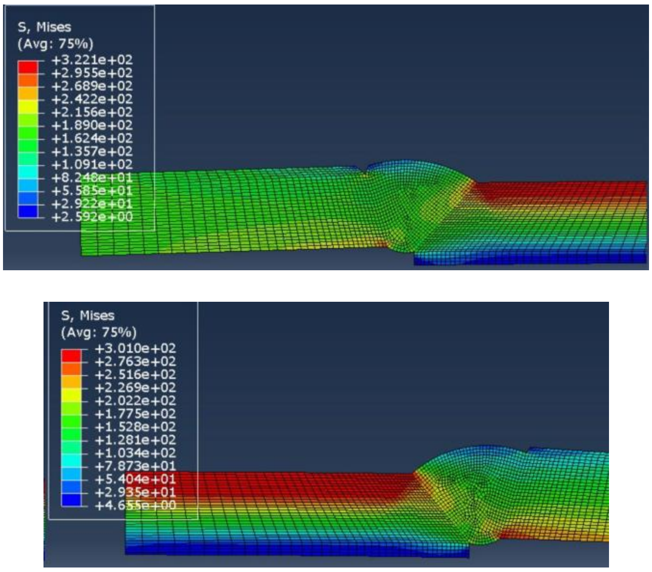


Figure 1. Comparison of two different fourth group specimen models

# #352 Effect of post-processing heat treatment on cyclic plastic behavior of AlSi10Mg aluminium alloy processed by L-PBD

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*Cyclic plastic behavior* *Laser powder bed fusion* *Heat treatment*

**Abstract** Some effort has been put on the understanding of the mechanical performance of engineering metals processed by laser powder bed fusion (L-PBF), particularly on the triangular relationship between processing parameters, microstructure, and mechanical properties. Concerning the AlSi10Mg aluminium alloy processed by L-PBF, although the research focused on processing routes, microstructure and monotonic properties is relatively abundant, studies dealing with the cyclic plastic behavior rarely have been conducted. Another unclear topic is the effect of heat treatment on the fatigue strength of AlSi10Mg aluminium alloys processed by L-PBF. Recent studies have reached some antagonist conclusions, namely about the benefits of stress-relief and T6 heat treatments. Therefore, the present paper aims to study the effect of different heat treatment routes on the cyclic plastic behavior of AlSi10Mg aluminium alloy manufactured by L-PBD. Uniaxial strain-controlled fatigue tests are conducted on polished smooth specimens in the low-cycle and high-cycle fatigue regimes for different material states, encompassing standard T6 and stress relief heat treatments, and a non-standard stress relief heat treatment. It has been found that the microstructural transformations associated with the standard heat treatments are detrimental to fatigue strength in the AlSi10Mg aluminium alloy processed by L-PBF, while the non-standard stress relief heat treatment, performed at a lower temperature, hinders the substitution of the matrix supersaturated with Al-Si phase by spheroidal Si in an Al matrix, resulting in a better fatigue performance.

# #353 Influence of ITZ between steel inclusion and cement composite on fracture response of specimen

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*Steel inclusion* *Fracture test* *Numerical simulation*

**Abstract** In this work, the influence of the ITZ between steel inclusion and matrix on fracture behaviour of fine-grained cement-based composite is investigated. Specimens of the nominal dimensions 40 × 40 × 160 mm with steel inclusion of the shape of prism with nominal dimensions 8 × 8 × 40 mm were provided with an initial central edge notch with a depth $a_0 = 12$ mm. To determine the influence of the interface on fracture behaviour, three-point bending fracture tests were conducted (see Fig. 1) and evaluated (Young's modulus $E$, fracture toughness $K_{\mathrm{Ic}}$, specific fracture energy $G_F$). After fracture tests, the specimen was examined by 3D scanning technology, see Fig. 1, and the microstructure was observed by a scanning electron microscopy.

The aim of this work is to analyse the behaviour of such specimen by means of finite element method (ANSYS software), and with the knowledge of crack propagation and the microstructure of fracture surfaces. A simplified 2D model (plane strain) based on the fracture test configuration was created. The crack propagation assessment was based on the criterion based on an average value of tangential stress $\sigma_{\theta\theta}$ over a certain distance $d$ and determined in dependence on the polar angle $\theta$. It is assumed that the crack is initiated when the average value $\bar{\sigma}_{\theta\theta}(\theta_0)$ reaches its critical value $\bar{\sigma}_{\theta\theta,\mathrm{c}}(\theta_0)$, which depends on the value of fracture toughness $K_{\mathrm{Ic}}$ of the material and on the distance $d$.

From the detailed numerical analysis of the described fracture test, we concluded that the mechanical fracture parameters of the interface must be lower than expected. The reasons for the lower values of the mechanical fracture parameters of the interface are lower degree of hydration in the ITZ (the age of the tested samples was only 14 days), imperfect compaction of fresh cement composite and lower values of adhesive bond. The fracture toughness of the interface $K_{\mathrm{Ic,ITZ}}$ was estimated based on the knowledge of crack propagation path and measured load versus crack mouth opening displacement diagrams, whose ascending branch consisted of two approximately straight sections.

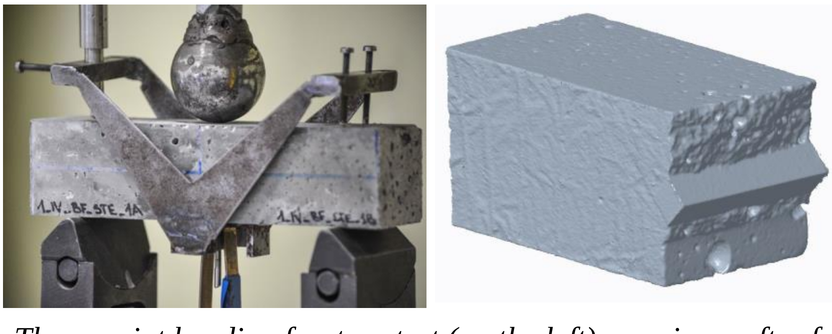

***Figure 1** – Three-point bending fracture test (on the left); specimen after fracture test.*

**Acknowledgement**

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# #355 Fatigue crack closure numerical analysis using a three-dimensional model for crack growth and plastic wake

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*Crack Growth* *Crack Closure* *Plastic Wake*

**Abstract** Fatigue crack closure has been the focus of many authors and previous analysis. While two-dimensional models provide accurate results with low computational effort, they established the base methodologies to analyze the stress and strain fields around the crack tip. The current computational capabilities, allow for the development of three-dimensional models, not limited to plane stress or strain conditions. Several parameters allow for the numerical simulation optimization. The element size around the crack tip, affecting both crack opening and closure values. The crack growth scheme, affecting the plastic strain distribution around the crack tip. And the material model used for fatigue analysis, allow the development of more realistic models, where the material behavior can be analyzed all along the specimen thickness.

In this paper a three-dimensional model of an aluminum MT specimen was developed, in order to analyze the stress and strain fields distribution around two different crack tips. Fatigue crack growth was simulated using the release node technique. Each node was released when the applied load reached the maximum value, for greater stability. The plastic wake size and the crack closure were determined for different element sizes, along the crack tip. Crack closure was measured using virtual clip gauges, placed along the crack length. The obtained results were compared against previously obtained numerical and experimental results. The numerical results included two-dimensional models, where the full fatigue crack growth process was simulated. The experimental results included both DIC and ESPI analysis.

Three-dimensional models allow for accurate results, with very good agreement with both already tested two-dimensional models and experimental analysis. Element size analysis, provide additional insight for future model development and optimization.

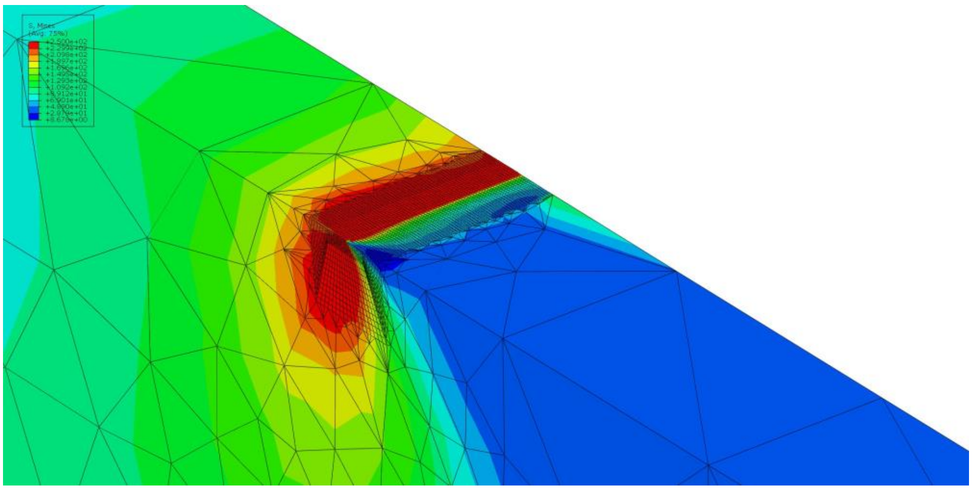

***Figure 1** – Three-dimensional model for fatigue crack growth.*

# #357 Structural integrity of a self-adaptive grasping system at highly iterative operation

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*Highly iterative grasping* *Durability* *Structural integrity*

**Abstract** Manufacturing companies, such as automotive suppliers, frequently use robotic cells in line, as well as in matrix production. Operations performed in these cells through the interaction of conveyors, robot arms, grippers, feeders, and more include but are not limited to part assembly, object picking, placing, and manipulation, as well as packaging of intermediate and final goods. To reach a maximum degree of capacity utilisation while handling an increasing number of product variations the single components of a robotic cell along with the entire cell itself must be flexible and rapidly adaptable. In the presented study the authors decreased the occurring errors in a robotic cell and increased its overall efficiency through the advancement of the utilised grasping system. The system in question handles cylindrical objects with varying diameters along the object height and changing sizes and proportions among product variations. To guarantee the correct positioning of a cylinder it must be in an upright position with its cylinder axis centred in the grasp of the gripper. Most past failures of the robotic cell were caused by misalignment during this step. The newly developed system is self-adaptive to the different shapes. The cell performs up to ten thousand iterations per day, hence about three and a half million cycles yearly. Therefore, the new system not only had to precisely position a variety of different objects but also, do so with repeatable accuracy while withstanding the cyclic stresses. In the ongoing research work the authors currently test their system intensively in the lab and in a relevant industrial environment before undertaking a full system integration. The experimental results will be compared with numerical analyses to ensure the durability and structural integrity of all components.

# #360 X-ray Computed Tomography and an erosion algorithm and for rapid defect detection

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*Battery* *X-ray Imaging* *Data reduction*

**Abstract** X-ray computed tomography is an estabished method of non-destructive evaluation of materials[1], and has been applied to the lithium-ion battery industry for over a decade[2]. Over this time, the quality of imaging has improved, enabling cracks with battery electrodes to be visaulized[3]. These cracks, which cause batteries to store less energy with each use are problematic, particularly as the transport sector looks to electrify through the use of battery electric vehcicles.

The current method of finding cracks is largely qualitative, and requires time consuming high resolution imaging, only enabling > 100 particles a day to be analysed, with results shown in Figure 1a. Imaging with a higher throuput, 1000s of particles a day, results in lower resolutions, with defects less prominent or below the resolution of imagng, Figure 1b. Through combination of lower resolution high throughput imaging, and novel erosion algorithms, particle defects can be identified and quantified, as seen in Figure 1c.

This workflow has been applied to battery electrodes, containing 100s of particles, to gather statistically relevant information about the extent of cracking present in each sample. In this presentation, the results and opporunnity of this technique will be discussed.

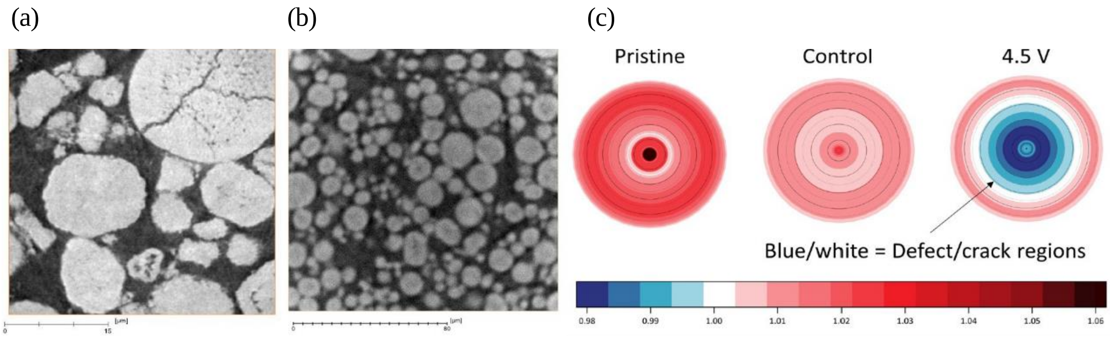


*Figure 1 (a) high resolution CT slice, (b) low resolution 3D volume (c) identification of particle defects from low resolution CT scans and accompanying algorithm*

1. du Plessis, A., le Roux, S. G. & Guelpa, A. Comparison of medical and industrial X-ray computed tomography for non-destructive testing. *Case Stud. Nondestruct. Test. Eval.* **6**, 17–25 (2016).
2. Shearing, P. R. *et al.* Multi Length Scale Microstructural Investigations of a Commercially Available Li-Ion Battery Electrode. *J. Electrochem. Soc.* **159**, A1023–A1027 (2012).
3. Heenan, T. M. M. *et al.* Identifying the Origins of Microstructural Defects Such as Cracking within Ni-Rich NMC811 Cathode Particles for Lithium-Ion Batteries. **2002655**, (2020).

# #361 Inverse-designed buckling-resistant lattices

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*Machine learning* *Architected materials* *Buckling*

**Abstract** Advances in additive manufacturing has allowed scientists and engineers to fabricate materials with complex architected structures at different length scales, from the micro- to macro- scale, reaching superior mechanical performance, such as high stiffness- and strength- to-weight ratio. Designing the architecture of materials to obtain targeted properties (i.e., inverse design) has hence become one of the primary research goals. With their lightness, stiffness and strength, strut-based lattice structures have in particular shown to exhibit exceptional combinations of mechanical properties. Despite the massive research on lattice architectures, inverse-designing them remains challenging. In this work we propose a bottom- up machine-learning-guided inverse design approach, using buckling strength as an example targeted property. Basic (2-D) architected building blocks are combined to generate $n \times n$ unit cells (for arbitrary integer $n$), which are then periodically tessellated to obtain lattice structures. Serving as surrogate model, a deep neural network (DNN) is trained on nonlinear post-buckling finite element simulations for predicting the buckling strength of the generated lattice architectures along different loading directions. In combination with DNN, a genetic algorithm explores the design space searching for quasi-isotropic high buckling-resistant architectures (i.e., combinations of building blocks). Our inverse-designed candidates exhibit similar or superior buckling strength (from 10 to 30 % gain) than deep sea glass sponge-inspired design, recently discovered to have exceptional stability resistance compared to traditional grid-like structures. Experimental results on 3D-printed compressive-loaded structures confirm the machine learning and simulation predictions. With this work we provide a simple yet powerful machine-learning-guided approach for the inverse design of strut-based lattices with superior mechanical performance, opening an avenue for controlling both geometric and topological features through bottom-up techniques. In addition, some physical insights on the buckling resistance of lattices are extracted from the inverse design process.

# #362 Contemporary questions in fatigue crack closure: simulation, experiments, effects of material, geometry, load ratio, testing procedure and air humidity

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*crack closure* *cyclic crack tip plasticity* *oxide debris*

**Abstract** Influence of load ratio on fatigue crack propagation (FCP) rate is often expressed by effective stress intensity factor range $\Delta K_{eff} = K_{max} - K_{cl}$, where $K_{cl}$ is the crack closure load (alternatively, $K_{op}$ as the opening load is used in literature). In the Paris regime, the available models to predict $K_{cl}$ have only slight dependence on material. However, experiments show much greater variation of $K_{cl}$, which cannot be explained, unless the out-of- plane constraint factors in tension and in compression are adjusted. Discussion over the validity of the crack closure concept is presented. It was proposed that the differences could be attributed to the material cyclic softening and cyclic hardening behaviour. 3D finite element simulations were done to determine the constraint factors for given monotonic and cyclic yield stress. Plasticity-induced crack closure was modelled using both the strip-yield model and 3D finite element analysis.

Distribution of crack closure and crack tip opening displacement (CTOD) along the crack front in 3D with various curvatures allowed obtaining more realistic values and a better insight into the mechanisms of closure. Presumption, that the 2D plane-stress solution is valid for the free edge of a 3D cracked body, is wrong. The stress field and plastic zones look much differently. CTOD is smaller near the free edges than in the middle section (the near plane strain area) even for a crack without consideration of crack face contact or crack front curvature. This contributed to understanding of distribution of oxide debris along the specimen thickness in the near-threshold crack propagation.

In the near-threshold regime, oxide-induced crack closure has a higher influence in steels than it was previously thought. Production of oxide debris can result in variation of threshold by the factor of 2. This has enormous consequences for the estimated residual fatigue lives of components. Influences of air humidity, testing frequency, testing methodology and specimen thickness on threshold were studied for various steels.

Experimental measurement of crack closure using crack mouth opening displacement (CMOD) gauge was found to be more reliable than local strain gauges mounted on the sides of the CT specimen. The recorded dependence between the applied force and CMOD is often used for experimental evaluation of crack closure. The ASTM offset criteria can underestimate the real crack closure level. Other sources of non-linearity of the force- compliance record were analysed to improve accuracy of closure measurement.

**Acknowledgement:** This work was financially supported by the Technology Agency of the Czech Republic in frame of the project CK03000060 of the program Doprava 2020+.

# #363 Fracture of austenitic stainless steels at cryogenic temperatures

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*Fracture toughness* *Cryogenic temperatures* *Strain-induced martensite*

**Abstract** The Austenitic stainless steel has become a strategic material for high-field superconducting magnet applications due to the high strength, ductility and toughness that it retains from ambient to cryogenic temperatures. Though, austenitic stainless steel is susceptible to strain-induced martensitic transformation, especially at cryogenic temperatures, which might lead to a modification of the material mechanical properties. Here, we characterize the fracture behaviour of two of the most widely used grades, AISI 304L and AISI 316LN, at liquid nitrogen temperature (77 K) and at liquid helium temperature (4 K) with the aim of analysing the influence of the strain-induced martensitic transformation on their fracture failure caused by crack propagation under static loading. Mode I elastic-plastic fracture toughness tests have been performed according to the “resistance curve procedure" (ASTM-E1820-20a, 2020), and four different methods have been used for the calculation of the crack-growth resistance curves. Post-mortem microstructural analysis of the specimens near the fracture surface has been carried out to reveal the content of martensite. Furthermore, in order to get a deeper understanding of the fracture behaviour, simulations of fracture toughness tests using a dedicated constitutive model for the multiphase material are being performed. The comparison between experiments and finite elements aims at providing new insights into the role of martensitic transformation in the fracture behaviour of austenitic stainless steels at cryogenic temperatures.

# #364 Multilayer polymer pipes – The methodology for residual stress determination

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*Multilayer pipe* *Residual stress* *Ring slitting method*

**Abstract** It has been shown that residual stress in polymer pipes is an important factor, which has considerable effect on their lifetime. Previously published papers dealt with the experimental determination of residual stress in polymer pipes made of one raw material – polyethylene or polypropylene mainly. This study is focused on experimental determination of residual stress in multilayer polymer pipe, that consists of 3 layers. All the 3 layers are made of polyethylene, however, the material used for the middle layer has slightly worse mechanical properties. The experimental procedure for obtaining the residual hoop stress distribution by measuring the deflection of axially slit ring specimens is used. Then, the data are evaluated by a method based on theory of a curved beam member, which is broadened to multilayer pipes by considering different Young's modules. Numerical modelling by finite element method is employed to simulate the behavior of the ring specimens.

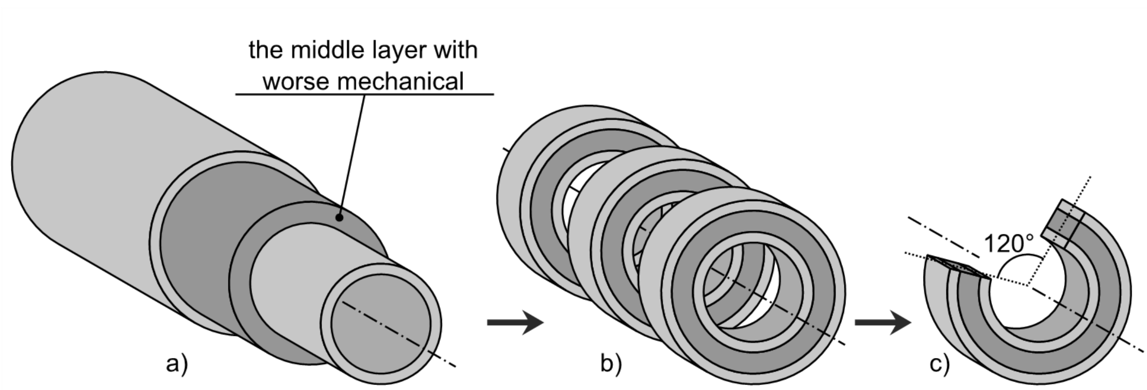


***Figure 1** – Scheme of procedure of creating axially slit rings.*

# #365 Fatigue life assessment in the very high cycle regime of AISI 316L stainless steel after additive manufacturing

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*L-DED* *Ultrasonic fatigue* *Crack initiation*

**Abstract** Additive manufacturing technologies have arisen great industrial interest for manufacture of components and final parts intended for applications in several sectors of the industry. Most of these components are designed to have a service life greater than $10^7$ cycles, making the analysis of the fatigue behavior in the very high cycle regime (VHCF) an essential design criterion. The 316L stainless steel is one of the most processed and discussed in the literature. However, there is still no consolidated knowledge about the fatigue life of this material manufactured by different available techniques and their respective mechanisms of initiation of cracks predominant in the VHCF regime. The present work is intended for an experimental study of the VHCF failure mechanism of AISI 316L steel after additive manufacturing by laser directed energy deposition. In order to also identify the effect of post-processing steps, two different conditions of the material (as-built and heat treated) were analyzed. The specimens were submitted to ultrasonic tests with a target number of $10^9$ cycles, at a frequency of 20±0,5 kHz and R=-1. The fracture surfaces were analyzed later and the influence of heat treatment on the population of metallurgical defects, “fish eye” formation and material’s fatigue life was verified.

# #366 A bending fatigue test method for strip specimens using a 20 kHz ultrasound fatigue testing system

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*VHCF* *Strip steel* *Cantilever*

**Abstract** Strip steels are used in many demanding applications with the requirement to withstand fatigue failure up in the Very High Cycle Fatigue regime (>$10^7$ cycles). To design such components information and test results on the VHCF properties of the material is essential, and hence, high frequency fatigue testing is required. In the present study an investigation of a new bending fatigue test setup using an ultrasonic fatigue testing system was conducted. A cantilever bending fatigue test setup running at 20 kHz in 2$^{nd}$ bending mode resonance was simulated using FEM, Figure 1. The stress/strain distribution in the specimen was computed using a FEM dynamic analysis including inertia effects. Cantilever specimens were mounted in the ultrasonic fatigue testing system, and the FEM analysis was confirmed by experimental measurements of the displacement distribution along the length of the specimen. Additionally, a fatigue test series was run to determine the VHCF bending strength, to determine failure mechanisms and evaluate the agreement between simulation and experiments. Thus, the study presents a viable method to assess fatigue strength and fracture mechanisms of thin structures in high frequency bending fatigue loading.

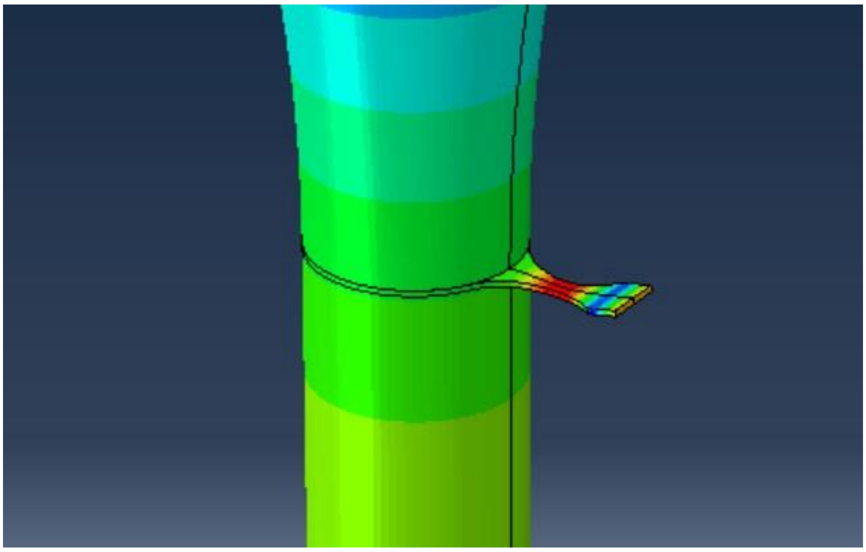

***Figure 1** – FEM 3D-model of a strip steel cantilever specimen in the ultrasonic fatigue testing system.*

# #367 Micromechanical analysis of a polymer composite material using Phase-Field fracture coupled with plasticity

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*Finite element method* *Phase-Field* *Micromechanics*

**Abstract** Failure in composite materials when studied at the component or macro-scale is a collection of several interacting damaging phenomena such as fiber and matrix fracture, interface friction and debonding, and even plasticity effects in the matrix. Most of these events take place simultaneously and depend on a great number of material parameters. These parameters can potentially be related to the scale such as the fracture toughness and strength, but also to the degree of volumetric constraint, such as the plastic response and fracture properties. As a consequence, realistic material parameters are very difficult to measure and approximation of bulk properties may be inaccurate if used to approximate micro-scale behavior. In this work, the Phase-Field (PF) method coupled with pressure dependent and pressure independent plasticity models have been used to investigate the influence of material behaviour in the process of failure initiation and progression of polymer composite materials at the micro-scale. Matrix brittle fracture using standard linear elastic PF formulations is compared with PF coupled with pressure independent and pressure dependent plasticity models. This work studies the influence of the material model and material parameters in the global response of the composite through the study of a representative volume element (RVE) under different loading conditions. It is observed that deformation modes that promote brittle failure are less affected by the material plastic behaviour, while other failure modes may be strongly dependent on the plasticity formulation and in the cohesive damage formulation used to model fibre/matrix debonding.

**Acknowledgements:** The authors acknowledge the funding received from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 861061 – Project NEWFRAC.

# #368 Study on Fatigue damage in Additively Manufactured IN718 Alloy

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*Additive Manufacturing* *Fatigue* *Inconel*

**Abstract** Superalloy IN718 is extensively used in the aerospace and power generation industry owing to its superior mechanical properties and excellent corrosive resistance at elevated temperatures of up to $600-800$℃. To get the better efficiency as per design codes, the geometrical accuracy and complex shape are the prime concern in these applications that are challenging due to the limitation of conventional manufacturing processes. A laser powder bed fusion (LPBF) additive manufacturing (AM) technology facilitates the freedom to fabricate complicated and near desired shaped components. However, parts manufactured using AM techniques come with several inherited defects such as porosity, lack of fusion, etc. High thermal gradient and rapid heating-cooling cycles also often develop tensile residual stresses, leading to premature cracks in the components and thereby reducing the fatigue properties. These problems have been addressed in this study using finite element simulations and the experimental tests. The simulated results were then validated with the experimental ones.

IN718 samples without any aid of post-fabrication machining were fabricated using a selective laser melting (SLM) based additive manufatcuring process with 30 µm layer thickness and optimized parameters using Renishaw make AM400 machine. Some of the as-built samples were then heat treated (HT) at 980°C ± 10 °C for 1 hour in order to relieve the tensile residual stresses induced due to the manufacturing process. Melt pool and microstructure were examined using optical microscope and FE-SEM. Texture analysis revealed distinct regions of coarse elongated grains with a strong orientation uniformly embedded in a randomly distributed fine-grained matrix. Few tensile tests, low-cycle and high-cycle fatigue tests were performed at different stress ratios of -1,0.1 and 0.5 at 10 Hz (at 24℃) using 250kN MTS servohydraulic fatigue testing machine. The endurance limit (ran-out spcimens till $10^7$ cycles) of the as-build IN718 at stress ratios of $RR=-1$ , 0.1 and 0.5 were 400 MPa, 250 MPa, and 185 MPa, respectively. More tests are still continuing for different HT and surface conditions. The fracture surfaces of the broken specimen were investigated to improve the understating of micro-mechanism and damage mechanism of the fatigue damage. Finite element simulations were accomplished to validate the size of the melt pool with experimental results, which helped in predicting the thermal profile and residual stresses accurately and closer to the observed values. The validated simulated results of the melt pool with a depth of 60±10 µm and width of 150±10 µm is shown in figure below. Further detailed investigation alongwith the observed results and plausible explanations shall be discussed and presented during the conference.

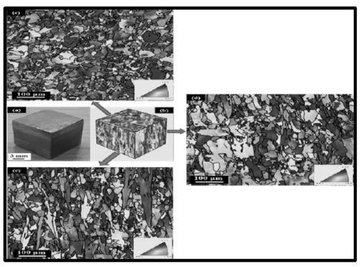

**Figure 1 –** EBSD IPF Map of SLM IN718 both in build direction and transverse to build direction

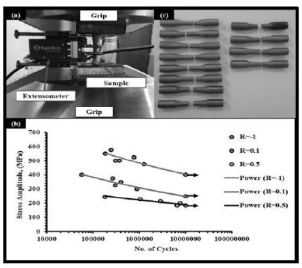


**Figure 2 –** S-N Curve at different R-Ratios

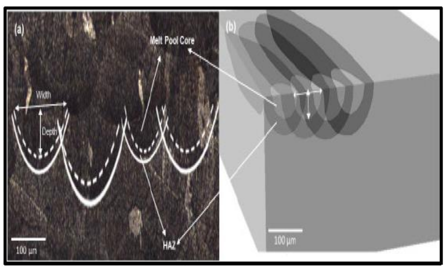


**Figure 3**. Optical and FE Simulation Validation of Melt pool

# #370 Investigations on the delamination of pre-notched UHMWPE composite plates at the low impact velocity

Rotariu Adrian[1], Matache Liviu[1], Bucur Florina[1], Pulpea Bogdan[1], Dirloman Florin[1]Trană Eugen[1]

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*delamination* *impact* *composite*

**Abstract** The composite materials are used for various purposes, ballistic protection being the technical application that involves the most violent loads accompanied by deformation and failure of impacted composite structures. The composite nature of such structures implies a complex mechanical response, involving phenomena such as delamination in the case of UHMWPE laminated boards. The interest towards this phenomenon is given by the fact that it represents a mechanism of consumption/dissipation of projectile kinetic energy. In this study, one experimental setup is proposed to determine the values of the loads that cause this phenomenon and the dynamics of delamination in plates made of Dyneema HB26. In the chosen setup, pre-notched plates were used to stimulate the occurrence of delamination on a strip delimited by the notches. The depth of the notches controlled the distance between the delamination plane and the free surface of the plate. The delamination occurred by impacting the central area of the plate (40 x 40 mm) with a flat-head projectile, Figure 1 (a), at the base of which was attached a PCB 350C03 accelerometer with a sensitivity of 0.0543 mV/m/s$^2$. The plates measuring 150 x 150 x 10 mm were fixed in a test rig with the help of butterfly head screws, Figure 1 (b). Optionally, the complete removal of the strip by delamination could be prevented by tightening the strip ends to the test rig with those butterfly head screws, Figure 1 (b). Following the tests, the strips were completely delaminated, Figure 1 (c), starting from the central part towards the edges, the decelerations suffered by the projectiles being recorded with the help of the accelerometer. The tests were filmed with a PHOTRON SA-Z high speed camera. For the calculation of the delamination forces, the values of the registered accelerations were multiplied by the projectile mass value, 400 grams. The projectile was pneumatically accelerated at the impact velocities around 12 m/s. The projectile energy loss through delamination of the strip was found to be sensitive to the strip thickness. The same dependency was observed in the case of the maximum deceleration of the projectile, attained in the first sequence of the impact/delamination process.

(a) (b) (c)

***Figure 1** – Details of the test set-up (a), (b) and post test photo capture (c)*

**Acknowledgments**

This work was supported by a grant of the Romanian Ministry of Education and Research, CCCDI - UEFISCDI, project number PN-III-P2-2.1-PED-2019-3997, within PNCDI III

# #371 Initiation and short environmentally assisted crack behavior of new generation 7XXX aluminum revealed by in situ microscopy

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*EAC* *Hydrogen Embrittlement* *Aerospace*

**Abstract** New generation (new-gen) 7xxx aluminium alloys offer benefits in improved toughness and corrosion resistance. However, they can be more susceptible to Environmentally Assisted Cracking (EAC) in humid air. EAC initiation to sustained propagation can be refined into the mechanistically distinct stages of incubation, development of pre-cursors, proto-crack formation, short crack growth, and long crack growth. Incubation describes the stage whereby the original material surface evolves on exposure to the environment under load. Pre-cursors, describe the features that result from incubation, which can include oxidation or corrosion sites that create a localised environment chemistry, stress concentration, and modification to the material surface/sub-surface microstructure. It is from these pre-cursor features that proto-cracks form. Indeed, pre-cursors are necessary to make the transition from a 'feature' to an EAC crack. Proto-cracks are the very initial stage of cracking and are directly linked to the ability to nucleate EAC cracks from the pre-cursor features. Once an EAC crack is formed, the cracks will first grow as microstructurally short cracks, with distinct behaviour, before achieving sustained propagation.

In this work, a high-resolution optical scaning system has been develped, capable of in-situ monitoring the surface of constant displacement (4-point bend) tests. This system was coupled with global digital image correlation (DIC) to automatically monitor and compare the incubation, initiation, and short crack growth behaviour of 7xxx alloys (AA7085 T7651 and AA7449 T7651) exposed in humid air. This has allowed for the unambiguous detection of EAC initiation sites and the ability to monitor the growth behaviour of short cracks in relation to the local microstructure. Subsequent site-specific fractography, combined with high–resolution SEM-EDX, has revealed the nature of the dominant initiation sites. FE modelling validated by X-ray CT measurements has also been used to determine the appropriate stress intensity (K) for short cracks that can be estimated from monitoring their surface length in 4 point bending. This has brought new insights into the factors affecting crack growth behaviour in the short crack regime when observed from initiation compared to the behaviour observed for the arrest of long cracks in (DCB) fixed displacement tests. This has led us to re-define the meaning of $K_{EAC}$ threshold in these materials.

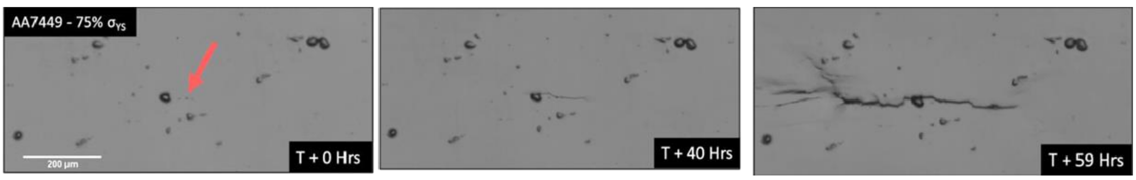


***Figure 1*** *– Time-lapse optical images showing the initiation of an EAC crack in AA7449 T7651 loaded to 75% of yield strength at 70 °C and 50 %RH.*

# #372 Damage prediction of ferritic pipeline using Artificial Neural Network

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*GTN* *Pipeline* *ANN*

**Abstract** The purpose of using the GTN model for complex geometries such as pipelines is to handle the constraint effect. In the case of using traditional data in fracture mechanics, we will face the issue of transferability. In other words, the fracture mechanical properties, determined by measurements of specimens, are valid for certain stress-state conditions, mainly for plain strain states. However, in the case of real complex geometries, we have stress triaxiality and we can be far from the stress-strain condition of the specimens, so the applicability of the measured values is limited. For this reason and others, instead of using the J-R curve or $J_{Ic}$, we can use a geometry and stress-strain field independent local GTN model to predict the failure of the pipeline. The main important point is that we need to find reliable GTN parameters, so to reduce the time consumed during the determination of reliable GTN parameters for the pipeline, the artificial neural network ( ANN) was integrated in this study, and the results show that we can reduce the time of GTN parameter identification from thirty days to six hours.

# #373 Challenges of materials and corrosion management: Stress corrosion cracking (scc) & hydrogen embrittlement mechanisms & gaping in our understanding of the subject

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*Keywords:* SCC, EAC, Inclusions, Crack Initiation Process, $H_2S$ and Hydrogen Embrittlement.

**Abstract** An essential step in materials degradation is the determination of the failure mechanism. For example, stress, metallurgical (microstructure), or environment-assisted cracking (EAC), helps the determination of the fundamental cause of failure and recommendation on proper measures to prevent failure recurrence. In this context, environment-assisted cracking, or environmentally induced failure, is a form of corrosion that produces a failure/fracture in alloys with minimal corrosion. As for example, environmentally assisted cracks in linepipe steels are initiated either because of stresses in combination with environmental effects, as in SCC, or because of trapped hydrogen in the steel or HIC. To understand better the mechanism of the crack initiation process, key metallurgical and environmental elements that can affect the cracking phenomena were investigated and reviewed. The complexity of both cracking phenomena results from the dependence of SCC and HIC on multiple metallurgical, mechanical, and environmental parameters that may all influence both crack initiation and propagation.

Cracking of linepipe steels is analyzed critically, with particular attention to the *crack initiation process*. The paper is divided into two parts: (i) stress corrosion cracking (SCC); and (ii) hydrogen-induced cracking (HIC) also referred to as hydrogen embrittlement (HE). Many non-metallic particles and stringers, and the anomalous microstructures are excellent trapping sites for diffusing H atoms and the initiation and growth of cracking. Figures 1 and 2.

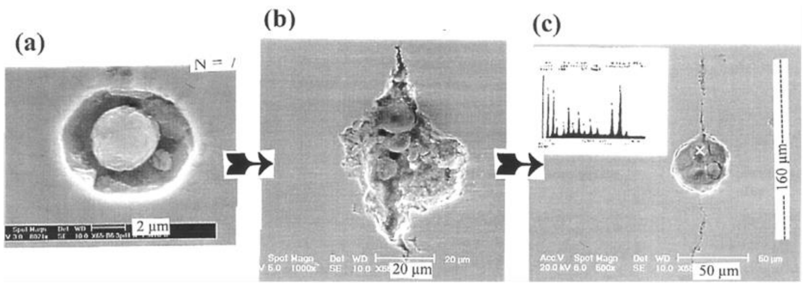


*Fig. 1. **(a)** Development of pits from inclusions; **(b)** nucleation of cracks at pits; and **(c)** EDS spectrum reveals the elements: Na, Mg, Al, Si, P, S, and Ca, etc. Sample of Steel X65 and was tested in NS4 solution saturated with $CO_2$ at $\sigma_{max}$=70% SMYS.*

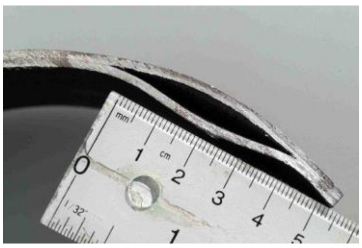

*Fig. 2a. Hydrogen Blister in NPS 6 Sour Gas Pipeline*

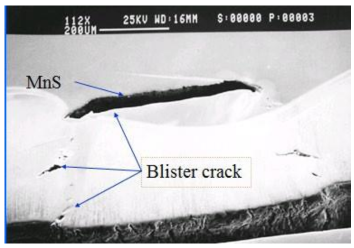


*Fig. 2b. Blister (Laboratory Test) in X-65 linepipe Steel.*

# #374 SEM investigation and uniaxial compression of flexible graphite

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*Flexible graphite* *SEM* *Compression*

**Abstract**

The mechanical response of flexible graphite sheets is yet to be fully investigated and understood as today experimental data are only available for uniaxial tension static tests in the plane of the sheet and uniaxial static compression in the out-of-plane direction. This information is critical for specific applications such as beam absorber material in the CERN's Large Hadron Collider (LHC) beam dump. No constitutive model describing the plastic behavior and available for FE modeling has been proposed yet. In this work, pressure-dependent plasticity models available in Abaqus and LS-Dyna have been reviewed, and a first discrimination thereof is given based on the observation of the uniaxial compression stress-strain curves. On one side, some properties are very similar to crushable foams, such as the nearly zero plastic transverse deformation and the large difference between the tension and compression strengths; on the other side, analogies with compressed powders are noticeable, starting from the production process based on particles compaction and cohesive interaction. To understand the material micro-structure, give a quantitative description of its properties and further support the choice of a material model suitable for FE software, SEM imaging was also found to give extremely useful insights.

# #375 Atomistic and Mesoscale Simulation of Crack-Dislocation Interactions

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*Crack-tip plasticity* *Atomistic Simulation* *Multiscale Simulation*

**Abstract** The fracture toughness of a material is critically influenced by its microstructure. Understanding the underlying crack-microstructure interactions is therefore necessary to model and predict materials failure. In order to gain insight into the interactions of dislocations with the crack-tip, large scale atomistic simulations are carried out.

While the interaction of cracks with long ranging stress fields of dislocations can in principle be studied with mesoscale methods, the direct interaction of dislocations with the crack-tip can only be studied systematically with atomistic simulations. Here we present results of the interaction of individual dislocations with a static crack from large scale atomistic simulations. FCC-Nickel is chosen as model material, as it has the same active slip systems as silicon, for which extensive experimental studies exist, in particular for the (110)[001] crack system ((crack plane)[crack front]). Due to the symmetry of this crack system only three different classes of dislocations need to be studied. Besides cutting of the dislocation through the crack front, local crack front reorientation due to shielding/anti-shielding from dislocations and cross slip of screw-oriented dislocation segments, stimulated emission, in which the intersection of the crack with a dislocation leads to the emission of new dislocations, is observed. The interplay between these mechanisms can lead to complex dislocation processes, including the formation of spiral sources. The results are discussed within the framework of resolved shear stresses in the near field of the crack-tip.

Furthermore they are used to adjust a discrete-dislocations-dynamics model that in return allows for larger simulations with several dislocations spanning longer timeframes.

# #379 Mechanical behavior and fracture of closed-cell structures with shape variation: Numerical analysis

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*Closed Cells* *Finite-element Method* *Morphology*

**Abstract** Some inclusions in matrices of particle-reinforced composites can be geometrically described using regular polyhedra. Usually, such microstructures have some degree of randomness. Effective properties of such composites are determined primarily by the properties as well as volume fractions and distribution of constituents, but it is assumed that at microscale shape of particles also has an impact. So, numerical simulations of representative volume elements (RVEs) are used for the detailed study of the microstructure of heterogeneous media and its effect on mechanical behaviour.

In this study, geometric models of structures with disjoint inclusions of tetrahedral, cubic, octahedral, hexagonal, icosahedral and spherical shapes were investigated, taking into account differences in their sizes and the character of distribution. These shapes were chosen based on the increasing number of angles, from the most acute-angled polyhedra to a sphere. Comparison of morphological characteristics for these structures was carried out using multipoint correlation functions, the values of which were obtained with the integration method. Elastic properties and internal stress distributions in RVEs of the studied composites are estimated numerically, using finite-element analysis. Models of the fracture of porous structures were also developed.

It was concluded that the shape of inclusions affected the isotropy of effective properties of the studied RVEs. Besides, additional stress concentrators formed near sharp-angled inclusions can influence the initiation of fracture processes. The effect of inclusions with unusually large sizes in the structures on anisotropy of macroscopic elastic properties was assessed. A link between mechanical properties and statistical characteristics was investigated. A degree of correlation between morphological parameters and elastic properties was established. The proposed relations between the characteristics of the internal structure, on the one hand, and mechanical behavior and properties of the composites, on the other, can be used, for example, to develop the machine-learning algorithms for estimation of the mechanical behavior of structures from the data on their micromorphology.

# #380 Mechanical behavior of two-phase auxetic structures: effect of properties contrast

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*Mechanical Metamaterials* *Negative Poisson's Ratio* *Auxetic Structures*

**Abstract** Metamaterials are materials that are specially engineered to have properties unattainable in natural or traditional manufactured materials. One of the most studied properties in mechanical metamaterials is their negative Poisson's ratio. It can be achieved in lattice structures by means of designed architecture of their unit-cell geometry. Additive manufacturing allows production of complex periodic lattice structures with required features consisting of regular repeating elements. Unique deformation mechanisms can provide the auxetic structures with excellent mechanical properties, such as energy-absorption capacity, high levels of shear modulus, specific strength and indentation resistance, etc. This underpins their broad application potential for lightweight structures, impact protection, biomedical devices, sensors and others. One of the most common auxetic materials is formed using a reentrant/concave hexagonal honeycomb unit cell. Its auxetic behavior is preserved independent of orientation of the unit cell (vertical or horizontal).

This study is focused on the numerical analysis of mechanical behavior of a two-phase auxetic lattice structure filled with polymer. Numerical modelling was performed using the finite-element method. Mechanical behavior of the auxetic lattice was examined for different orientations and geometry of unit cells. Stress concentrators and possible fracture initiation zones were located. Comparison of mechanical behavior and properties of the porous lattice and the filled auxetic structure was performed. The influence of the filler on the level of auxeticity of the whole structure was investigated. Application of the results obtained in numerical modelling for development of biomedical devices is discussed.

# #381 The synergy of hydrogen embrittlement mechanisms in steel and metals: HELP + HEDE model

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*Hydrogen embrittlement* *Plasticity/decohesion* *Steel*

**Abstract** The coexistence and simultaneous activity of the hydrogen-enhanced localized plasticity (HELP) and hydrogen-enhanced decohesion (HEDE) mechanisms of hydrogen embrittlement (HE) was fully experimentally confirmed for the first time in low carbon structural steel, grade 20 - St.20 (or 20G, equivalent to UNS G10200, AISI 1020) in situ enriched by hydrogen, and not only through simulation or modeling [1]. The proposed HELP + HEDE model of HE in steels is based on the correlation of macro-, micro-, and nano-mechanical properties to SEM microscopy fractography analysis of fracture modes in the presence of simultaneous action in a cooperative manner of the HELP and HEDE micro-mechanisms of HE depending on the local concentration of hydrogen and the microstructural characteristics of the investigated steel [2]. Also, the effect of hydrogen on the mechanical properties and ductile to brittle fracture transition resulting from the concurrent and synergistic (HELP + HEDE model) or a competing action of HELP and HEDE mechanisms of HE is discussed [3,4]. The proposed HELP + HEDE model for the synergistic action of HE mechanism by Djukic et al. [1-4] is recently widely accepted to be operative in various metallic materials including steels, iron, nickel alloy, and aluminum alloys. The particular emphasis is given to the proposal of the novel and unified HELP + HEDE model for HE based on the specific microstructural mapping of the dominant HE mechanisms with implications on the fracture process and resulting hydrogen-assisted fracture modes in steels. The most contemporary experimental and modeling approaches, the current state of the art, and future challenges in the investigation of the coexistence and synergistic interplay of HE mechanisms in different grades of steel and metals are analyzed and critically discussed.

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# #382 Analogy between crack initiation due to dynamic pulse load and mass-spring system failure: fracture delay effect

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*Fracture delay* *Incubation time* *Linear oscillator*

**Abstract** The incubation time fracture criterion (ITFC) was used to analytically investigate fracture delay – a fundamental dynamic fracture effect observed in experiments where short pulse loads are applied. The effect can be shortly described in the following way: the material failure may occur after local stresses reached their maximum values, meaning that the fracture takes place at a drop stage of the load and thus delay is present. In this particular work we address dynamic crack initiation due to pulse load applied to the crack faces using corresponding analytical solutions for the transient stress fields in the crack tip vicinity showing that the ITFC is able to capture the fracture delay effect. In addition to this we managed to construct an interesting analogy between the crack initiation and an oscillator failure when short pulse loads are applied. This has been done formally, however it shows a fundamental link between two seemingly different phenomena and proves that cracks can exhibit inertial behavior even at the onset stage.

# #384 Growth of multiple cracks grouped into different arrays

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*Crack growth* *Crack interaction* *Mechanochemical model*

***Abstract.*** Crack propagation is a highly complicated phenomenon, especially in the presence of aggressive environment, involving multiple processes from nano- to macro-scales. Acting simultaneously, tensile stress and aggressive media influence each other and may result in stress corrosion cracking (SCC). The present work considers this problem in macro- scale, within the frame-work of 2D linear fracture mechanics. Growth of multiple rectilinear cracks in an infinite isotropic plane, grouped into different arrays, under the uniaxial tension normal to the cracks surfaces is studied. Deviation from the rectilinear path is neglected. The mechanochemical model of crack growth rate presented in [2, 3] for type 304 austenitic stainless steel submerged in high-temperature water is utilized. However, this model may be applied to various combinations of the material and corrosive environment. Estimation of the stresses in the cracked plane is performed by the approximate numerical method introduced in [1]; the key simplification accepted there is that only the mean (uniformly distributed) part of the loading induced on the edges of one crack by the others is taken into account, which makes the calculations cheaper. Graphical dependencies of mode I stress intensity factors on the relations between the cracks lengths and the distances between them are also presented.

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# #385 Finite Element implementation of the Coupled Criterion based on the Principle of Minimum Total Energy subjected to a Stress Condition to predict crack onset and growth

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*Finite Fracture Mechanics* *Stress and Energy Criterion* *PMTE-SC*

**Abstract** A numerical procedure predicting crack onset and growth in brittle materials is developed using the Coupled Criterion of Finite Fracture Mechanics (CCFFM) [1] which assumes crack advances by finite steps and requires both stress and energy conditions are fulfilled. Crack advances are bridged by a continuous distribution of springs, similarly to the Linear Elastic-(perfectly) Brittle Interface Model (LEBIM) [2] combined with CCFFM [3]. The Principle of Minimum Total Energy subjected to a Stress Condition (PMTE-SC) [4,5] is implemented by a load stepping algorithm, minimizing the total energy change due to a crack advance allowed by the stress criterion. The PMTE-SC appears to be more versatile than the classical formulation of CCFFM using stress and energy criterion curves, providing a tool to solve complex problems of industrial relevance.

A simple implementation of PMTE-SC in FEM code Abaqus considers cracks geometrically modelled as topological discontinuities in the finite element mesh, with cracks introduced explicitly during the discretization of the domain, the crack faces coinciding with the element edges. Several numerical examples are solved, showing that accurate predictions are obtained for short cracks, holes and notches.

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# #388 An in-situ analysis of the influence of residual stresses on the fatigue damage evolution in a martensitic spring steel

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*Short fatigue crack propagation* *Martensitic steel* *Residual stresses*

**Abstract** The underlying mechanisms for short fatigue crack propagation in a martensitic spring steel are still not fully understood, especially if the effect of residual stresses is relevant and, hence, must be taken into account. This study aims at an improvement of the knowledge base by investigating the short fatigue crack propagation in a martensitic spring steel by means of a miniaturised testing device enabling in-situ fatigue tests in a confocal laser microscope. Detailed electron back-scattered diffraction analyses were conducted to link the short crack propagation behaviour with the local crystallographic orientation. The results obtained indicate that fatigue damage evolution is characterized by an early formation of slip bands leading to short crack initiation at the surface. Most of those slip bands and correspondingly most of the short fatigue cracks initiate at or close to prior austenite grain boundaries. A correlation was found to exist between the number of slip bands and short fatigue cracks on the one hand and both the stress amplitude and the number of loading cycles on the other hand. The subsequent early crack propagation occurred primarily in an intergranular manner along the prior austenite grain boundaries. A detailed analysis of the local crack propagation rate in correlation with the local microstructure revealed an oscillating crack propagation rate because of a strong interaction of the fatigue crack with microstructural barriers. Especially, the prior austenite grain boundaries seem to act as obstacles to short crack propagation. To determine the effect of residual stresses, samples with prior shot peening treatments are tested as well. The residual stress value on the surface of the shot peened sample were determined before and after the fatigue testing by means of X-ray diffraction. The shot-peened samples also show an early formation of slip bands and short cracks. Furthermore, the results document similar short crack propagation mechanisms. However, the shot-peening treatment leads to a higher fatigue resistance indicating a transition to a preferential internal crack initiation of the fatal crack.

# #391 Effect of heat treatment on fatigue crack growth performance of AlSi10Mg aluminium alloy submitted to LPBF

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*Fatigue crack growth* *Laser powder bed fusion* *Heat treatment*

**Abstract** Aluminium alloys are used in several industries, namely in the aeronautic and aerospace industries due to its good corrosion resistance and good mechanical strength/weight ratio. The optimization of fatigue crack growth resistance in AlSi10Mg aluminium alloy is a vital issue for safety-relevant components, which are designed to work for a large number of loading cycles before periodic inspections. An unclear subject is the benefit effect of heat treatments in the fatigue crack growth of AlSi10Mg aluminium alloy submitted to LPBF. Therefore, the current work purposes to analyze the effect of a heat treatment at low temperature on fatigue crack growth of AlSi10Mg aluminium alloy submitted to LPBF. Fatigue crack growth tests in Mode I are performed in compact tensions (CT) specimens at two different conditions: as-build and heat treated at low temperature. The possible befits effect is analyzed, as well as, the effect of the average stress on the fatigue crack growth. The crack closure parameter is studied in order to analyze the different fatigue crack growth behaviors, as well as the microstructure, hardness, and fractography. From this work, the main achievement is the microstructural transformations associated with the standard heat treatments (T6 and stress relived at 300 ºC) are unfavorable to fatigue strength in the AlSi10Mg aluminium alloy submitted to LPBF, while the non-standard stress relief heat treatment, performed at a lower temperature, cause a benefic effect in the fatigue crack growth resistance.

# #392 Effect of the direction of printing on the fracture of additively manufactured Duplex stainless steel

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*Additive Manufacturing* *Fracture* *Duplex stainless steel*

**Abstract** Nowadays, mechanical properties of metals produced by additive manufacturing can meet or even exceed those of their traditionally produced counterparts [1]. Recent studies on materials such as polycarbonate [2] have shown that materials produced by additive manufacturing can present a nearly isotropic elastic behavior coupled with anisotropic fracture behavior, caused by their specific microstructure. The current study aims to investigate if such an effect also occurs in a Duplex stainless steel produced by Directed Energy Deposition (DED).

Dense volumes have been built such that the printed tracks are all mutually parallel. From these volumes, compact tension (CT) fracture specimens were machined, with the notch being either parallel or perpendicular to the layers of the print. Each specimen has been pre-cracked in cyclic fatigue. The fracture behavior of both types of specimens were then studied through a quasi-static tensile rupture test.

The two configurations showed noticeably different behaviors (Figure 1). In the parallel case, the crack propagated in the plane of the machined notch. In the second case, the crack deviated from the straight path, and the recorded maximum load was significantly larger. Metallographic analysis of the bulk material and SEM observation of the fracture surfaces were performed to evaluate the effect of the building strategy on fracture. These observations reveal a highly oriented micro-structure which dictates the fracture behavior.

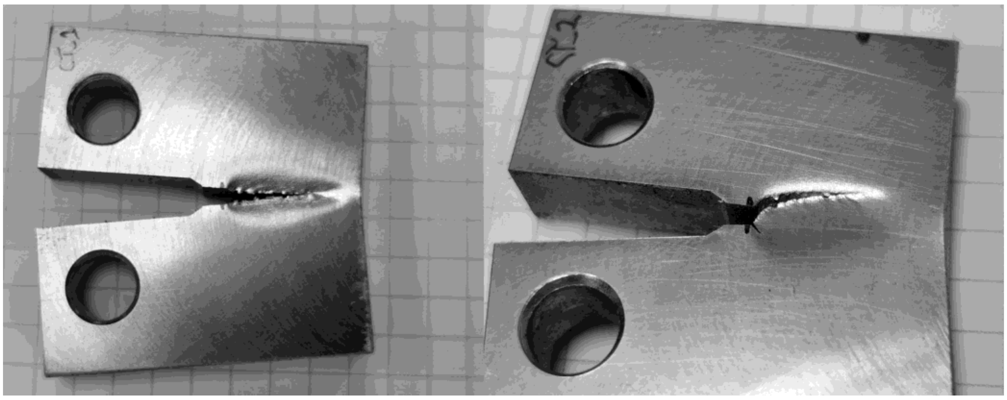

***Figure 1** – Post-rupture images of CT specimens machined with the notch parallel (left) or perpendicular (right) to the printed tracks.*

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# #393 Nonlinear eigenvalue problems resulting from nonlinear fracture mechanics and damage mechanics boundary value problems

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*Nonlinear eigenvalue problems* | *Eigenspectra and eigenfunctions* | *Mode III, Mode I, Mode II and Mixed Mode*

**Abstract** It is well-known that the stress - strain state in the vicinity of the crack tip in power law materials can be obtained by the eigenfunction method. Thus, the boundary value problems result in nonlinear eigenvalue problems. The overarching objective of the study is to obtain analytical presentation of the eigenspectra and eigenfunctions corresponding to the stress-strain state in the vicinity of the crack tip under antiplane shear, Mode I and Mixed Mode loaing in materials with power law constitutive equations. The boundary value problems for mode III cracks and notches in power-law materials are classical problems for nonlinear fracture mechanics. Despite an intense scrutiny carried out in the previous century the antiplane shear crack is still attracting the interests of researchers. Rice's analytical solution for the mode III crack problem in a power-law hardening material [1] is well-known. The problem can be tackled by hodograph transformation. M. Anheuser and D. Gross [2] found singular fields and higher order fields near a sharp notch in a power-law material under longitudinal shear by the perturbation method. They reduced the problem to the nonlinear eigenvalue problem and used the artificial small parameter which was the difference between the eigenvalue of the "undisturbed" linear problem and the eigenvalue corresponding to the nonlinear problem. Using this technique, the whole set of eigenvalues was analytically determined. However, in the best of the authors' knowledge, the whole set of eigenfunctions has not been obtained yet. The analytical study of the whole set of eigenfunctions has received far less attention so far. In the present study the exact solution for the whole set of eigenfunctions is found. Relevant, exact expressions for mode III stress field corresponding to the whole spectrum of eigenvalues are obtained. The exact solution is derived by two approaches. The first approach is based on the classical hodograph transformation whereas the second one relies on the artificial small parameter and on the perturbation theory. It is shown that it is possible to reduce the series obtain by the perturbation technique to the analytical expression.

The work is supported by the Russian Science Foundation (project 21-11-00346).

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# #395 Numerical investigation of self-similar crack propagation during DCB test: A comparison between non-elastic behaviours of bonded interfaces

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*Double Cantilever Beam* *Self-similar crack propagation* *Non-elastic interface*

**Abstract** Double Cantilever Beam (DCB) test allows to focus on the crack propagation in mode I along the bonded interface for different kind of structural assemblies [1]. The theoretical framework for the data reduction method of current standards assume linear or nonlinear material behaviour but considering no time or strain rate dependence [1]. Thus, standards post-treatment could be questionable for adhesives exhibiting rate-dependent and non-elastic behaviour (*i.e.* viscosity, plasticity) and/or for different loading conditions (*i.e.* creep or relaxation). In these cases, the complex behaviour of the interface should drastically modify the energy balance considerations which leads to the critical Strain Energy Release Rate evaluation.

In this work, the study of self-similar crack propagation along viscous or viscoplastic interface is investigated from numerical virtual testing. Hence, stable regime (steady-state) of crack propagation is intentionally assumed. Viscous and viscoplastic effects of the interface behaviour can be considered through different rheological models. The efficient model is based on a finite difference scheme combined with Eulerian approach [2]. It allows to evaluate the stress / strain distribution along the bondline for different crack propagation rates. From these evaluations, critical moments leading to crack propagation can be computed for different DCB configurations as shown in Figure 1 for viscoelastic and elastoplastic interface behaviour. These results (assuming a constant breaking criterion) prove a clear influence of the bonded interface behaviour on the mechanical fields which drive to crack propagation. Thus, the energy balance can be computed and compared with standard analysis techniques, in order to evaluate the contribution of different mechanims through the interface behaviour. These works could be complemented by experimental characterisation. Master curves concerning the energy balance as function of crack propagation rate could be extracted and compared with numerical predictions to describe the debonding of assemblies in mode I for durability conditions.

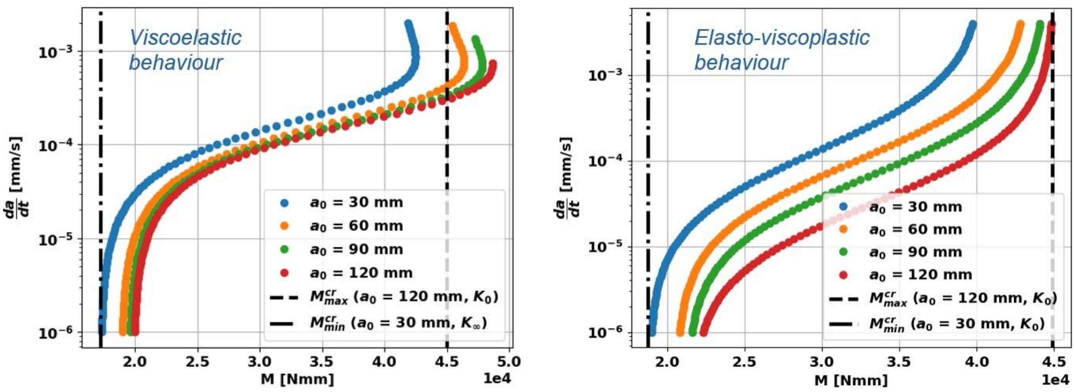


***Figure 1** – Crack propagation rate as function of the critical applied moment*

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# #399 Measurement of Elastic Stresses and Dissipated Energies at Cracks – Is the Lock-In-Evaluation an Appropriate Tool?

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*Crack* *Thermography* *Dissipated Energy*

**Abstract** Lock-In-Thermography is a common technique for determining local stresses in cyclic-loaded components. This so-called Thermographic Stress Analysis (TSA) uses the cyclic change of the temperature, which results from the elastic stress by the thermoelastic effect. To reduce the noise in the measured temperature signal, the evaluation is performed using a Discrete Fourier Transformation. Brémond [1] and Sakagami [2] have shown that in case of plastic deformation a second mode, coupled with the double loading frequency appears in the DFT-evaluation. This part is known as the so-called D-Mode and is assigned to dissipative energies. Investigations of Bär et al. [3] on unnotched flat specimens have shown that there are discrepancies in the elastic and dissipative temperature changes between the Lock-In evaluation and an analytical evaluation, showing that the Lock-In evaluation is just qualitatively but not quantitatively correct. The usage of higher modes in the DFT evaluation leads to a correct description of the temperature changes, but the deconvolution into an elastic and a dissipative part is not possible.

In this study a detailed study of the temperature changes in front of a crack and along the crack flanks in a high alloyed steel was undertaken. A determination of temperature-force hysteresis based on a frequency synthesis of the different modes of the Lock-In evaluation can be carried out on precracked specimen. The comparison with temperature-force hysteresis of an analytical evaluation showed very good accordance. The description of the hysteresis by using only the E- and D-Mode leads only to an approximate match. The compensation of the thermoelastic effect with force proportional local stress changes uncovers the dissipative temperature behavior at the crack. On basis of the determined local stress changes the stress distribution in front of the crack was determined, showing a good accordance with the theoretic values. A simple isolation of the stress change or rather the dissipative temperature changes out of the E Mode and D-Mode is not generally possible. Crack opening and compressive loads cause thermoelastic temperature changes, which affect the E-Mode as well as the D-Mode and higher harmonic modes.

[1] Brémond, P., New developments in Thermo Elastic Stress Analysis by Infrared Thermography. In: IV Conferencia Panamericana de END 2007.

[2] Sakagami, T.; Kubo, S.; Tamura, E.; Nishimura, T.; Identification of plastic-zone based on double frequency lock-in thermographic temperature measurement, In: ICF11 Italy, 2005.

[3] Bär, J.; L. Seilnacht, L.; Urbanek, R.; Determination of dissipated energies during fatigue tests on Copper and AA7475 with Infrared Thermography, Procedia Structural Integrity 17 (2019) 308-315, DOI: 10.1016/j.prostr.2019.08.041

# #400 Experimental determination of a Kitagawa-Takahashi diagram of the aluminum alloy AA2024 using potential drop measurements

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*fatigue* *Potential drop measurement* *Kitagawa-Takahashi diagram*

**Abstract** The fatigue limit of metallic materials is a function of the defect size. This relationship is normally shown in form of a Kitagawa-Takahashi (hereafter KT-) diagram. The El-Haddad approach [1] is often used to determine the KT diagram. A weak point of this approach is that the KT diagram is given by the equation and especially in the medium range of the diagram this approach is not conservative. The approach suggested by Chapetti [2] is less conservative but also here a check of the course should be done with experimental values. However, this experimental verification is laborious and is usually performed with a staircase method that requires a large number of samples with identical notches.

In this work a new method will be presented that allows a verification of the KT-diagram with a small number of specimens and only a few experiments. The notches were introduced into the flat specimens of AA2024 T351 using an Engraving Laser. With this method, sharp notches can be introduced into specimens with minimal effort. By traversing the notch several times, the depth of the notches can be varied very well. For the potential drop measurements copper-wires are laser-welded onto the surface below and above the notch.

The experiments were carried out with load blocks where the load is increased from block to block. If a crack occurs within the load block, it can be detected via the potential drop measurement. A crack arrest could also be detected very well with the Potential drop measurement. This method allows the determination of the course of the KT-diagram at a defined notch depth ideally with a single specimen. By using several specimens with different notch depths, the course of the curve in the KT diagram can thus be determined very accurately with a small number of specimens.

[1] El Haddad, M. H. ; Topper, T. H.; Smith, K. N.: Prediction of non propagating cracks. Engineering Fracture Mechanics 11, (1979) 573–584. DOI: 10.1016/0013- 7944(79)90081-X

[2] Chapetti M. Fatigue propagation threshold of short cracks under constant amplitude loading. International Journal of Fatigue 2003;25:1319–26, DOI:10.1016/S0142-1123(03)00065-3

# #403 Application of Miniaturized Brazilian Disc Tests for the Determination of High-Temperature Strength of Ceramic Filter Materials

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*brazilian disc test* *material parameter identification* *ceramic filter materials*

**Abstract** Open-cell ceramic foams are used for the filtration of molten metals with the aim of improving the final quality of cast products. Among the various filter materials that have been developed and studied, carbon-bonded alumina (C-$Al_2O_3$) have drawn the most attention due to their superior properties. However, to decrease the hazardous effects of coal tar pitch binder Carbores℗, environmentally friendly C-$Al_2O_3$ based Tannin and Lactose binder systems have recently received much attention. A systematic characterization and assessment of their properties are required to replace the currently used binder systems. Considering the service temperature of these filter materials, a test method performed at elevated temperatures is needed. Due to the thermal and mechanical loads applied on these filters, the fracture strength of the bulk material is a key indicator of their structural integrity. The Brazilian Disc Test (BDT) is a method of determining fracture mechanical properties of brittle materials with indirect tensile stresses, formed perpendicular to the loading direction. Due to the porous structure of the materials under investigation, the contact points between the specimen and the loading device are susceptible to major deformation and damage. The aim of this study is on the one hand to define the geometry at the contact points in such a way that valid fracture toughness values can be determined even for small specimen dimensions. For this purpose, the deformations on the surface of the specimens are determined at room temperature using digital image correlation during the test. On the other hand, the optimized test geometry is used to perform hightemperature tests on specimens with different binder systems to evaluate their strength and fracture toughness. This evaluation is performed with accompanying finite element analyses using cohesive models. The required parameters of these models are identified using methods of nonlinear optimization

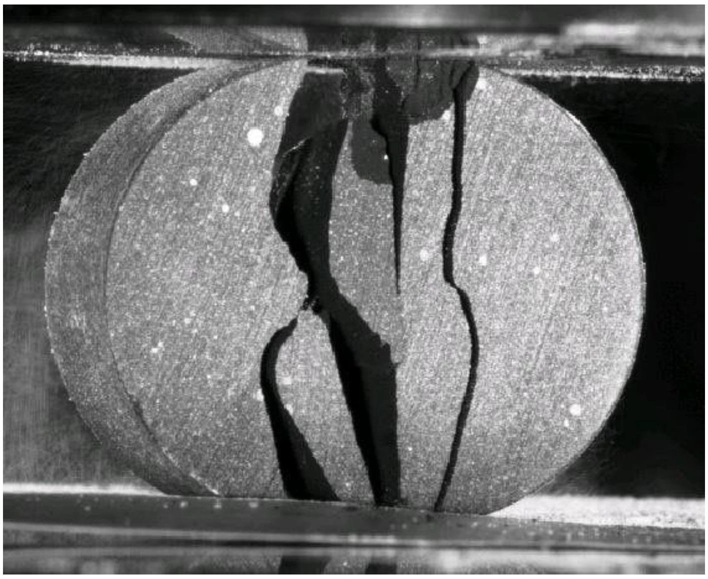

***Figure 1 -*** *View of a BDT specimen after failure*

# #404 Numerical simulation of EFP impact on armored steel plate

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*EFP* *numerical simulation* *impact*

**Abstract** An explosively formed penetrator (EFP) or an explosively formed projectile is generated, as its name suggests, by detonating a high-explosive charge initially in contact with a high-density metal plate. By detonation, the metal plate takes the shape of a slug or rod which is accelerated toward target and can reach a 2.000 – 3.000 m/s speed. Although the perforating depth is lower than in the case of a shaped charge, the main advantages of an EFP are the diameter of the perforation and the fact that EFP remains intact and is therefore able to penetrate armor at a long range. Given this, it can be used as a first stage in a new tandem charge concept formed of two stages: explosively formed projectile and thermobaric.

In order to design this first stage, the perforating effect on a 10 mm thick armor plate was studied using the finite element method (FEM) implemented in LS-Dyna software. In Figure 1 it can be observed the physical configuration of the numerical simulation model. By detonation of a RDX charge, the slug is formed and is accelerated by the air to a steel plate initially at 80 mm from it. A structured mesh with hexahedral elements for all parts (RDX, EFP, armor plate and air) for the domain discretisation was used. For RDX detonation modeling, the number 8 material model (*MAT_HIGH_EXPLOSIVE_BURN) was used to which was added a Jones-Wilkins-Lee equation of state (*EOS_JWL). *MAT_PLASTIC_KINEMATIC, the number 3 material model, for simulating the armor plate and for air and LS-Dyna material model number 9 (*MAT_NULL) with a polynomial equation of state (*EOS_LINEAR_POLYNOMIAL) were used. Since the explosion and propagation of the shock wave are performed using an Euler method and the EFP and armor plate are modeled using the Lagrange model, the connection between them is made using the *CONSTRAINED_LAGRANGE_IN_SOLID command.

For model validation, experimental tests in firing rage were performed, the results obtained can be observed also in Figure 1.

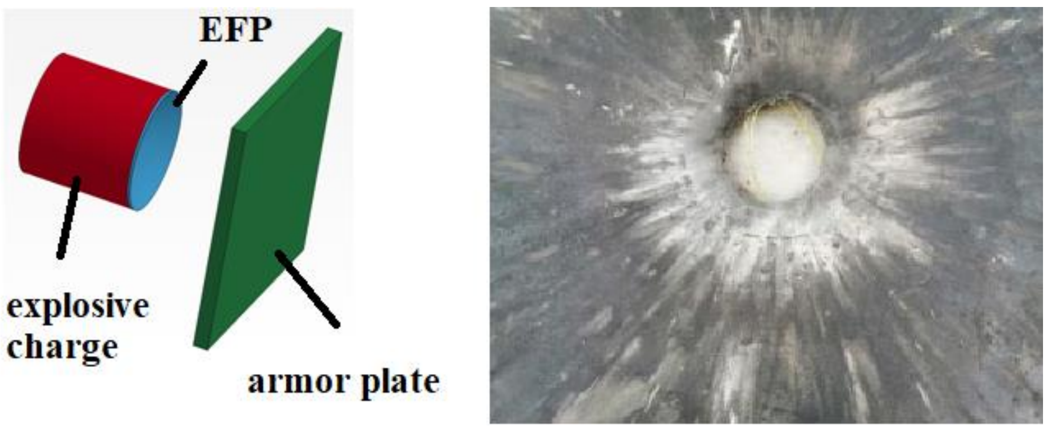


***Figure 1** – Simulated configuration and experimental armor plate*

# #405 Accuracy of models of concrete in square and rectangular columns confined with FRP with different failure strain proposals

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*Failure Strain* *FRP sheets* *Confinement*

**Abstract** Confinement with externally applied fiber reinforced polymers (FRP), such as carbon, glass and aramid-based composites, results in notorious improvement of ductility and strength. Several constitutive models, regarding stress–strain relationship, have been proposed. However, few models exist for square and rectangular columns confined with FRP when compared with the number of models for circular concrete columns, and even fewer models satisfactorily predict the failure strain of FRP. In this paper, the accuracy of existing models for the prediction of the failure strain of the FRP is evaluated. Comparison of analytical results with experimental test results of concrete columns reported in literature is presented, focusing different parameters such as strength, maximum strain and strain energy density.

***Figure 1 -*** *Failure of GFRP on a reinforced concrete square column*

# #406 Hydrogen and hydrides impact on zirconium based alloys

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*Zirconium alloys* *Hydrogen embrittlement* *Neutron radiography*

**Abstract** Zirconium alloys are used in nuclear light water reactors as structural material or as cladding for nuclear fuel rods due to the low neutron absorption, good corrosion resistance combined with an excellent mechanical strength. During operation in the nuclear power plant, zirconium cladding rods are immersed in water, where they slowly corrode generating hydrogen as side product. Part of the hydrogen generated is picked-up by the cladding, where it remains trapped into the metal lattice.

Spent nuclear fuel needs to be safely stored for decades, first in the spent fuel cooling pool and later, where applicable in an intermediate dry storage facility. The mechanical integrity of the fuel cladding must be ensured in all phases of their life cycle, including during interim dry storage, handling and transportation and its final disposal. As long-term dry storage of spent nuclear fuel becomes increasingly significant, it is crucial to achieve a complete understanding of the hydrogen embrittlement (HE) mechanisms active in zirconium cladding materials in conditions relevant for the nuclear fuel clad application.

Due to the slow decreasing decay heat of the fuel, the cladding tends to cool down over decades. When the terminal solid solubility of hydrogen in zirconium alloys is reached, hydrogen precipitates into a brittle zirconium hydrides phase. The detrimental effects of hydride precipitates on the mechanical properties of the cladding have been well documented and is of primary concern during the handling and transportation of spent nuclear fuel. The overall hydrogen embrittlement of the zirconium cladding alloys is dependent on the amount of hydrides, their morphology and orientation, as well as the total hydrogen concentration in the cladding material. In addition, special mechanisms can take place in localized areas of the cladding, like delayed hydride cracking (DHC) in presence of stress-risers, or hydrogen- enhanced localized plasticity (HELP) in areas where the majority of hydrogen is expected in solid solution.

In this work, the influence of hydrides accumulation and its distribution along the radial direction of zirconium cladding tubes has been studied under controlled stresses, cooling conditions and with different hydrogen concentrations of in- and active zirconium claddings. Experimental results obtained were compared with FEM simulations and will be presented. High-resolution neutron imaging of inactive and highly radioactive cladding rods provides quantitative assessment of hydrogen content along the rod's wall thickness.

Moreover, thermo-mechanical investigations of hydrogen charged Zry-2 and Zry-4 through compression and three-point bending were performed. Hydride reorientation in the high stress regions were observed by scanning electron microscopy and hot gas vacuum extraction was used to check the overall hydrogen concentration of the sample. The hydride distribution along the wall thickness was evaluated by high-resolution neutron radiography imaging. Reorientation of hydrides is strongly influenced by hoop stress in the zirconium cladding tubes and the results will be presented.

More specifically, three-point bending tests were performed with Zry-2 arc-shaped specimens to investigate various effects on radial DHC, such as hydrogen concentration, temperature, an inner liner and irradiation damage. Furthermore, the influence of hydrogen on the mechanical properties of Zry-4 at elevated temperature have been evaluated by three-point bending flexural tests, micro-hardness test, and strain-rate sensitivity test at temperatures between 25°C and 400°C in the presence of up to 700 wppm of hydrogen addition. Besides the well-known hydride-induced hardening effect, results indicate the presence of a small but significant hydrogen-induced softening effect in conditions where the majority of hydrogen is expected to be in solid solution. This effect is compatible with the HELP model, according to which solid solution hydrogen tends to reduce the energy barrier required to generate dislocations and lower the Peierls stress needed to move them, leading to increased ductility in the metal.

In summary, different hydrogen embrittlement mechanisms on zirconium cladding alloys were investigated and their results will be presented.

# #407 Effect of selected processing routes on microstructure and hydrogen embrittlement behavior of aluminum alloys


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*Hydrogen embrittlement* *Aluminum alloys* *Trapping behavior*



**Abstract** Aluminum alloys with low mass are ideal material choices for aerostructures that should withstand the tough corrosion and mechanical conditions. The deterioration of mechanical properties due to absorption of hydrogen from the water vapor in the atmosphere made the aluminum alloys susceptible to hydrogen embrittlement in slow strain rate of loading. In aluminum alloys, it is well-known that the mechanisms and root causes of failure are related to the microstructure which is driven by different processing routes. In the present study, some selected processing routes are considered, and their effect on hydrogen embrittlement behavior of the aluminum alloys are studied. The study includes detailed analyses of microstructural features resulted from different processing routes, and the corresponding effects on trapping and transport of hydrogen are discussed. Different techniques e.g. thermal desorption spectroscopy, hydrogen microprint technique, X-ray diffraction, electron backscattered diffraction, simulation and modeling, and other relevant techniques are applied to elucidate the effect of selected processing routes on hydrogen embrittlement behavior. The results have utmost importance in the design of different materials processing routes for different industrial applications to minimize the possibility of hydrogen-assisted fracture.


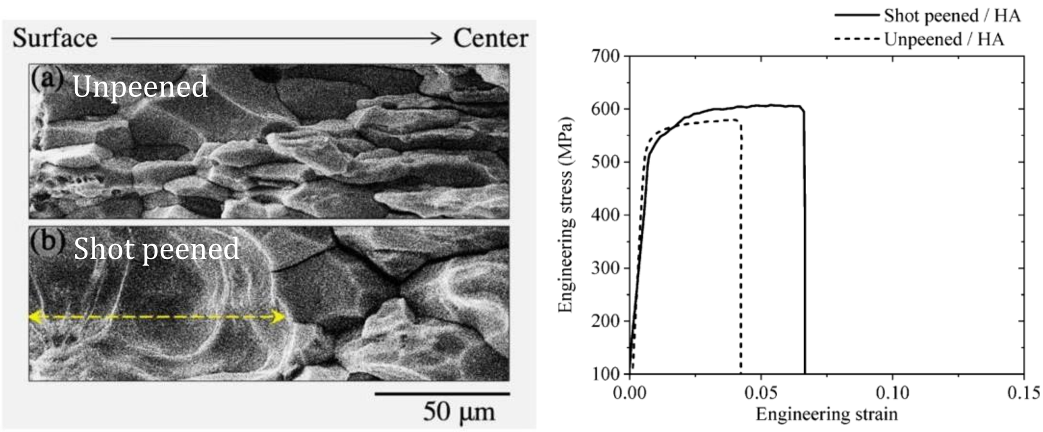


***Figure 1** – An example of processing route effects on the microstructure and hydrogen embrittlement behavior of aluminum alloys.*

# #408 Interaction of a fatigue crack and a corrosion dimple in a high-strength steel specimen

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*High-strength steel* *Corrosion* *Crack behaviour*

**Abstract** Resistance of high-strength steels depends generally on two phenomena: fatigue damage accumulation and corrosion failure. Thus, the paper is devoted to investigations of crack behaviour in a specimen made of high-strength steel under corrosion. A parametric study is performed via finite element method and the principles of the classical fracture mechanics are applied in order to assess crack propagation near a corrosion dimple. Influence of various parameters, see the scheme in Fig. 1, on the basic fracture parameters are analysed and a detailed discussion is provided in order to bring new findings important for reliable application of high-strength steels.

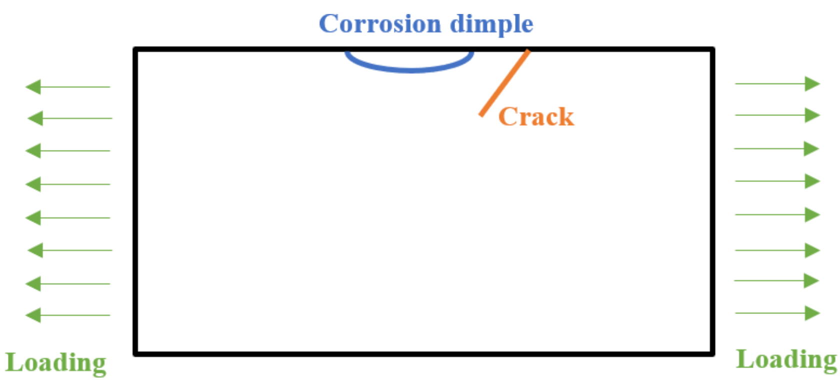


***Figure 1** – Scheme of the specimen with a crack propagating near a corrosion dimple*

# #409 Comparison of crack propagation rates in selected AISI 304 grades: Three-point bending test

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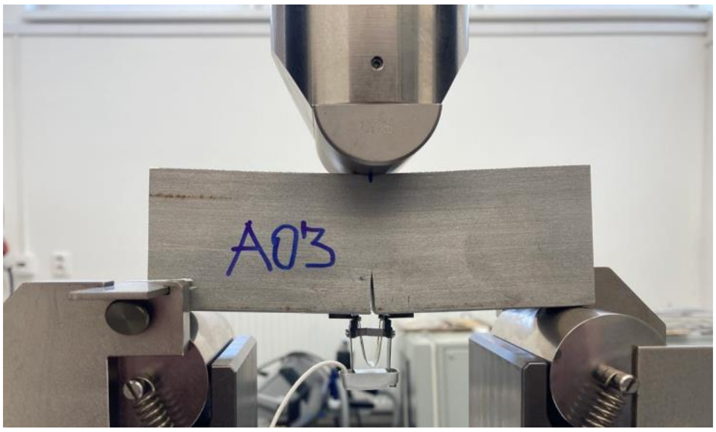
*Three-point bending* *Stainless steel* *Paris law*

**Abstract** The research is focused on analysis of specimens made of AISI 304 stainless steel from two different productions loaded in three-point bending. Specimens with the edge notch were submitted to cyclic loading with a stress ratio $R$ = 0.1 under a constant force and crack mouth opening displacement was measured. Three-dimensional numerical model representing the real specimen's dimensions took place in finite element method software ANSYS and it was used to evaluate the experimental data. The experimental setup together with numerical model are shown in Fig 1. For each specimen relation between crack growth rate and stress intensity factor range was observed and Paris' law material coefficients $C$ and $m$ were determined for linear part on a double logarithmic plot.

The results of this experimental study serve as input for future assessment of the estimation of the service life of cyclically loaded steel structures.



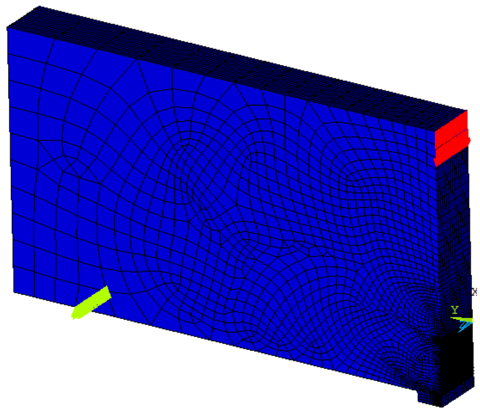



***Figure 1*** *– Experimental configuration and 3D model from software ANSYS.*

**Acknowledgment** The research is supported by the Faculty of Civil Engineering, Brno University of Technology (project No. FAST-J-22-7959) and by Czech Science Foundation, (project No. 20-00761S).

# #410 An algorithm to improve critical plane factors detection

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*Critical plane factor* *Fatigue* *Tensor invariants*

**Abstract** Fatigue is a widely discussed subject on which considerable research is still being done, both in the scientific and industrial communities. Fatigue damage still represents a major issue for both metallic and non-metallic components, sometimes leading to unforeseen failures for in-service parts. Among all the methodologies for assessing fatigue, two main groups can be identified: energy-based and local or global stress/strain-based damage models. Specifically, within the local stress/strain-based methods, critical plane factors have become widely adopted. Critical plane methods allow the identification of the component's most damaged location and the direction of crack propagation. In practice, these factors are computed by scanning several planes in the three-dimensional space and computing for each plane the damage factor until a maximum value is found. However, the standard method for calculating critical plane factors is very time-consuming as it makes use of nested *for/end* loops and is typically applied to critical areas of the component. Very often, however, the critical areas are not identifiable, due to complex geometries, loads or part constraints. In these cases, a reduced critical plane factor computational time is required to allow their application to the whole component. In this work, an improved algorithm for calculating critical plane factors is presented. The algorithm applies to all critical plane factors that require maximization of structural parameters of stress, strain or their ranges. The methodology maximizes a structural quantity by means of tensor invariants and coordinates transformation law. As an applicative example, the Fatemi-Socie critical plane factor was considered in the present work. The new algorithm was tested on different component geometries (i.e. smooth and notched specimens) under different loading conditions (i.e. tensile and torsion loading) and showed a reduction in computation time of a factor of one hundred.

# #411 The Theory of Critical Distances to perform the static assessment of 3D-printed concrete weakened by manufacturing defects and cracks

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*3D-printed concrete* *Critical distance* *Crack/Defect*

**Abstract** The present paper deals with the use of the Theory of Critical Distances to model the detrimental effect of cracks and manufacturing defects in 3D-printed concrete subjected to static loading. The validity and robustness of the proposed approach was assessed against a number of experimental results that were generated by testing, under three-point bending, 3D-printed rectangular section specimens weakened by saw-cut crack-like sharp notches, surface roughness (due to the extrusion filaments) and manufacturing defects. The sound agreement between experiments and predictive model (Fig. 1) allowed us to demonstrate that the Theory of Critical Distances is not only a reliable design approach, but also a powerful tool suitable for guiding and informing effectively the additive manufacturing process.

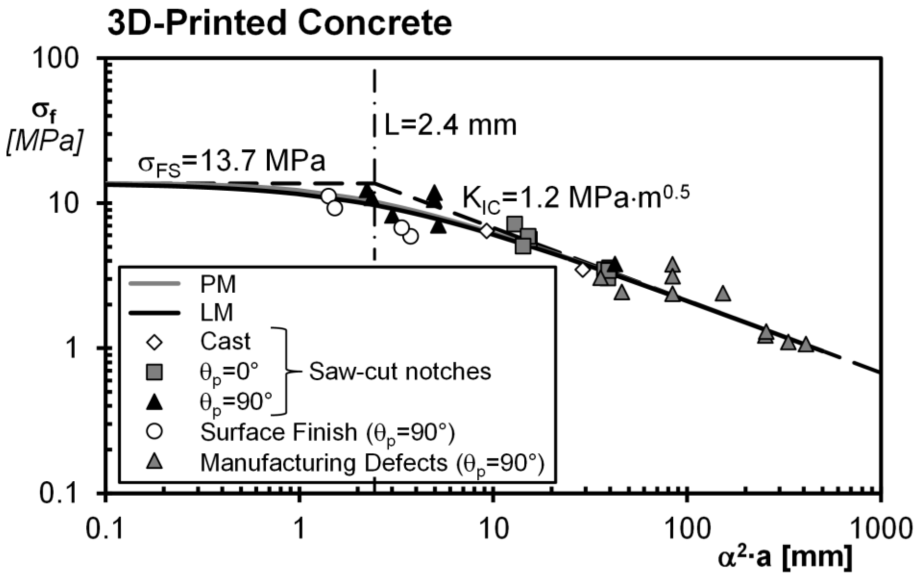


***Figure 1*** *- Accuracy of the TCD in modelling the detrimental effect of cracks and defects in 3D-printed concrete loaded in three-point bending.*

# #412 Non-pneumatic tire designs suitable for fused filament fabrication: an overview

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Additive Manufacturing Tireless wheel Cellular structures

**Abstract** The inherent structural properties of traditional Pneumatic Tires (PT) are the result of a complex production process that determines it is easily punctured and that it needs frequent air pressure maintenance. Besides trying to deal with these issues, Non-Pneumatic Tires (NPTs) surge due to their potential of performance advantages, and research has been showing that functional design by geometric manipulation of NPTs is a fruitful path to pursue. As an example, when compared with PTs, the ground pressure of NPTs is relatively small, which can reduce energy losses, improving tire efficiency. A typical NPT has an annular type of conception, and its structure consists of a hub, flexible spokes, and an outer shear ring. Contrary to PTs, which damping, and stiffness behavior is deeply related with the air pressure inside, in NPTs, this behavior is linked with the geometrical structure of its spokes and shear ring. Tireless wheel concepts are already present in commercial solutions, even so, researchers and engineers are still debating issues such as how to address trapped debris within the spokes, what is the best way to evenly distribute weight and consistently transmitting loads, or how to predict collapse of NPTs. Considering this, endeavors are related with a search for optimal functional designs, most often very complex and feasibly demanding. The geometrical design freedom offered by additive manufacturing technologies highlights its adequacy to produce such complex geometries. This research is focused on reviewing how authors have been addressing the mechanical design of NPTs. In the end, a qualitative analysis on the suitability of such designs to be additively manufactured by fused filament fabrication is made.

# #413 Residual life of a historic riveted steel bridge - engineering critical assessment approach

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*Steel structures* *Structural integrity* *Fracture mechanics*

**Abstract** The current fatigue evaluation procedures in steel bridges design codes and normative (Eurocodes) do not account for the degree of uncertainty in load and resistance models. However, the variability of cycling loading and material properties have a significant influence on fatigue safety verification. A fatigue verification is contingent on the accumulated load cycles and the fatigue category; which, in turn, depends on member type and its connections. Assessment of structural safety can be evaluated more completely using probabilistic methods that provide fatigue prediction in terms of the probability of crack initiation. The paper is presenting a study case for a historical riveted steel bridge build in the beginning of twentieth century. There are presented solution for consolidation of the bridge and retrofitting, taken into account fatigue design and structural integrity assessment. Critical flaws values were determined for each case type using the failure assessment diagrams. These values are used as limit values for fatigue analysis based on fracture mechanics principles, to determine the number of cycles for a crack to extend from initial to critical dimension, i.e. failure. For the assessment was used the code cyclic loading as a block independent iterative solver – applying the specified stress ranges sequentially line by line, repeating the entire cyclic loading - entire group of cycles for a number of blocks (one block representing all the applied cycles of stress ranges). In the end of the study it is calculated the residual life of the steel bridge.

# #414 Early Crack Growth from Notches under Creep-Fatigue Loading

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*Transient Crack Closure Simulation* *Effective Crack Tip Loading* *Creep-Fatigue Loading*

**Abstract** Linked to components, notches as design features significantly influence the early crack growth process. Usually, the number of cycles to crack initiation is determined by standardized LCF tests with round bar specimens without a notch. This procedure neglects the gradient in stresses and strains originating from the notch root and its effects on early crack growth. To investigate the fracture mechanical portion of this notch support effect, series of tests performed on two different notch geometries as a circumferential notch in a round bar specimen were investigated at high temperatures in LCF regime. The local loading at the notch root was chosen equal to the loading level in LCF tests with standardized round bar specimens. After crack initiation in the notched specimen, the crack grows slower than compared to the un-notched samples, resulting in a higher cycle number to achieve comparable crack depths. The ratio of cycle number at same local loading for a specimen with and without notch leads to the notch support factor. This factor has been determined for different heat-resistant steels at their typical maximum operating temperatures, the two notch geometries mentioned, different loading levels and loading conditions. In order to examine the transferability, a cruciform specimen with a hole as a third, component-near structure with notch was investigated.

Beside the undertaken experimental measurements, a purely theoretical based approach is outlined and utilized. Here, a cyclic elastic-(visco)plastic simulation of the crack growth considering plasticity induced crack closure was used to determine the effective fatigue and creep crack tip loading. In combination with available crack growth laws, the cycle number for the early crack growth was determined. The results indicate, that all three approaches are capable to describe the crack depth as a function of cycles for a growing crack between 0.2 and 1 mm depth initiated at the notch root.

Out of those results, notch support factors of the various cases are compared first based on single influencing factors like the referenced stress gradient. It turns out that the notch support under creep-fatigue loading conditions depends not only on the notch geometry itself. Additionally, the loading level show a significant influence depending on the material's plasticity and the notch geometry. Furthermore, the influence of creep on notch support is investigated. It turns out, that dwell times in the cycle reduce the notch support, because of creep crack growth and a pronounced influence on crack closure. Oxidation slowed down crack growth additionally, which was observed specially for the heat-resistant steels with low chromium contents. The results achieved for the cruciform specimen with hole are in line with the round bar specimens with notch showing the transferability of the achieved findings.

The theoretical approach is suitable for transferring the results to arbitrary geometries and use cases. As an example in the paper, the application for a surrogate model of a borehole in a thick-walled casing with different diameter under creep-fatigue loading is presented. Overall, the consideration of notch support effect based on measured and simulated early crack growth by means of the introduced fracture mechanics based approach leads to a reduction of conservatism in lifetime assessment procedures of components

# #415 3D tools for building inspection from thermal UAS data

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*Thermal Imagery* *3D Point Cloud* *Building Inspection*

**Abstract** Thermal imaging has been widely used for the inspection of human-made and natural scenarios. Accordingly, electrical installations, advanced machinery and buildings have been previously reviewed. Regarding buildings, it can be used to assess problems concerning heat, airflows, and water. Hence, thermography has been increasingly applied to the energy efficiency of new and old buildings. Some examples of applications are the detection of heating and cooling losses, moisture sources, missing insulation, floor heating failures, and the evaluation of building restorations (Vollmer and Möllmann, 2017). However, the main drawback of thermal imagery is their reduced resolution, e.g., 640x512, which is significantly lower than RGB imagery dimensions with 50 or 100 megapixels (MP). In the case of buildings, cameras or thermal sensors mounted on UAS (Unmanned Aerial System) offer a wider range of possibilities by acquiring areas not accessible by other surveying methods. Also, thermal images are mainly studied as two-dimensional data, though they are a direct simplification of 3D reality (4D if we wish to monitor changes over time).

This paper presents a tool that allows enhancing 3D point clouds with thermal information. The theoretical foundations of the method are described by our previous work (López et al., 2021). This process has already been implemented in a tool (GEU-Thermal) that offers inspection services with this technology. The aim of this study is to apply this technique for an specific application concerning the conservation of building facades. For this purpose, a method for the identification and segmentation of building materials is proposed. In addition, the comparison of thermal point clouds produced over time will allow us to study multi-temporal data.

***Figure 1.*** *Thermographic imagery applied to the inspection of building facades (Vollmer and Möllmann, 2017).*

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# #416 Nucleation and propagation of cracks under multi-axial loading in phase-field modelling

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*Damage* *Phase-field* *Variational methods*

**Abstract** The phase-field approach to brittle fracture is based on the following minimization problem

$$\min_{\boldsymbol{u},\alpha} \mathcal{E}_{tot}\,(\boldsymbol{u},\alpha) = \int_\Omega \left[\varphi(\boldsymbol{\varepsilon}(\boldsymbol{u}),\alpha\,) + \psi_{\text{diss}}(\alpha,\boldsymbol{\nabla}\alpha)\right]\mathrm{d}\Omega \qquad \text{with} \;\; \varphi(\boldsymbol{\varepsilon}(\boldsymbol{u}),\alpha) = \mathrm{a}(\alpha)\varphi_R(\boldsymbol{\varepsilon}(\boldsymbol{u}),\alpha) + \varphi_D(\boldsymbol{\varepsilon}(\boldsymbol{u}),\alpha)$$

where $E_{tot}$ is the total energy functional, $u, \alpha, \varepsilon(u)$ are respectively the displacement and damage fields and the strain tensor, and $\varphi$ and $\psi_{diss}$ are respectively the elastic and the dissipated energy density. The minimization problem is solved under the irreversibility constraint for the damage field. The elastic energy density is split into a damageable part ($\varphi_D$) and a residual part ($\varphi_R$), which serves the double purpose of avoiding interpenetration of the crack surfaces under compression and reflecting the physical asymmetry of fracture behavior between tension and compression

Recent results have proved that phase-field approaches can quantitatively predict crack nucleation for mode-I loading [1]. However, the prediction of crack nucleation under multiaxial loading is crucially influenced by the energy decomposition, and currently available decompositions (e.g., those in [2,3]) are insufficiently flexible [4] as they do not allow to reproduce the experimentally measured tensile and compressive (or shear) strengths.
To solve the issue, a novel decomposition was proposed in [4], giving a parametric strength surface à la Drucker-Prager to be adjusted based on the experimentally measured tensile and compressive strength. In this contribution, the new theoretical model is implemented numerically to verify the analytical nucleation curves. Moreover, the analysis is extended beyond nucleation to analyze the localization modes under multiaxial loading and to study the propagation behavior. This implies dealing with the non-linearities introduced by the new model and with bad conditioning and locking issues related to the corresponding linear system.

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# #417 Study of the fracture-mechanics behavior of $BaTiO_3$ piezoceramic in the vicinity of transformation temperature

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*Fracture toughness* *Piezoceramic* *FE model*

**Abstract** The main aim of the paper is to clarify fundamental processes taking place in the vicinity of Curie temperature with a focus on the fracture behavior of pure polycrystalline barium titanate [1,2]. Special attention will be paid to an explanation of the fracture toughness drop of the barium titanate upon crossing of the transformation temperature. An explanation of observed changes in the mechanical behavior of this material is based on the experimental measurements supported by numerical simulations utilizing features of the real microstructure on the grain level. Several model materials with various grain microstructures were manufactured from the submicron barium titanate powder sintered at various temperatures. Two resulting materials with a suitable distribution of grain sizes in the microstructure were selected for further investigation. The grain size influences not only the exact position of the Curie point temperature but also kinetics of the lattice transformation, elastic, and fracture properties. A significant drop observed in the fracture resistance was attributed to the development of localized internal thermal stresses, which was supported by results of the performed numerical simulations. The coincidence of the volume change of neighbouring grains due to a lattice transformation together with a significant variation in elastic properties can lead to up to a 20% decrease in the measured fracture toughness. Understanding this behavior is essential for the processing and correct application of lead-free barium titanate materials.

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# #418 Failure modelling of open cell foam structure using coupled criterion

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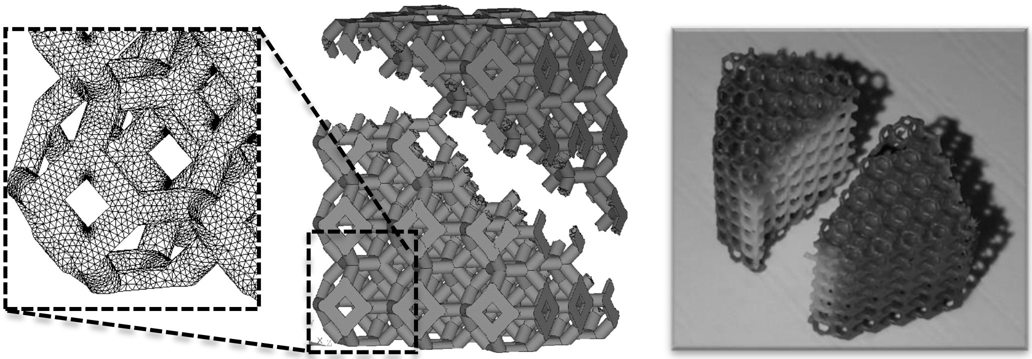
*Coupled criterion* *Fracture* *FE model*

**Abstract** The contribution deals with a modelling and prediction of failure of open cell foam architectures subjected to mechanical loading. The considered solid element-based FE model of the foam structure is prepared from CT scans of a real foam specimen (prepared by 3D printing technology) to reflect precise geometry of the sample. The failure criterion used for prediction of the failure onset on particular struts of the foam structure is based on the stress-energy condition, and is known as the coupled criterion (defined within the framework of Finite Fracture Mechanics – see e.g. works [1-3] ). In this work, a 3D version of this criterion is utilized (together with a 3D FE model) in order to predict both the critical applied load and also the fracture surface of the complex foam architecture. Numerical predictions and available experimental observations are in a very good match.



a) b) c)

***Figure 1*** *– a) Detail of the FE mesh of the studied foam architecture, b) predicted fracture surface upon compressive loading, c) experimentally observed fracture.*

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# #421 Fretting fatigue of multiaxially loaded shrink-fit connections – effect of material sensitivity on fatigue strength

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*Fretting Fatigue* *Multiaxial Fatigue* *Shaft-Hub-Application*

**Abstract** An accurate estimation of the high-cycle fatigue of shaft-hub connections is desired for the safe machine design. Especially in drive train applications, different multiaxial loads act on the joined parts. The resulting multiaxial stress state in vicinity of the contact edge as well as the corresponding tribological state influences the fatigue strength in high-cycle fatigue regime. Investigating different load parameters, staircase fatigue experiments under combined rotating bending and dynamic torsion of shrink-fitted shaft-hub connection with equal material pairing were performed. Especially the comparison between a normalized steel C45+N with quenched and tempered steel 42CrMo4+QT show different sensitivity to the tribological stress. In case of higher material strength, higher loads leads to higher relative movements between shaft and hub and higher contact pressure variation due to bending. This higher tribological stress leads to the higher surface degradation and the crack initiation occurs at lower relative loads compared to the higher material strength. To consider these effects in the fatigue calculation, integral fatigue criteria are used to determine the critical distance, where the equivalent stress should be evaluated (Fig. 1). Due to crack-closing compressive loads caused by the contact pressure, higher critical distances (point method) where determined using the finite element method. The experimentally determined material sensitivity was reproduced by adaptation of the critical distance. For this purposes the crack threshold value is scaled based on the values determined with free-surface specimen from literature.

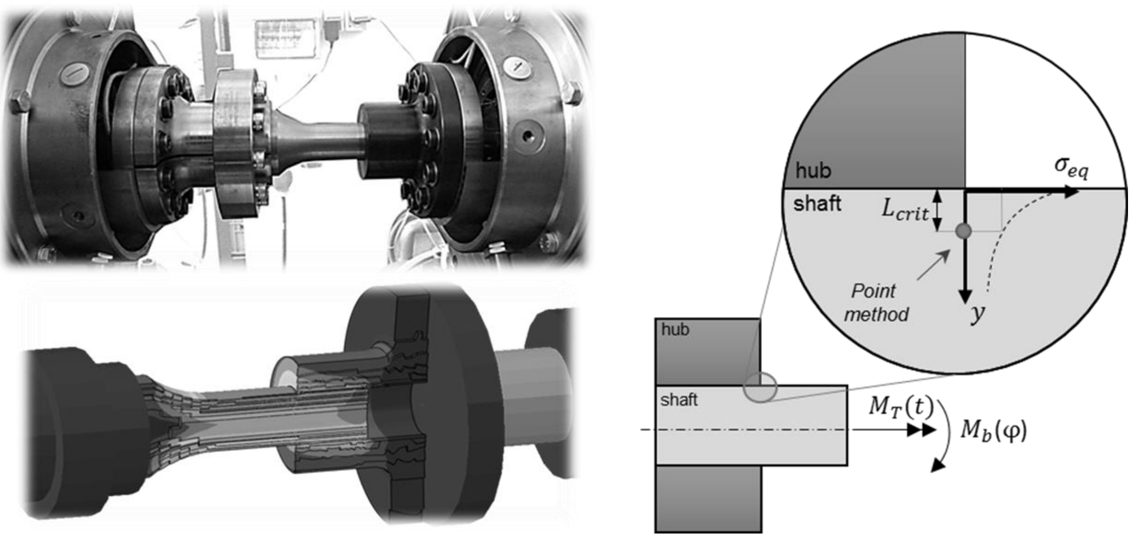


***Figure 1** – Determination of critical distance for multixially loded shrink –fit connections based on experimental investigations*

# #422 Structural Integrity Assessment of a Spent Nuclear Fuel Transportation Cask under Aircraft Engine Crash

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*Spent Nuclear Fuel* *Aircraft Engine Crash* *Impact analysis*

*Trasportation Cask*

**Abstract** The transportation of spent nuclear fuel is expected to increase in the future, but regulatory standards such as protection performance evaluation methods and protection design standards for spent nuclear fuel transportation casks are insufficient. Accordingly, it is necessary to evaluate the reliability of the spent nuclear fuel transportation cask for aircraft crashes. In this study, structural integrity assessment was performed when it collided with an aircraft engine flying at a specific speed by simulating the body part of the spent nuclear fuel transportation cask. The impact analysis was modeled assuming that a cylinder flying at 150 m/s collides horizontally in the center of a stationary cylinder wall. The programs used for analysis were Abaqus Explicit, Ansys Autodyn, and Numerics SPEED. For the constitutive eqations, the Johnson-Cook Model, Mie Grüneisen equations of state, and the Johnson-Cook dynamic failure model were used. As a result, plastic strain magnitude corresponding to 0.052 to 0.053 were derived for all three analysis programs. Plastic deformation occurred, but the aircraft engine did not penetrate the body. Through the results of impact analysis performed using various finite element analysis programs, it was verified that the spent nuclear fuel transportation cask is safe under aircraft engine crash.

# #423 Fatigue lifetime of GFRP laminates in critical planes defined by equivalent normal and shear stress

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*Composite materials* *Multiaxial loading* *Fatigue*

**Abstract** The study analyzed the fatigue tests of GFRP laminates $[0/(\pm 45)_2/0]_T$ of specimens cut at different angles (0°, 30°, 45°, 60°, 90°) in relation to the axis 0 [1, 2]. The value of the equivalent stress has been determined according to two popular criteria taken from statics. Assuming the parallelism of the basic fatigue characteristics of the specimens cut at 0° and 90° and defining the values of X, Y and S, which are maximum values of stress in different directions, we modified criteria proposed by Azzi-Tsai-Hill [3, 4] and by Norris [5]. Due to the fact that these criteria are nonlinear due to the components of the stress state, they cannot be applied to operational or non-conforming loads in phase [6, 7]. Therefore, it is proposed to apply a linear relationship for the components of the stress state. In this paper we took into consideration two approaches to calculation of the equivalent stress in critical plane. In the first one we defined the critical plane by the normal stress and in the second one by the shear stress. In the second case the value of the equivalent stress is the linear sum of normal and shear stress in this plane. In the proposed criteria, weighting factors were used as multiplicators of the relevant stress amplitudes, just as it was done in the Azzi-Tsai-Hill or Norris criteria. As a result, the obtained amplitudes of equivalent stresses were compared with the experimental fatigue life. It has been shown that the newly proposed criteria for reduced stress, can be successfully applied to composite materials.

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# #424 Fracturing and degradation study of an earthen historical wall

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*Fracturing* *Ultrasonic test* *Earthen rampart*

**Abstract** Meknes city is one of the four imperial cities of Morocco and was listed as UNESCO world Heritage site since 1996. It is famous by their 17th Century historical earthen rammed walls ringing the Medina. These big ramparts have more than 40 km length, between 7 and 12 m height and the thickness is reaching sometimes 3 m. The ramparts suffer meteoritic weathering and show obvious deterioration and fracturing threatening their stability.

The survey and analysis of fractures in a chosen portion of the rampart (about 1Km length) has been made in 1 and 2D.

In 1D, a scanline survey let to estimate the fracture parameters as orientation, dip, aperture and spacing between adjacent fractures. A statistical quantification described the fracturing degree and the random distribution of fissures.

In 2D, a sequence of orthophotos has led to study the fracture network and to subdivide the rampart in different panels of 15m length each one. The digitalization of different structural disorders has been used to map visible pathologies. The combination of different parameters has served as health diagnosis and vulnerability map highly suitable to establish further a risk map. This methodology is to be generalized to the entire historical rampart in order to assess its instability and to prioritize interventions.

We applied also the ultrasonic auscultation test to detect fractures and weak structures and to assess damages.

The ultrasonic testing using Pundit 54 Khz transducers allowed to characterize and to compare none restored and restored chosen panels of the rampart and to assess their mechanical states.

P-wave velocity tomography and signal attributes allowed a good diagnostic and a better understanding of the healthy state of the studied cases.

These applied techniques seem to be very useful for this particular historical material and will help to assess and to monitor the restoration works for a better conservation of this universal heritage.

# #425 Interface cracks under dynamic loading: cracks' closure and friction

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*Cracks* *Contact interaction* *BIEs*

**Abstract** The systems of linear cracks between two dissimilar elastic isotropic half-spaces under dynamic (harmonic and impact) loading were considered taking effects of the cracks' faces closure and friction into account.

The system of boundary integral equations for displacements and tractions at the interface was derived from the dynamic Somigliana identity, and in order to take the crack faces' closure into account we assumed that the contact satisfies the Signorini constraints and the Coulomb friction law. The normal and tangential components of the external loading, the displacement discontinuity and the tractions at the interface were approximated by the exponential Fourier time series. For every Fourier coefficient number the appropriate system of linear algebraic equations was obtained from the boundary integral equations and solved numerically, so the displacements and tractions in the form of Fourier exponential series with a finite number of the members were found. During the numerical solution divergent integrals of various order (hypersingular, singular and weakly singular) were regularized and calculated.

The problem was solved numerically using the iterative process – the solution changed until the distribution of physical values which satisfies the contact constraints had been found. The numerical convergence of the method with respect to the number of the Fourier coefficients and mesh size was also analysed.

The distributions of the displacements and tractions were obtained and the dynamic stress intensity factors were computed as functions of the parameters of the incident loading and properties of the bi-material. The results were compared with those obtained neglecting the cracks' closure. The effects of material properties and values of the friction coefficient on the distribution of stress intensity factors (opening and shear modes) were presented and analysed. Special attention was paid to the effects of the mutual location of the cracks.

# #427 Influence of crack length and maximum stress on constant amplitude fatigue crack growth rates of metallic alloys

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*S-N curve* *Fatigue crack growth rate* *Power law exponent*

**Abstract** The fatigue crack growth rate (FCGR) curve of metallic alloys is usually divided into three regions. Region II is often referred to as the Paris regime and is usually modelled with a power law relationship, while regions I and III are frequently modelled with asymptotic relationships. In this paper we hypothesize that fatigue crack growth is governed by power law behavior at all crack lengths and all stress intensity factor ranges ($\Delta K$). To accommodate for the changes in the FCGR slope at regions I - III mathematical pivot points are introduced in the Paris equation. Power law behavior with the presence of pivot points enables direct fitting of the crack length vs. cycles (a-N) curve to obtain the FCGR as a function of $\Delta K$. This novel approach results in accurate multilinear FCGR curves that are suitable for reconstruction of the measured a-N curves. The method is subsequently applied to i) different engineering alloys and heat treatments, ii) naturally increasing $\Delta K$ testing of small cracks to obtain accurate small FCGR data. The results show that small cracks are faster, but the transition from region I to region II occurs at a specific fatigue crack growth rate which results in an apparent shift in $\Delta K_{threshold}$, iii) long cracks, which show that the FCGR increases with maximum stress for a given $\Delta K$ and stress ratio when the maximum stress approaches the yield stress. This maximum stress phenomenon becomes important in the case of fatigue testing, where maximum stresses are typically high due to stress concentrators or cracks with small initial lengths.

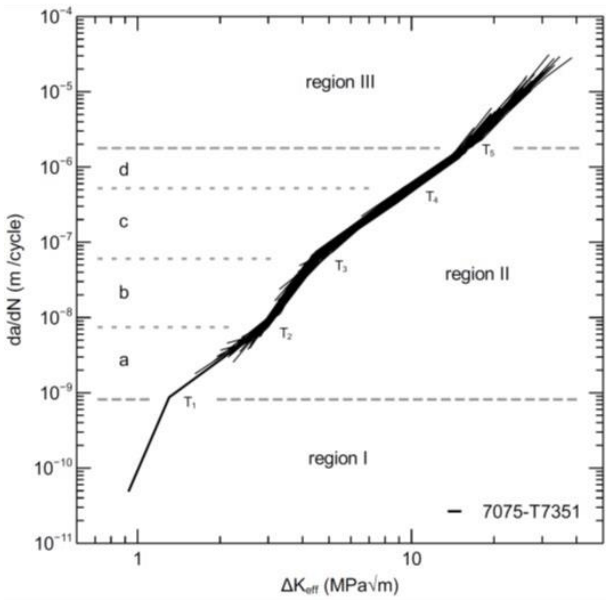


***Figure 1*** *- FCGR master curve as a function of $\Delta K_{eff}$ with horizontal indications for the transitions between regions.*

# #428 Fracture arrest test for identifying fracture stress in steel

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*Local fracture stress* *Crack arrest* *Brittle crack* *steel*

**Abstract** The purpose of this research is to establish a rational identification method of local fracture stress. The local fracture stress theory assumes that the local stress near the front edge of a fast propagating brittle crack is a constant value specific to the material under any conditions and previous studies have shown that the criterion for brittle fracture propagation and arrest behavior is not the conventional dynamic stress intensity factor, but the local stress. To obtain the local fracture stress, it is necessary to do a test that ensures the crack arrest and identify the local fracture stress by "crack arrest position" and "inverse analysis of fracture simulator". However, the conventional crack arrest test using temperature gradient type test is very hard and no rational evaluation method has been established. Therefore the new compact arrest test method is developed and the local fracture stress is identified by using the finite element method.

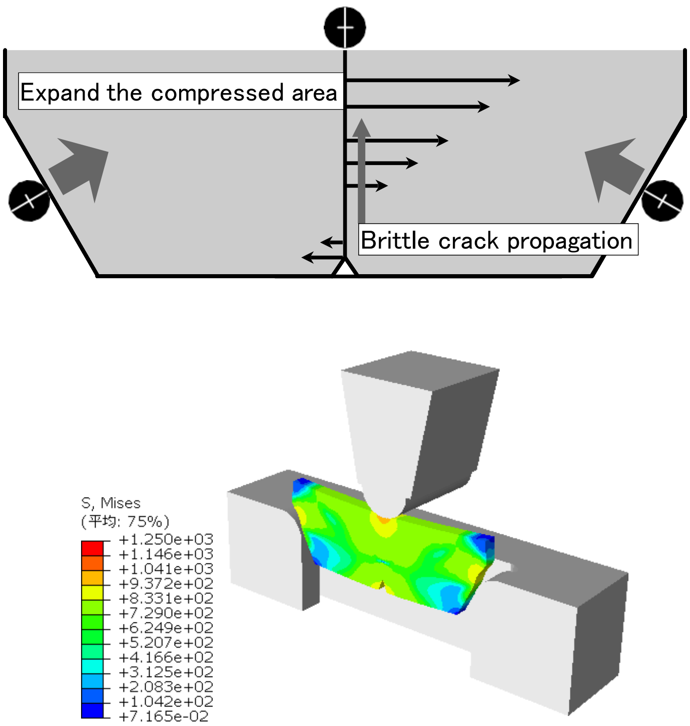


***Figure 1** – outline of newly proposed compact arrest test*

# #429 Combined High Energy X-Ray Diffraction and Small-Angle Scattering Measurements of Strain, Dislocation Density and Porosity Near Steel Fatigue Cracks Grown in Hydrogen

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*Hydrogen Embrittlement* *Diffraction* *SAXS*

**Abstract** Elucidating the mechanisms of hydrogen embrittlement of steels is complicated by the fact that multiple mechanisms may be activated at once or may even require a synergistic co-existence for activation. Some leading preposed mechanisms of hydrogen embrittlement include hydrogen-enhanced decohesion (HEDE), the hydrogen-enhanced localized plasticity (HELP) mechanism, and the Nano-Void Coalescence Mechanism (NVC). In HEDE, accumulation of hydrogen at locations of high triaxial stresses lead to the weakening of Fe-Fe bonds once the hydrogen concentration reaches a critical concentration. In HELP, the introduction of hydrogen gas creates areas of extended dislocations in the Fe lattice and enhances dislocation mobility in the steel framework. In NVC, hydrogen is predicted to lead to the stabilization and promotion of vacancy ("nano-scale void") agglomeration. A full understanding of these mechanisms, their relationship to fatigue properties, and their interaction with each other requires a measurement capable of probing all three mechanisms at once. Here we present simultaneous High Energy X-ray Diffraction (HEXRD) and Small-Angle X-ray Scattering (SAXS) measurements during fatiguing of a steel crack. HEXRD measurements probe HEDE And HELP through a determination of strain and dislocation density; SAXS measurements probe NVC through a determination of nano-pore size distribution. We will present strain, dislocation density, and pore size distributions maps ahead of crack tips grown in air and in hydrogen. We will discuss the differences in each between the crack tips grown in air and in hydrogen in the context of the HELP, HEDE, and NVC mechanisms.

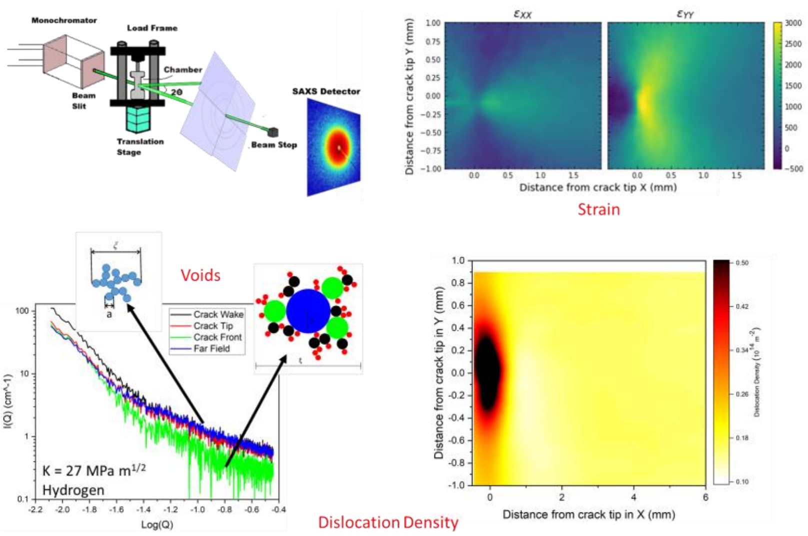


***Figure 1** – Strain, dislocation density, and a measure of pore volume near cracks grown in hydrogen (top) and air (bottom)*

# #430 Numerical analysis of damage and fracture in steel sheets undergoing non-proportional loading paths

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*Ductile damage* *Steel sheets* *Non-proportional loading*

**Abstract** The presentation discusses the numerical analysis of damage and fracture mechanisms in steel sheets. Newly developed specimens are taken from thin sheets and are tested under different biaxial loading conditions covering a wide range of stress states. Results of numerical simulations of a series of biaxial experiments are presented showing also the effect of non-proportional loading paths on damage processes on the micro-level and corresponding fracture modes on the macro-scale. In this context, an anisotropic continuum damage model is presented based on yield and damage conditions as well as evolution laws for plastic and damage strain rates. Different stress-state-dependent branches of the damage criteria are taken into account corresponding to various damage and failure processes on the micro-scale depending on the stress triaxiality and the Lode parameter. Experiments with the biaxially loaded X0- and H-specimens have been performed. Results for proportional and corresponding non-proportional loading histories are discussed. During the experiments strain fields in critical regions of the specimens are analyzed by digital image correlation (DIC) technique. In addition, the fracture surfaces are examined by scanning electron microscopy (SEM). Numerical simulations of the experiments have been performed and numerical results are compared with experimental data. Furthermore, based on the numerical analysis stress distributions in critical specimen's areas are detected and are used to predict stress-state-dependent damage and fracture mechanisms which can be validated by the SEM pictures. The numerical results also demonstrate the efficiency of the experimental program and the new specimen's geometries covering a wide range of stress states even in the shear-tension and shear-compression regime as well as the effect of the loading histories on damage and fracture behavior in steel sheets.

# #431 Thermal fracture resistance of functionally graded thermal barrier coatings with systems of multiple cracks

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*Functionally graded coating* *Fracture resistance* *Thermo-mechanical load*

**Abstract** The problem of thermal fracture of functionally graded thermal barrier coatings on a homogeneous substrate under the influence of thermo-mechanical loadings is studied in the presented work. It is assumed that FGCs contain a pre-existing system of multiple cracks, edge and/or internal. The FGMs are special type of composites, which properties are continuously varying mainly in one direction, which is achieved by changing the composition of the material and its structure. FGMs have a wide engineering application, in particular, in thermal barrier coatings, where ceramics are used on the coating top and then continuously varies up to metal in the substrate.

The problem is formulated using classical but rather effective analytical and numerical methods, such as the method of analytical functions of complex variables and singular integral equations, as well as a numerical method based on Chebyshev polynomials for solving integral equations. The thermal and mechanical properties, as well as the fracture toughness of the FGC, are modeled by continuous functions with respective inhomogeneity parameters. The rule of mixtures is also used with a power-law coefficient as the graded parameter.

The goal of this model and the investigation based on the model is to find ways to improve the fracture resistance of FGC/H structures. The following fracture characteristics are calculated: stress intensity factors, energy release rates, critical stresses and fracture angles. It is important to know the main parameters of the problem for FGC/H structures that affect the fracture characteristics. In Petrova, Schmauder 2019 and 2020, the significance of taking into account the fracture toughness and its change in FGM layer was shown for evaluating the fracture resistance of structures. The fracture angles mainly depend on the geometry of the cracks including the direction of change in the properties of FGCs, which is also investigated in this work.

A series of computational experiments is carried out for FGC/H structures with typical systems of multiple cracks in the FGC for different inhomogeneity parameters, which correspond to different material combinations. Examples of such typical systems are: system of edge cracks, edge cracks with presence of internal cracks, and internal cracks only. The desirable combination of FGC materials (for better fracture resistance of the FGC/H structure) for each crack system is determined and discussed.

**Acknowledgments**

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# #432 Effect of microstructure on trabecular-bone fracture: numerical analysis

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*Trabecular Bone* *Fracture Mechanics* *Crack Propagation*

**Abstract** Research of mechanical behaviour of bones is a special subject area in the modern biomedical field. Generally, it is necessary to fully determine a mechanical response of bone to external factors in order to protect or strengthen any part of a human musculoskeletal system. The mechanical behaviour of bone plays a key role in determining its strength, reliability, and durability, since in any material, including natural ones, defects such as microcracks can occur under different conditions. Analysis of the onset of cracking in bones and the limiting loading cases related to bone breakage allows the development of requirements for bone implants. So, it is important to study the mechanical behaviour of bones at various length scales. Trabecular bones with their open-cell structure with pore channels and a solid-phase network of ligaments carrying the load is a challenge for such an analysis.

This work considers representative volumes of trabecular bone as random porous composite material, which mechanical behaviour is numerically investigated. The stochastic nature of these volumes is related to internal microstructure of the bone. Fracture behaviour of bones is numerically studied using models of degradation of their mechanical properties described by various fracture criteria and employing approaches of linear elastic fracture mechanics with the extended finite-element method implemented in the SIMULIA Abaqus FEM software. The effect of microstructural morphology on a stress-strain state and fracture processes in the elements of trabecular bone is studied under various combinations of applied mechanical loads. The areas of localization of fracture initiation are observed in the stress concentrators - thin ligaments of the structure. The data obtained show a good agreement with the results of other authors.

# #434 On the non-monotonic behaviour of the dynamic yielding diagram and the incremental relaxation plasticity model

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*Dynamic plasticity* *incubation time criterion* *Strain-rate effect*

**Abstract** An incremental variant of the relaxation plasticity model considering the incubation time approach is proposed to describe and investigate the stress-strain relationship in a wide range of strain rates. Some phenomenological models, such as the Johnson-Cook model, are implemented in many researches and engineering software as a yield function to simulate the dynamic plastic behaviour of various materials. However, in some impact cases, the yielding criterion contained in these models gives less accurate results. The yield drop phenomenon and the subsequent non-monotonic behaviour cannot be described by them as well. The dynamic performance of the proposed incremental model is compared with that of the Johnson-Cook model and the relaxation plasticity model. A better agreement with the experimental results is reported to the incremental model.

# #435 Characterisation of fracture toughness with sub-size CT samples

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*Toughness* *Size effect* *Fracture*

**Abstract** This study is part of the French-ANR industrial chair Messiah (Mini-tests for In-Service Monitoring of Structures with Application to Hydrogen Transport). The design of structures requires an understanding of the crack propagation properties of the materials used. For that purpose, standardized mechanical tests on cracked specimens are mainly used. To be considered valid (ASTM E1820 standard), these tests must be performed on specimens large compared to the size of the fracture process zone. These dimensions are of the order of a few centimeters, but they are even larger when the material is very tough. However, the use of sub-size specimens is unavoidable in several cases: (i) specimens extracted from an in-service structure in order to characterize the in-service behavior or during their reception, (ii) during the development of new materials in limited quantities, (iii) when the structure does not allow specimens to be extracted according to the recommendations of the standards (e.g., thin structure). It is difficult or impossible to perform "valid" tests according to the standards in all these cases. One approach to solving this problem would be establishing procedures for accessing macroscopic properties from sub-size specimens. This study is carried out on a gas line pipe steel (Vintage API X52 grade ). A test campaign is first conducted on usual-size CT specimens according to the ASTM E1820 standard. The process is repeated for sub-size CT (mDCT) specimens. The sub-size specimens do not allow to measure the crack opening (CMOD) at the position recommended by the standard. It is then necessary to modify the test procedure using FEM analysis to determine the crack growth resistance curve. The use of sub-size specimens allows showing a strong anisotropy on fracture. Very reproducible results are obtained. A substantial size effect is also shown: the crack growth resistance curves on sub-size specimens are systematically lower than those on standard CT specimens, as shown in Figure 1.

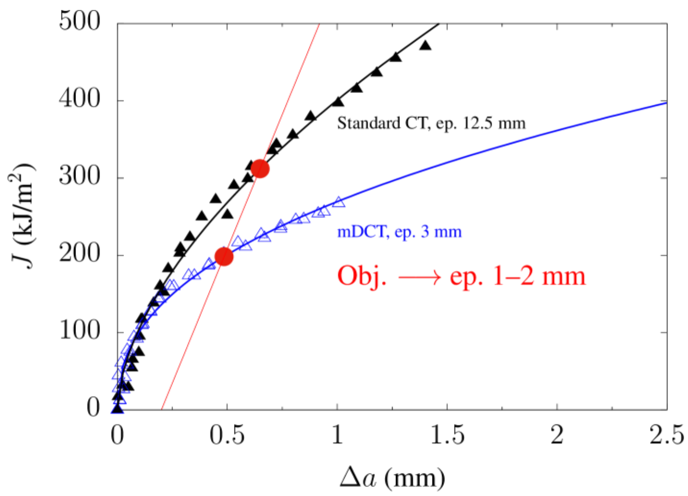


***Figure 1*** *- J-Δa crack propagation curves for standard CT and sub-size mDCT specimens.*

# #436 Additive manufacturing of head surrogates for impact analysis

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*Head surrogate* *Additive manufacturing* *Impact*

**Abstract** Consequences of head impacts are a major concern in several fields, including civilian accidents, professional sport and security and military personnel. Different mechanical magnitudes can be used as damage indicators related to injury severity, such as linear and rotational acceleration and intracranial pressure. Damage mechanisms can be split into skull fracture and brain injury, for which respectively each of the above is the most relevant damage indicator. Development of proper head protections depends on the accuracy of realistic physical models of the human head allowing testing of these protections. Mechanical properties of the surrogate material and geometrical aspects are determining factors in the impact wave propagation and in the damage indicators. A 3D-printed model in Poly(Lactic Acid) is designed to reproduce skull behaviour. Different printing parameters and four possible building orientations are explored, analysing their implications in the mechanical properties and mechanical tests are carried out to characterise the impact behaviour. A selection of printing parameters is proposed to reproduce the skull mechanics and advance in the standardisation of the manufacture of human head surrogates.

***Figure 1 -*** *3D-printed anatomically correct human skull*

# #437 Passive Safety Solutions on Coach according ECE R29: Experimental and Numerical analyses

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*FEM DIC Crashworthiness Bus Transportation R29 Standard Regulation Structural Analysis*

**Abstract** Accidents involving passenger public transports can pose serious dangers to the driver and passengers owing to the close closeness to the impacting region volume caused by the original structural design and the high rate of energy or accelerations involved. This issue implies a continuous research of structural optimization with the intent of enhancing safety. The goal of this research is to provide novel technologies for new passive safety solutions used on coaches. The major goal is to research boosting driver safety capabilities in the event of a frontal hit and passenger safety in a rollover test. As a result, it seeks to develop a new generation of coaches equipped with technologies capable of mitigating the impact's collateral effects.

This research focuses on the structural behavior of a coach (M3 Class III vehicle) in the case of a head-on collision in line with Regulation ECE R29. Globally, there are only regulations concentrating on the certification of heavy trucks with separate driver's cabs, not covering coaches. To accomplish this frontal crash test, a mock-up was built, and an impactor freely hung by two steel beams imparted 55 kJ of energy to deform the structure. The experiment was carried out, and the experimental data was obtained using a Digital Image Correlation (DIC) system, extensometers and accelerometers placed on the structure.

To derive the relevant structural response, the research model was solved using Finite Element Method (FEM) formulations with a dynamic explicit model in this study. Virtual testing saves the developer time & expense while still ensuring quality standards. This effort seeks to be the first step in validating experimental data and identifying weak regions in present structures, therefore helping to the prevention of driver and passenger fatalities. As a consequence, the strain vs. time curve, as well as the accelerations and contour displacements, were numerically obtained for the ECE R29 test. A comparison of the experimental and numerical solutions was performed. As a result, the internal energy was assessed and compared to the value prescribed by the standards. According to the findings, it is possible to determine if the investigated models are capable of meeting the criteria of standard rules or whether a solution suggestion is required to enhance the outcomes.

# #438 Comparison of incubation time approach with scaling law through SPS-data processing method

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*Dynamic strength* *incubation time criterion* *scaling law*

**Abstract** The problem of material strength under dynamic loading is studied in order to compare two theoretical methods of analysis – the incubation time approach and the scaling law. The main peculiarities of both methods are considered so as to reveal relations between their parameters. The incubation time approach is also enhanced by the Sign-Perturbed Sums method to determine the standard procedure of model parameters assessment. The applicability of the approaches is checked on by experimental data processing for some brittle materials. The incubation time approach advantages that are stipulated by its phenomenological nature are demonstrated.

# #439 Investigation of micropitting and wear in rolling/sliding contacts operating under boundary lubrication conditions

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*Rolling contact fatigue* *Micropitting* *Gear*

**Abstract** Rolling contact fatigue is a common failure mode in gears and bearings. However, this failure mode is getting greater attention due to the increasing tendency to use lower viscosity lubricants, specifically in transmission applications, to reduce power loss. Therefore, the lower film thickness can enhance the chances of surface oriented fatigue that initiates micropitting on the contact surfaces.

Though several types of research have been done over the past decades, still there are scopes for further investigations. This study aims to study the effect of the slide to roll ratios (SRR), surface roughness and surface treatment on wear and pitting behaviour under realistic contact conditions. Fatigue and wear damages were quantified by studying the surface topography alteration at different contact cycle intervals.

It was found that under boundary lubrication, initiation of micropitting took place in almost all test runs. However, once the adhesive wear mechanism activated at a higher contact cycle, the initially formed micropitted area started to wipe off. Moreover, for a longer test period, wear volume is almost similar irrespective of SRR. Later on, a surface treatment was studied, and it was found effective in delaying the micropitting initiation by improving the tribological parameters compared to the untreated samples

# #440 Damage evolution predictions on ILTS specimens

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*Unfolding* *Curved laminates* *Damage*

**Abstract** Several finite element models implemented in Abaqus are presented in this investigation for the simulation of the Inter-Laminar Tensile Strength (ILTS) test. L-shaped composite coupons with laminas having different orientations are considered. Experimental results have shown that, in many cases, the coupons fail under interlaminar stresses lower than their allowable values (determined with unidirectional coupons). Preliminary analytical studies have qualitatively attributed this inconsistency to the failure mechanism called induced unfolding. According to this mechanism, failure starts with an intralaminar crack which, under a sufficiently large interlaminar stress (although under its allowable value), propagates instantaneously as a delamination. In the present investigation, this mechanism is modelled combining the Hashin's degradation criterion included in Abaqus (used to model the intralaminar failure) and the use of Linear Elastic Brittle Interface Model (LEBIM) interface elements developed by the Group of Elasticity and Strength of Materials of the Universidad de Sevilla, able to simulate delaminations. Due to the degradation criterion considered, models are solved under plane stress conditions. Additionally, as the crack propagation is highly instable, a new control algorithm developed by Martinez Pañeda is used to overcome the convergence problems due to the snapback behaviour observed during damage evolution.

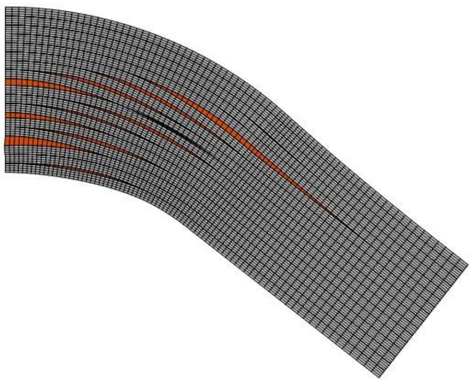

***Figure 1** – Damaged ILTS half-specimen*

# #441 Experimental determination of generalized stress intensity factors from full-field measurements

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*Digital Image Correlation* *Generalized SIF* *Finite Fracture Mechanics*

**Abstract** at the square hole corners, highlighted by inclined cracks with respect to the Vnotch bisector. Generalized stress intensity factors (GSIF) of the opening and shear modes at a V-notch are derived experimentally in a direct manner from digital image correlation (DIC) displacement and strain fields by means of a path independent integral. With increasing square hole side, the opening mode GSIF increases whereas the shear mode one decreases so that the mode mixity globally decreases, together with the crack deflection with respect to the V-notch bisector. GSIFs predictions obtained by means of finite element calculations are in good agreement with those determined experimentally. Applications of the method to real experiments and loading conditions allowed for a better interpretation of the experiments together with a proper identification of the fracture parameters Gc and Sc within a finite fracture mechanics approach.

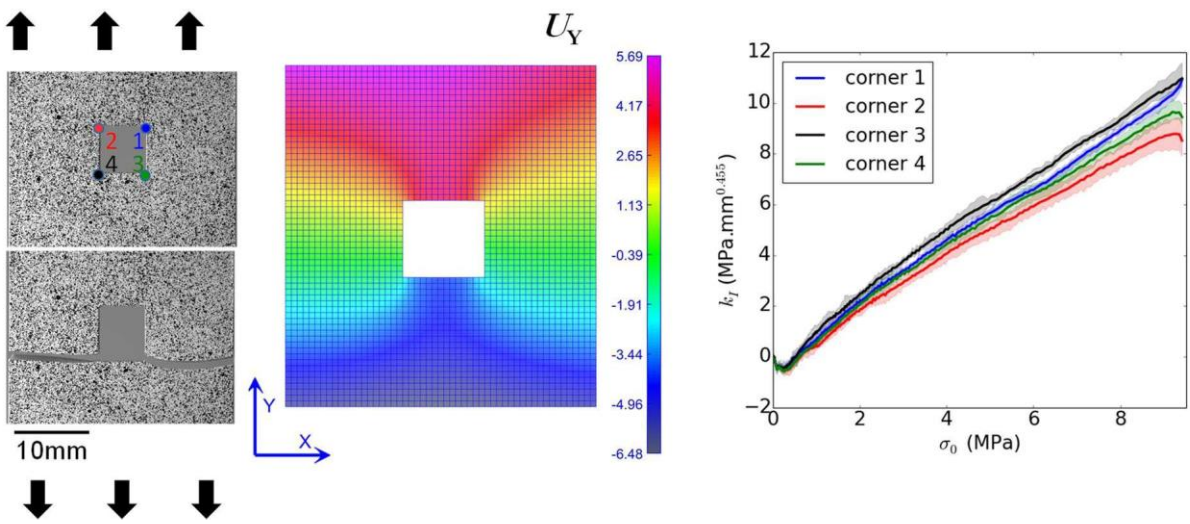


***Figure 1*** *– Description of the methodology, (left), tensile test with a speckle to (center) DIC for extracting the displacement field and (right) derived the generalized stress intensity factor.*

# #442 Delamination Properties of the Aortic Wall

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*Delamination* *Dissection* *Peeling test*

**Abstract** Cardiovascular diseases are the most common cause of death in developed countries. Aortic dissection is one of these life-threatening diseases. It is manifested as a delamination process. Typically, a crack is initiated in the innermost layer of the aorta, referred to as *tunica intima*. Subsequently, it propagates into the middle layer *tunica media*. As blood enters the wall, it causes delamination of its layers. Consequently, the blood flows also in the false lumen that is created between separated parts of the wall. The crack can even reach the external layer, *tunica adventitia*, resulting in hemorrhage with potentially lethal consequences. The effective cross-section of the aorta can also be reduced by the dissection to a degree in which the final rupture of the wall occurs.

The underlying mechanics of this disease has not yet been fully clarified. The experimental research carried out in our study would like to contribute to an explanation of the delamination properties of the artery wall. The delamination strength, which is a quantity that could suggest a risk of dissection, is investigated in the peeling experiments, which resemble mode I crack opening well-known from the fracture mechanics. Peeling experiments were designed to take into account possible effects of material anisotropy and site-specific differences in the mechanical properties that occur along the aortic length. The computational branch of our study is based on the XFEM model of the peeling experiment built in Abaqus and attempts to find location-dependent parameters of the traction-separation law that would reflect age-related changes in the delamination mechanics.

Among others, the results showed that the delamination strength strongly depends on the age of the donor. It was also found that the delamination properties of the aortic wall differ significantly with respect to the crack tip orientation. It suggests that anisotropy is not only a bulk property, but also a phenomenon, which plays a role in discontinuity propagation. In contrast to the aortic aneurysm thrombus delamination properties, our results suggest that the delamination properties of the aortic wall itself are not rate-dependent.

**Acknowledgement** This study has been supported by the Czech Science Foundation in project 20-11186S entitled “Mechanics of arterial delamination and crack propagation”.

# #443 Interaction between tension and cyclic torsion of non-ferrous materials

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*Uniaxial loading* *Fatigue* *Torsion*

**Abstract** In the literature, we may find experimental studies that involve pre-stretching the sheets above the yield stress and then the analysis of impact of such a procedure on the fatigue life under tension-compression conditions. However, we have not found any analyzes of the impact of such procedure on the fatigue life during torsion.

The materials we have examined in the tests and calculations were non-ferrous metals: Mo58 brass and aluminum 6082-T6. We subjected the specimens to two sequences of loading. In the first case, the fatigue tests were performed at the constant load, at the level of n = 20%, 40% and 60% of the number of cycles to failure. Then, the initially damaged specimens with the degree of damage depending on the value “n” were subjected do tension until break. In each case, the yield stress $\sigma_y$ was determined. The second type of fatigue tests consisted of pre-stretching the specimens above the yield stress and then unloading. In this way, the tensile plastic deformation was left in the specimens. In the second step, the specimens preloaded in such a way were subjected to cyclic torsion test until fatigue failure.

A different effect of the combination of static tension and cyclic torsion, depending on the analyzed material, was demonstrated. The microstructure of materials and a different combinations of loads have a decisive role in the propagation of fatigue cracks, so the microstructure and fatigue fractures of the analyzed materials are presented.

# #444 Evaluation of the $T_0$ Reference Temperature for an Ultra High Strength Martensitic Steel

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*Master curve* *Reference temperature* *Ultra high strength steel*

**Abstract** The Master Curve methodology defines an indexing (or reference) temperature, $T_0$, related to the median fracture toughness of $K_{Jc}$-values experimentally measured from standard 1T fracture specimens. Several previous studies have shown that the Master Curve approach is highly effective in describing the dependence of fracture toughness on temperature for a wide range structural ferritic steels, including irradiated conditions, with a yield strength in the range of 275 MPa ~ 825MPa. In view of the technological importance of assessing the fracture integrity of containment vessels, engineering applications of the Master Curve procedure have been primarily focused on describing the temperature dependence of fracture toughness for pressure vessel steels and low carbon structural steels. Moreover, the approach has also been shown to hold for tempered martensitic steels having very high strength, provided they can be considered as falling into the category of ferritic steels for which the Master Curve method and ASTM E1921 are applicable.

However, despite these advancements, more systematic studies to support the extension of the methodology to characterize the dependence of fracture toughness on temperature in ultra high strength steels (UHSS) with nominal strengths exceeding 1000~1200 MPa remain limited. UHSS materials have been increasingly used in several engineering applications that require wear-resistant properties, such as excavator buckets and bulldozer blades, and in lightweight construction, especially for the structural members of mobile equipment, including chassis and superstructures for commercial vehicles, to reduce weight and fabrication costs. The application of such ultra high strength steels is rarely limited by inadequate strength but rather by other factors such as fracture properties. While rather extensive experimental data exist for UHSS steels, the majority of data focuses on tensile and impact (Charpy V-notch) properties. Consequently, further extensions and applications of the master curve methodology to describe the fracture toughness dependence of temperature for this class of material are largely justified as such studies can broaden the toughness-temperature relationship in the transition temperature for the existing toughness database of common structural steels to more advanced structural steels.

As a step in this direction, this work addresses an experimental investigation of the brittle fracture behavior for an ultra high strength martensitic steel using fracture toughness data measured in the ductile-to-brittle transition region (DBT). A primary purpose of this study is to assess the applicability of the Master Curve methodology to describe the fracture toughness transition curve indexed by the reference temperature $T_0$ for a direct-quenched, low alloy martensitic steel. Fracture toughness testing conducted on three-point bend SE(B) specimens and pre-cracked Charpy (PCVN) configurations at different test temperature in the DBT region provides the cleavage fracture resistance data in terms of the $J$-integral at cleavage instability, $J_c$, and its corresponding $K_{Jc}$-values for the tested ultra high strength steel. While this class of material having a martensitic microstructure is currently beyond the reach of ASTM E1921, the analyses described shown that the predicted normalized curves of median fracture toughness vs. temperature are in good agreement to the experimental measurements.

# #445 Advanced UT for structural integrity assessment of welded joints

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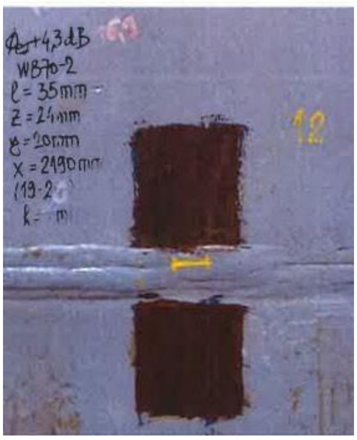
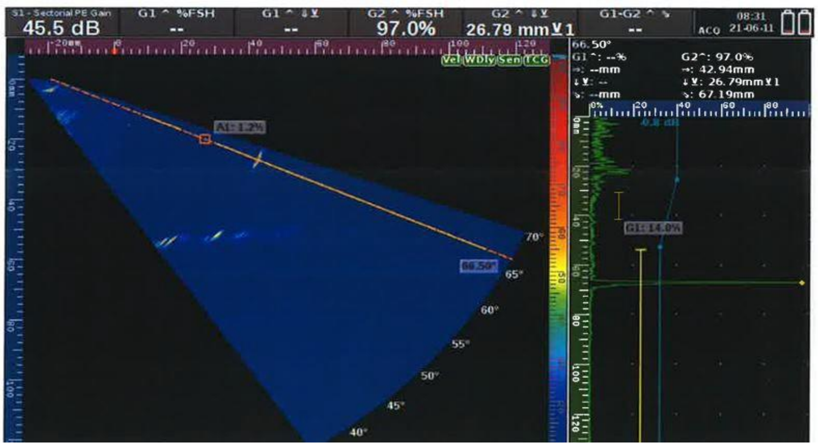
*Advanced UT* *Structural Integrity* *Welded Joints*

**Abstract** Welded joints are the ‘weakest’ location in some structures, in this case - tanks, and the detection of defects in welded joints is very important, since defects may cause failure with catastrophic events. NDT UT techniques that have been performed on welded joints show insight into the quality of the welded joints, and results imply whether tanks are safe to continue to be into exploitation. Two different UT methods are used for testing: conventional UT method, Phased Array UT method (PAUT) . All of these tests are performed in accordance with relevant standards. Assessing the integrity of pressure equipment is a very responsible job. Analysis of critical defects using methods of fracture mechanics will be given in this paper. The review of non-destructive testing of pressure vessel for compressed air is given, as well as the assessment and analysis of defects on the integrity of the vessel itself. Advanced UTs, such as Phased Array Ultrasonic Testing (PAUT) and Time of Flight Diffraction (TOFD), are used to evaluate defect position and size more precisely, as shown in the case of pressure vessel for the compressed air in Reversible Hydro Power Plant Bajina Bašta, in Serbia. The ultrasonic device SONATEST Veo+, 32:128 was used, with transverse waves, sound velocity 3240 m/s. The pulse-echo method was used, along with sector scanning and test amplification 45.5 dB. Figure 1 presents UT indication in a welded joint.






a) b)

***Figure 1** – UT indications: a) marked on the outer surface, b) as seen on the screen.*

# #446 Performance of RC beams externally strengthened with hybrid CFRP and PET-FRP laminates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*Strengthening* *hybrid* *FRP*



**Abstract** The use of fiber-reinforced polymers (FRP) composite materials in strengthening applications of reinforced concrete (RC) structures has been gaining wide popularity in the recent decades. This is due to its superior properties such as high strength to weight ratio, durability, and versatility. In fact, it is well established that bonding FRP materials to the soffit of the RC beams enhances its flexural capacity. However, the non-yielding characteristic of FRP materials is a major concern, and often results in a sudden and brittle failure mode of the strengthened member. To encounter this issue, a new type of FRP materials composed from polyethylene terephthalate (PET) fibers have been developed. Compared to conventional FRPs, PET-FRP have large deformability and possess a nonlinear stress-strain relationship. Employing PET-FRP in the retrofitting industry reduces construction waste, enhances the capacity of structures, and provides a solution that encourages the concept of sustainability. However, these types of large rupture strain (LRS) FRPs have lower stiffness and tensile strengths than conventional FRPs. Therefore, the main aim of this study is to combine the lower stiffness and large rupture strain of PET-FRP sheets with that of the higher stiffness and strength of carbon FRP (CFRP) sheets resulting in a new hybrid composite system. Accordingly, the research program consisted of four RC beams externally strengthened with CFRP, PET-FRP, and their hybrid combinations, in addition to a control unstrengthened beam specimen. The beams were tested under four-point bending and load-displacement curves along with the failure modes, strength, strain in the FRP, and ductility of the beam specimens were examined. Test results indicated that strengthening with PET-FRP laminates significantly enhanced the deformation capacity of the strengthened specimens compared to that with CFRP. In addition, the hybrid mix between CFRP and PET-FRP resulted in 46-48% strength improvement compared to the unstrengthened control beam. However, the effectiveness of the hybrid system was not pronounced in terms of ductility due to the premature debonding of the concrete cover that occurred before utilizing the strain of the hybrid system. Hence, it is advised for future research studies to anchor the hybrid sheets by means of end U-wraps or FRP spike anchors to delay the debonding failure and to exploit the benefits of the hybrid system.

# #447 Effect of flange geometry on the shear capacity of RC T-beams

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*Shear* *RC* *T-beam*

**Abstract** Shear failure in reinforced concrete (RC) beams is sudden and brittle with no warning signs prior to failure. As a result, extensive research has been conducted over the past century to develop design equations and models that combine the variables contributing to the shear resistance in RC members. Despite that, this essential phenomenon is still the least understood problem in reinforced concrete beams. In most current design codes of practice, the nominal shear capacity of RC beams is computed from the superposition of concrete and steel reinforcement strengths. The contribution of concrete in slender beams comes from three sources: shear resisted by concrete in the uncracked compression zone, shear transfer by aggregate interlocking at the edge of the diagonal crack, and dowel action from the longitudinal reinforcement. In most shear design equations, the shear is assumed to be resisted only by the web of the beams by aggregate interlock at the shear crack. The contribution of shear resisted by flanges of T-sections is usually ignored in the shear strength models even though it was proven by many experimental studies that the shear capacity of T-beams is higher than that of equivalent rectangular cross-sections. Ignoring such a contribution results in a very conservative and uneconomical designs. Therefore, the aim of this research is to evaluate and compare the shear capacity of RC T-beams using shear strength models available in the design guidelines and literature. Some of the chosen design models included the flange contribution to the shear capacity, while other models neglected this phenomenon. The models will be evaluated against an experimental data base that included slender RC T-beams with different geometry, flexural and shear reinforcement ratios, compressive strength of concrete, and shear span-to-depth ratios. In addition, the effect of the ratio of flange width to the web width and flange thickness to the total height of the member on the shear capacity of the T-beams will be assessed. The analytical results showed that the shear capacity of RC T-beams is higher than that of equivalent rectangular beams. The strength enhancement is mainly depended on the geometry of the flange. In addition, the shear capacity is underestimated by most of the current shear strength models. As a result, it is recommended that the effect of flange is included in the design equations to aid in a more economical design that is consistent with the actual capacity of such members.

# #450 Experimental Validation of the Formulation for Maximum Socket Depth Estimation of Non-Reduced Strength Bolts

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*Structural integrity* *Experimental validation* *Metal forming*

**Abstract** In fracture tests, fasteners are expected to fail from the thread region. Any failure from the under-head region suggests a deficiency in design, material, grade etc. Therefore, it is important to estimate the critical socket depths of fasteners without any sacrifice from mechanical properties, i.e. no failure from head region was expected. An analytical model was developed by the authors to calculate the maximum socket depth of the bolts with internal socket in cases where the shaft diameter is smaller than the socket diameter, and the accuracy of this model was verified by numerical simulation studies. In this study, the analytical formulation introduced for the estimation of the maximum depth of the socket of the bolts that have a shaft diameter smaller than the diameter of the socket was validated with experimental studies. The maximum socket depth of a chosen representative bolt calculated by the analytical formulation for weight reduction was verified experimentally. Bolts with varying socket depths were manufactured through cold forging method and bolt tension tests were carried out on quasi-static tension test machine. Results showed that experimental predictions were in good agreement with the results taken from developed analytical model. The critical depth of the socket calculated using the analytical formulation was 3.2% more secure compared to the experimental results. As a result, the validity of the analytical formulation to calculate the critical socket depths of bolts with smaller shaft diameter than socket diameter was confirmed by experimental studies.

# #451 Friction Stir Welding parameters effect on static and fatigue strength of dissimilar aluminum to polymer matrix composite joints

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*Friction stir Welding     Central Composite Design     Static Strength     Fatigue Strength*

**Abstract** An engineering grade, polymer matrix composite (PMC), Noryl$^{TM}$ Resin GFN2, and an aluminium magnesium silicon alloy, AA6082-T6, were joined by Friction Stir Welding (FSW) in overlap configuration. In order to assess the effects of advancing and rotating speeds on both static and fatigue strengths, a design of experiments (DoE) was carried out using Central Composite Design (CCD) as experimental methodology. The joints, from which the specimens were manufactured, were submitted to quasi-static tensile tests to assess the ultimate tensile load (UTL), while the fatigue behavior was assessed by cyclic loading under a stress ratio of 0.1, with both assessments being carried out at room temperature. Additionally, the cross-sectional macro and microstructures, as well as the chemical composition of the joints associated to each set of welding parameters, were also investigated to fully characterize the underlying joining mechanisms, either mechanical interlocking or chemical boding.

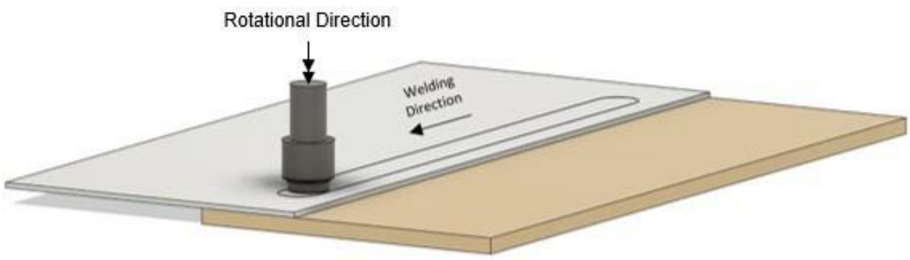


***Figure 1*** *– Three-dimensional schematic of friction stir welded dissimilar aluminum to polymer matrix composite joint.*

# #452 Very High Cycle Fatigue tests: temperature increase and material's performance

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*Ultrasonic fatigue* *Intermittent loading* *Fatigue life*

**Abstract** Very high cycle fatigue (VHCF) test machines made it possible to obtain fatigue life response after $10^6$-$10^7$ cycles in a shorter time than conventional fatigue machines. The high frequency (20 kHz) is responsible to accelerating tests. Although, in some cases, this ultrasonic frequency may exert a great influence on the specimens' temperature during the test, promoting the specimens to heat up and could interfere in the material's fatigue performance. In order to understand the temperature effects during VHCF test, this study proposed an experimental test with DIN 34CrNiMo6 steel, which is widely used in several engineering applications. The ultrasonic fatigue tests were submitted with different stress levels and intermittent loadings (pulse-pause technique) conditions with R=-1. VHCF tests were performed with the aid of thermographic test in order to describe the temperature evolution and material's fatigue performance. The test showed the fatigue life was shortened, in some conditions. Moreover, the temperature gradient at the beginning of the ultrasonic fatigue test ($\theta$) was extracted from the temperature-number of cycles ($T$-$N$) curve and the heat dissipation per cycle ($Q_{cyc}$) was calculated.

# #453 Improving Cruciform Test Specimens Frequency Response for VHCF Ultrasonic Biaxial Fatigue Testing

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*Biaxial Testing* *Very High Cycle Fatigue* *Ultrasonic*

**Abstract** Very High Cycle Fatigue (VHCF) using ultrasonic machines is a subject that is receiving growing attention. Recent developments focus on biaxial stresses which are of interest to industries such as the aeronautical where plane stresses appear in the fuselage and wings. This paper aims at improving the design of biaxial VHCF cruciform test specimens that have known issues which have not yet been solved. Studies are carried out by using both numerical and experimental methods. In the first part of the study, the shape of a cruciform type specimen is improved. The main goal is to ensure the test specimen only has one mode shape in the 19.5-20.5 kHz machine's operating frequency range, since it was observed that the existence of more than one mode may affect experimental results. The final specimen confirms the theoretical discussion and the design parameters that are obtained have managed to avoid undesired mode shapes in the operating frequency range of the test machine. The second part focuses on asymmetric models, used to create non-unitary biaxiality ratios. Comparing the simulation results with the experimental data shows that the strain rates can provide acceptable prediction of biaxiality ratios. Moreover, it was observed that the biaxiality ratios obtained from stress, displacement and strain are not equal to each other and, in fact, can be correlated by an expression that was derived in the course of this research.

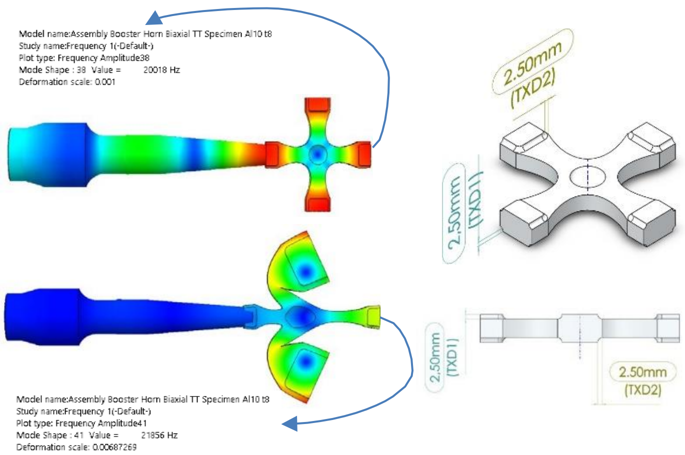


***Figure 1** – Example of results obtained from FEA after the optimization process.*

# #454 Shear Strengthening of Reinforced Concrete T-Beams using Carbon Fiber Reinforced Polymer (CFRP) Anchored with CFRP Spikes

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**Abstract** Reinforced Concrete (RC) structures deteriorate over years due to many reasons including corrosion of reinforcing steel, carbonation of concrete, overload on structural members, among others. This may result in flexural or shear deficiency in RC beams. The failure of shear-deficient RC beams is usually brittle, sudden and with little warning, if any. Diagonal shear cracks will form due to load increase that may result in complete fracture of the RC beam. Therefore, deteriorated and shear-deficient RC beams need to be strengthened to avoid such undesirable shear failure. This paper investigated shear strengthening of RC T-Beams using carbon fiber reinforced polymer (CFRP) laminates anchored with spikes. The beams have been strengthened in flexure to avoid flexural failure and then strengthened in shear using CFRP sheets that were anchored with CFRP spikes. Six beams were strengthened with CFRP laminates at 45$^{o}$ and at 90$^{o}$ inclination angles and anchored with embedded CFRP spikes with different depths (50 mm and 75 mm) and different diameters (10 mm and 12 mm). Wrapping (U-Wrapped) was also used for anchoring the flexural CFRP sheets. The beams were tested to failure and their capacity were compared with the capacity of an unstrengthen control beam. It is observed that the capacity of the strengthened beams is increased by up to 45% compared to that of the control beam. The U-Wrap anchoring of the CFRP sheets enhanced the beam capacity further. The inclination of the CFRP sheets and the embedment depth of the spike anchors influenced the cracks of the failure modes and fractures pattern of the tested RC T-Beams.

Keywords: CFRP, Reinforced Concrete, Shear Strengthening, Spike Anchors, U-Wrapped.

# #455 Comparison of Shear behavior of Normal and Recycled Aggregates Beams Strengthened with CFRP Sheets and U-wrap anchors

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**Abstract** In recent years recycled aggregates, from construction demolition waste, has been used as a replacement to normal (natural) aggregates in concrete. This is to preserve the depletion of natural resources and to further reduce the carbon footprints in terms of energy depletion and waste disposition. Mechanical properties, such as compressive and tensile strengths, of recycled aggregates concrete (RAC) have been investigated by several researchers and were compared with that of normal aggregate concrete (NAC). In this investigation, the shear strength and modes of failure of RAC and NAC beams have been investigated. In addition, the behavior of RAC and NAC beams strengthened with carbon-fiber-reinforced-polymer (CFRP) laminates and anchored with U-wraps have been studied. Several RAC and NAC shear-deficient rectangular beams were cast and some were strengthened in shear with externally bonded CFRP sheets with different orientations (45º and 90º) and different CFRP U-wrap anchor configurations. The beams were tested to failure under four-points bending. The test results indicate that the shear capacity of all specimens strengthened with CFRP composites increased significantly compared to the control beam specimens. The performance of the RAC and NAC beams before and after strengthening were compared. It was observed that the RAC outperformed the NAC beams in most of the cases studied. The percentage increase in the shear capacity of RAC beams reached almost 100% of the control beam for the beams with U-wrap anchors and 45° inclination of the CFRP shear strengthening sheets. The ACI440.2R-17 code was used to predict the shear strength of the tested RAC and NAC beams and it was observed that the predicted capacities were very close to the experimentally measured ones, especially for beams with side wrap anchors of 90°.

**Keywords:** *Carbon Fiber Reinforced Polymers (CFRP), Shear Strength, Recycled Aggregates, Normal Aggregates.*

# #458 Multiscale phase-field modeling of fracture in short glass fiber reinforced polymers

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*Short glass fiber reinforced polymers*   *Phase field modeling of fracture*   *Multiscale modeling*

**Abstract** Short glass fiber reinforced polymers (SFRPs) are of increasing interest in industrial applications. To ensure a safe use of SFRP components subjected to complex operational loads and harsh environments, the knowledge of their operating limits is of great importance. Therefore, we are interested in modeling and simulating fracture mechanical processes in SFRP components subjected to monotonic loads. Typically, such components are manufactured by injection molding, which results in locally varying fiber orientations [1]. This in turn significantly influences the macroscopic mechanical behavior of the composite material.

We approach the modeling task by a multiscale database approach. To resolve the relationship between the microstructure and the macroscopic behavior we extend the established, isotropic phase field models of fracture [2-5] towards the anisotropic case making use of the fiber orientation interpolation concept [6]. The developed model is implemented in the commercial finite element package Abaqus with the algorithmic approach in [7]. To feed the database, the anisotropic elastic coefficients are obtained from previously executed micromechanical simulations on realistic microstructures [1] using the efficient microscopic solver FeelMath [8]. The performance of the proposed approach is demonstrated by means of several numerical investigations.

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# #461 Combined SCC and EAF Crack Growth Rates for Alloy 600 in a PWR Environment

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*Stress-Corrosion-Cracking Environmentally Assisted SCC-Fatigue Interaction Fatigue*

**Abstract** A programme of testing has been performed to explore how different crack growth models and codes fared with loading conditions that bridge the gaps between what have traditionally been viewed as Environmentally Assisted Fatigue (EAF) and Primary Water Stress Corrosion Cracking (PWSCC). The testing in simulated PWR primary water conditions has used a combination of sawtooth waveforms, trapezoidal waveforms and constant loading in the attempt to promote different effects that might be associated with contributions from SCC or EAF. Materials with different microstructures and levels of cold work have also been used to understand the material conditions bound by the codes.

As-Received and 15% Cold Forged Alloy 600 have been tested, in an air and a PWR environment, under pure fatigue loading and combined SCC/EAF loading. The test data are compared against both the NUREG-6964 and ASME XI Non-Mandatory Appendix C equations for both EAF and SCC crack growth rates, and against the NUREG-6964 superposition law for the combined effects. It is shown that the inclusion of the rise-time cap of 30s in Non-Mandatory Appendix C may be inaccurate for EAF with long rise times, and that the NUREG law offers best agreement with the data. In both the As-Received and Cold Worked conditions, the heats of Alloy 600 tested also show some enhancement over the NUREG predictions.

The test methodology and results are presented alongside how the different codes and models represented the data. The material conditions and microstructures will be discussed, along with analysis of how these have influenced the crack growth rates and fracture surface morphology.

# #462 Fabrication and characterization of 316L stainless steel components printed with material extrusion additive manufacturing

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*Additive Manufacturing* *Material Extrusion* *316L stainless steel*

**Abstract** Material Extrusion Additive Manufacturing (MEAM) is an innovative technique recently used to produce metal and ceramic components. The fabrication process involves three main phases: shaping, debinding, and sintering. The shaping phase is obtained using a simple FDM printer with a filament composed by metal powder dispersed in a polymeric matrix. In this work several specimens were fabricated using the commercial filament BASF Ultrafuse 316L which contains the 88wt% of 316L powder. Specimens were printed to test the mechanical properties of the parts. The present work illustrates the main issues and the key parameters of the shaping phase to achieve high quality components before and after the debinding and sintering phase. The sintered parts were analyzed to assess the final density and the mechanical properties with both static and dynamic tests and the main failure mechanisms of the fabricated parts are studied and compared to wrought counterparts.

# #463 Revealing the Intrinsic Ice Adhesion at the Nanoscale

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*ice adhesion anti-icing, molecular dynamics simulations*

**Abstract** Weakening ice adhesion is one of the key goals in anti-icing materials development. The strength of ice adhesion is underpinned by the atomistic interactions at the real contact area between ice and its substrate. As such, deciphering the intrinsic ice adhesion strength at the real ice-substrate contacting area is crucial to the understanding of the anti-icing performances of different icephobic surfaces. The current study focuses on utilizing molecular dynamics simulations to probe the atomistic ice interactions with different substrates of varied inter-atomic interaction potentials.[1-3] Diving into the nanoscale origins of ice adhesion, the research offers insights on key factors in lowering ice adhesion, including the interesting impacts of an amorphous quasi-liquid water layer on ice adhesion as well as different ice rupturing modes from the substrate (Fig. 1).[4-6] The results of this study shed new light on the nanoscale fundamentals of ice adhesion, and at the same time seed design concepts of future anti-icing surfaces.

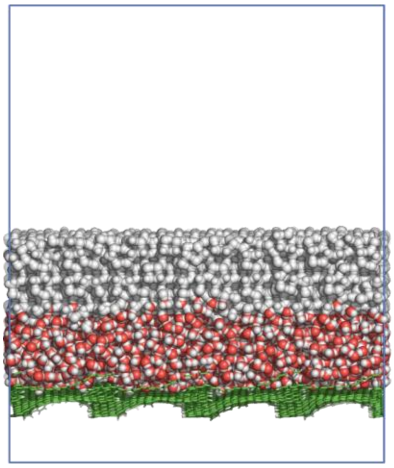

***Figure 1** – Ice adhesion on a substrate via a quasi-liquid water layer*

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# #464 Grain refinement effect on mechanical behavior of in situ $(TiB+La_2O_3)$/Ti-6Al-4V manufactured by laser melting deposition

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*Additive manufacturing* *Microstructure evolution* *Transgranular fracture*

**Abstract** The prevailing solidification conditions of titanium alloys fabricated by laser additive manufacturing (AM) are characterized with intrinsic ultrahigh cooling rate and thermal gradient, facilitating the growth of unfavorable and anisotropic columnar grains. Therefore, columnar to equiaxed transition (CET) during AM has been a significant challenge. In this study, Ti-6Al-4V (Ti64) powder was coated with micron-sized $TiB_2$ and $La_2O_3$ for the powder feeding and the reinforced $(TiB+La_2O_3)$/Ti64 was manufactured by laser melting deposition (LMD). The detailed morphological features of Ti64 matrix and in situ phases with different compositions were investigated to reveal microstructure evolutions and tensile refinement effect. Result indicates that in situ TiB and $La_2O_3$ can effectively provide sufficient constitutional supercooling and nucleating particles to tailor a three-dimensional quasi-continuous microstructure (Fig. 1). Besides, the mechanical performance of ultimate tensile strength is improved obviously as the increasing the addition of in situ reinforcements. The work promotes understanding the role of in situ TiB and $La_2O_3$ on the formation of equiaxed microstructure mechanism during LMD process and proposes a potential transgranular fracture mechanism of the composites.

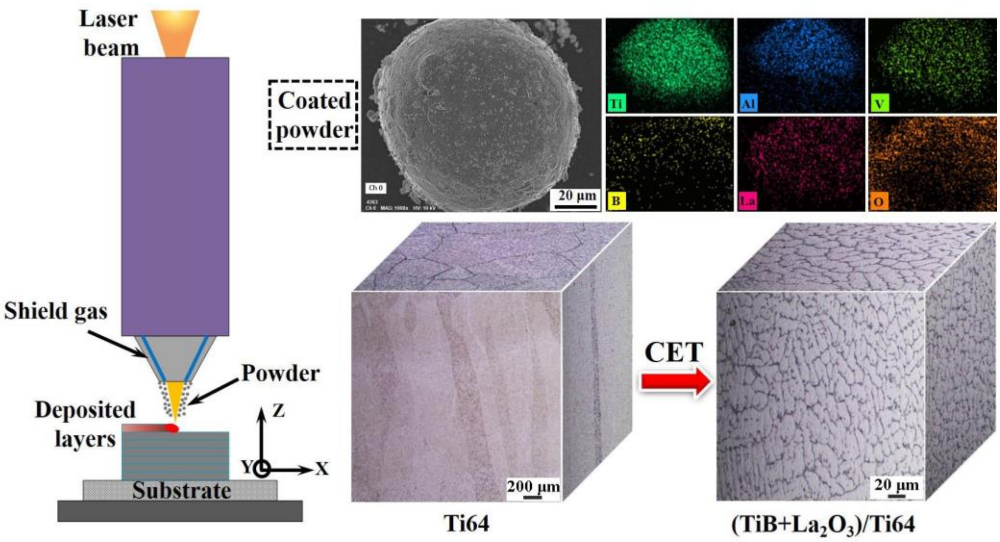


***Figure 1*** *– SEM of coated powder and optical microstructures of Ti64 and (5wt.% $TiB_2$+0.5wt.% $La_2O_3$)/Ti64 fabricated by LMD*

# #465 Size effect in PLA and PETG specimens obtained using FDM

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*Size effect* *PLA* *PETG*

**Abstract** The Semi Circular Bend Specimens (SCB) loaded in symmetric three point bending were considered to investigate the size effect in PLA and PETG specimens obtained using FDM technology. Four specimen sizes were manufactured (with radius R = 10, 20, 30 and 40 mm, with thickness of 6 mm, Fig. 1) and tested (Fig.2).

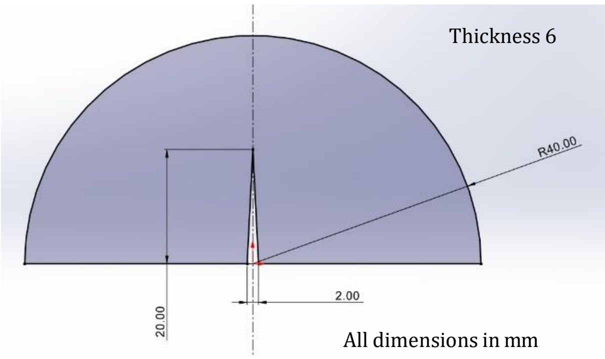


***Figure 1-*** *SCB specimen dimensions*

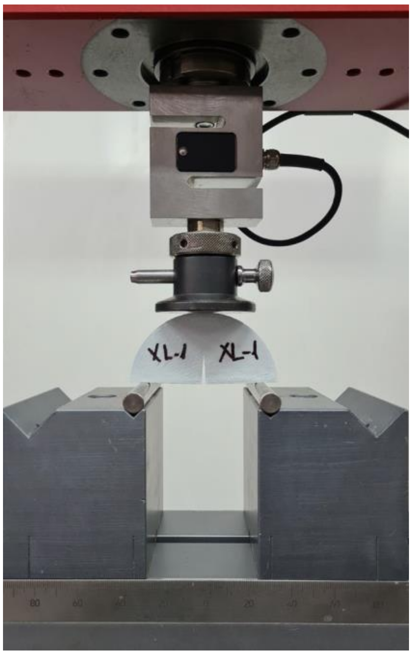


***Figure 2*** *– Specimen in bending grips*

A strong size effect for PLA and PETG materials obtained through additive manufacturing is experimentally demonstrated, representing the transition between strength of materials approach (with no size effect) and asymptotic case of linear elastic fracture mechanics. This agrees well with the size effect law proposed by Bažant (2002) and Zdenek et al. (2003).

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# #466 Evaluation of the Endurance Limit of Notch Intersections under inner-pressure Loading

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*Autofrettage* *Ultra High Strength Steel* *Residual Stress*

**Abstract** A large number of components subjected to internal pressure show intersecting holes from which failure originates. In order to extend the components' life-span, they can be subjected to the process of autofrettage which introduces life-prolonging residual stresses. These residual stresses prolong the components' life to crack initiation and can even provoke the phenomenon of crack arrest, leading to the possibility of loading the components with greatly increased pressures. In the present work, the practically important endurance limit of notch intersections under inner pressure-loading was investigated numerically and experimentally. For component-like specimens with intersecting holes in non-, partially- and fully-autofrettaged state, the endurance limit was numerically evaluated with a linear-elastic fracture mechanics based approach. To achieve reliable results, finite-element-analysis was performed with material data derived from extensive material testing to describe the residual stress distribution introduced by the autofrettage process. The numerically derived results are then compared to results from real testing of component-like specimens. It can be shown, that the fracture mechanics based approach is capable of predicting the endurance limits accurately. Furthermore, even the length of arrested cracks can be predicted by the method used.

The results in this work were part of an  research project funded by the German Federation of Industrial Research Associations (AiF) under grant number 19790 N and was supported by the Federal Ministry for Economic Affairs and Energy on the basis of a decision by the German Bundestag.

# #467 Design and development of a bioabsorbable interference screw for fused filament fabrication

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*Bioabsorbable screw* *Design for AM* *FFF*

**Abstract** In this work, the design and development of a new bioabsorbable interference screw is proposed. This interference screw is perforated along its length with holes that have an elliptical geometry to allow a calcium triphosphate-based bone cement to be introduced and that should flow along the screw and exit through the holes to contact with the bone, avoiding the enlargement of the bone tunnel. Several models consisting in different thread and hole geometries were designed and manufactured by fused filament fabrication. Finite element analyzes to simulate screw insertion into the bone tunnel and implant pullout from the bone tunnel were performed. The insertion torque resistance of several models of commercially available bioabsorbable interference screws was tested to obtain a threshold that the interference screw developed in this work had to exceed. Printed samples were tested to assess their resistance to insertion torque and implant pullout.

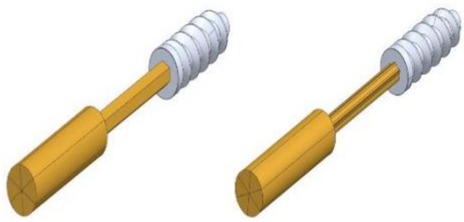

***Figure 1*** *– Screw and screwdriver of the two models studied*

# #468 Ironing process influence on the warping of ABS parts produced by Fused Filament Fabrication

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*Ironing* *ABS* *Warping*

**Abstract** Fused Filament Fabrication (FFF) technology is growing at an accelerated rate, being already widespread and used in many end use applications. As FFF becomes more important, its problems assume a bigger relevance. Warping is a distortion type of defect where the surfaces of the printed part do not follow the intended shape of the design and is one of the most common problems when printing in ABS. Ironing, a heat treatment process originally developed to reduce surface roughness has been previously proposed as a potential solution for this problem. To address this need, this work aims to determine the influence of FFF printing parameters on the warping deformation process of ABS and study the impact of applying the ironing process on warped specimens. The results obtained are promising in what regards the implementation of this solution in future applications. Under specific conditions, Ironing was successfully validated as a method to reduce warping in ABS parts produced by FFF.

# #469 Preliminary results on the optimization of shape memory polymers geometric parameters to enhance the thermal loads activation range

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*4D-Printing* *Thermal Loads* *Geometric parameters*

**Abstract** Over the last decades 3D printing has found applications in all areas of engineering ranging from electronics to biomedical industries due to its efficiency in the use of the material in terms of mass customization and waste reduction, and its high resolution and precision during the prototyping stage. Yet, while, the traditional additive manufacturing industry is developing new application or it is proposing some improvement of the static and inanimate 3D printed components; a novel technology i.e., the 4D printing, is arising. 4D printing adds a temporal dimension to 3D, by providing vitality to the design of shape memory materials through the use of an external stimulus to trigger the transformation of the object into another designed structure [1].

The shape memory materials consist of hydrogels, ceramics, metals, alloys, and polymers, and they have the tendency to change in shape due to exposure to specific stimuli, such as temperature, light, humidity, and electromagnetic radiation. This phenomenon has been studied in the scientific literature concerning different fields of application: e.g., in van Manen et al. 2017 [2] where the deformations induced by thermal stress are analyzed for polylactic acid (PLA) components obtained from 3D printers. Based on these analysis, the authors propose self- assembling origami for various applications. In Lantada and Rebollo, 2013 [3] the reversibility of transformations for continuous applications in the industrial field is analyzed; in Lee et al., 2017 [4] various types of activation methods for shape-memory materials are compared, to better exploit types of stimuli response (e.g. fabrics and paints) that may be implemented easily, quickly, and in an economic way. Finally, in Yu et al., 2020 [5] similar tests are carried out as in [1], both for PLA and Carbon Fiber composite PLA components, to obtain the activation temperature that characterizes these materials at room conditions.

Starting from this background of knowledge the objective of the present contribution is to improve the available information about the behavior of PLA shape memory polymer under the effect of homogeneous thermal stimuli. To achieve this goal, the variation of response of PLA samples - depending on its constitutive geometric parameters - such as density and infill angle – and on the temperature induced stimulus will be analyzed. The purpose of this work is to search for precise relationships between these parameters, to be able to expand the temperature range of activation of the PLA samples so that their transformation capabilities are enhanced even at lower activation temperatures.

In parallel, preliminary test results will be used to create a finite element model FEM as accurate as possible to support the experimental procedure and validate the results.

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# #470 2D finite elements for the computational analysis of crack propagation in brittle materials and the handling of double discontinuities

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*Extended Finite Element Method* *Discontinuities* *Equivalent Polynomials*

**Abstract** Crack growth simulations by way of the traditional Finite Element Method claim progressive remeshing to fit the geometry of the fracture, severely increasing the computational effort. Methods such as the eXtended Finite Element Method (XFEM) allow to overcome this limitation by means of nodal shape functions multiplied by Heaviside step function to enrich finite element nodes. Through the medium of a discontinuous field, the entire geometry of the discontinuity can be modelled regardless of the mesh, avoiding remeshing. In this paper two shell-type XFEM elements (a three-node triangular element and a four-node quadrangular element) to evaluate crack propagation in brittle materials are presented. These elements have been implemented into the widespread opensource framework OpenSees to evaluate crack propagation into a plane shell subjected to monotonically increasing loads. Moreover, in the perspective of fracture propagation simulations, the problem of managing multiple cracks without remeshing or operating subdivisions on the integration domain has been investigated and a four-node quadrangular finite element for the computational analysis of double crossed discontinuities by the means of equivalent polynomials is presented in this paper. Equivalent polynomials allow to overcome inaccuracies on the results when performing standard numerical integration (e.g. Gauss-Legendre quadrature rule) over the entire domain of XFEM elements, without the need of defining integration subdomains. The presented work and the computational strategy behind it may be extremely useful not only in the field of fracture mechanics, but also to solve complex geometry problems or material discontinuities.

# #471 Implication of the grain boundary character on the hydrogen embrittlement of nickel alloys: from the diffusion and trapping to the fracture assisted by hydrogen

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*Nickel alloys* *Hydrogen embrittlement* *Grain boundary*

**Abstract** Hydrogen Embrittlement (HE) is one of the causes mainly evoked in premature rupture of industrial components exposed to aggressive environment. Many studies have been conducted in order to understand the mechanisms involved during this degradation, and the influence of metallurgical states. However, the contribution of grain boundary character on the damage assisted by hydrogen remains a little studied and point of controversy. In fact, the brittle intergranular fracture promoted by hydrogen ingress in the material depends on densities and organizations of defects near grain boundaries. Particularly, we illustrate first the relation between the grain boundary character and the different defects and trapping sites stored, and their consequences on hydrogen transport and segregation. High-angle Random grain boundaries (R) are considered as a disorganized phase where the hydrogen diffusion is accelerated, while the Special grain boundaries (∑) constitute a potential zone for hydrogen trapping due to the high density of trapping sites as dislocations and vacancies. The predominance of one phenomenon depends on several parameters, such as the grain size, the probability of grain boundaries connectivity, the grain boundaries energy and the excess of free volume. Additionally, our experiments confirm that hydrogen promotes vacancies formation, probably in grain boundaries. In a second part, we have explored the role of the Random grain boundaries on damage assisted by hydrogen. Tensile strengthening is reduced under hydrogen flux when the fraction of random grain boundaries increases. These results support the idea that hydrogen flux promotes intergranular fracture more than the hydrogen concentration.

# #472 Mechanical behaviour of cycled shape memory alloy

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*Fracture* *Cycling* *Shape Memory Alloy*

**Abstract** The Shape memory alloys often are used in many industrial, medical and automotive fields due to the ability to recover the initial shape caused by after external loads. This aspect is due to the variations of the microstructure which can depend on thermal and/or mechanical causes (Fig. 1). Up to now, many models have been developed in order to describe the mechanical behaviour of SMA but most of them don't take into account the real microstructure. In this work a traditional equiatomic NiTi SMA has been investigated both in terms of microstructure evaluation and in terms of mechanical cycling behaviour up to degratate the memory ability, obtained at around 100 cycles. The cycling behaviour has been investigated and a model has been proposed to predict the mechanical behaviour and the ability to recover the initial microstructure. The damaged alloy has been investigated in terms of surface fracture analysis obtained by traditional tensile tests.

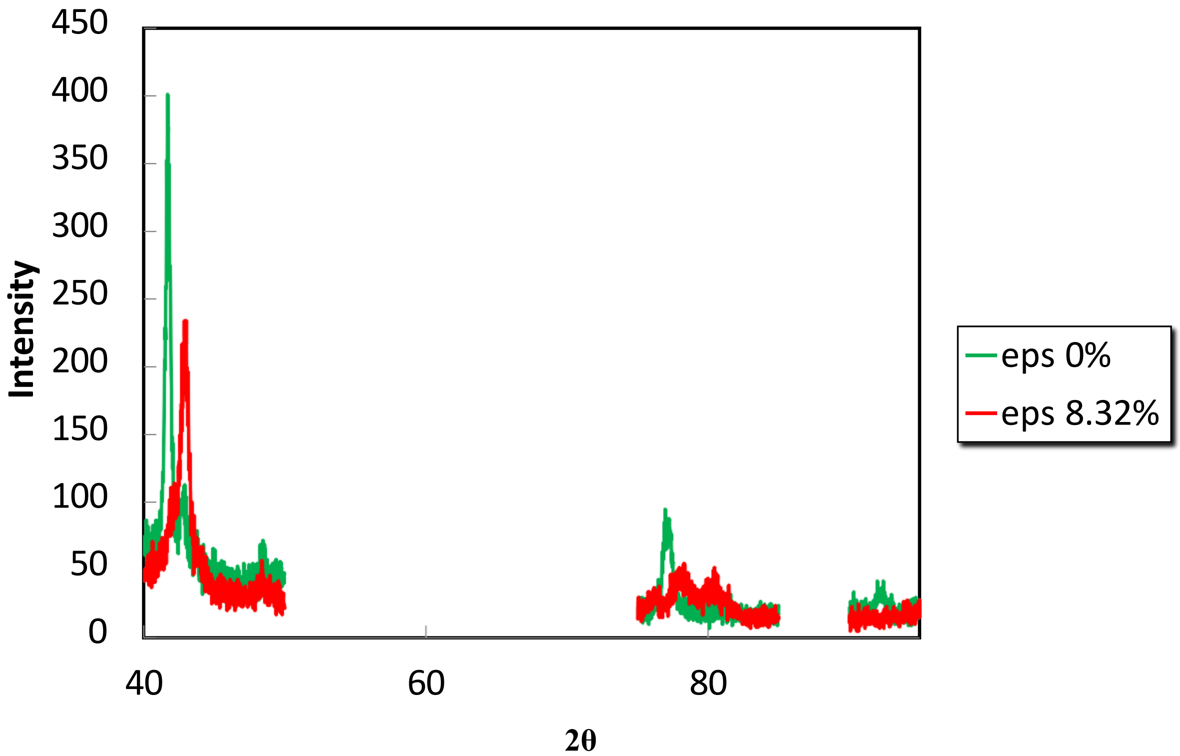


***Figure 1** – Austenite and Martensite diffraction spectra*

# #473 Damage detection of CFRP filament wound tubes using electrical resistance measurement

Nikola Schmidová[1], Tomáš Ponížil[2], Bohumil Kropík[1], David Blaha[1], Zuzana Ficková[3], Milan Dvořák[1], Karel Doubrava[1], Miloslav Poustka[1], Milan Růžička[1]

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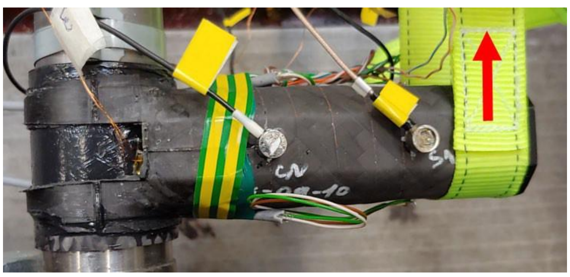
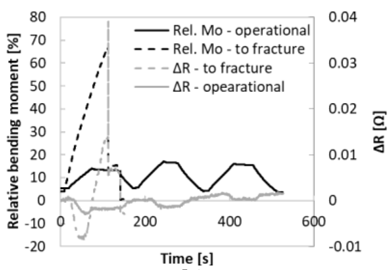
*Damage detection* *Filament winding* *Polymer-matrix composites*

**Abstract** The electrical resistance measurement method was used for damage detection of Carbon Fiber Reinforced Polymer (CFRP) tubes during torsion and flexural loading. The cylindrical shape specimens were manufactured using a filament winding technology. The specimens were manufactured with integrated loop joints at the ends in a single production step. This configuration of tubes with integrated joints allows very effective load transfer and it is also efficient from the manufacturing point of view. This type of components could be used in construction of robotic arms for automated processes. Possible collisions and resulting overloading can cause damage to the composite tubes. Such damage could be overlook due to to cabling, coating and casing covering the surface of the robotic arms. In addition to the above, the requirement for a smooth surface must also be met. Therefore, possible way how to easily detect serious damage of CFRP tubes was investigated, together with a testing of a novel approach to an electrical contact manufacturing. The el. contacts for damage monitoring were made of carbon fiber tows with electrically connected endings. They were integrated to the composite structure during filament winding process. This would not be possible with the el. contacts, which are usually glued to the surface of the specimen. A total of six specimens were made. Four specimens were loaded by flexural loading and two specimens were loaded by torsional loading. All specimens were loaded by three cycles of operational loading and then loaded to final fracture. It was shown that the presented type of electrical connection to the structure is feasible, does not disturb the surface of the sample and does not affect the ultimate strength of the specimen. According to our measurements, operational loading could be monitored only to a limited extend using the el. resistance measurement. This is because the fracture damage caused significant change in measured electrical resistance of the specimen for both torsional and flexural loading. The presented measurement configuration with electrodes made of integrated carbon fibers is suitable for further investigation in the field of fracture damage detection of carbon fiber wounded profiles.


a)



b)

***Figure 1*** *– Specimen for flexural loading: a) experimental setup of flexural loading, b) measured el. resistance during 3 cycles of operational loading and during loading to fracture*

# #474 Additively manufactured tensile ring-shaped specimens for pipeline material fracture examination - influence of geometry

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*PRNT* *Additive manufacturing* *Fracture mechanics*

**Abstract** In order to define a procedure for integrity assessment of pipelines and determining the fracture mechanics parameters, a new type of specimen with a sharp notch, Pipe Ring Notched Tension (PRNT) specimen, is tested. The aim of the study is to determine the influence of the specimen geometry (cylindrical shape, as well as number and length of stress concentrators) on parameters such as force, Crack Mouth Opening Displacement CMOD, Crack Tip Opening Displacement CTOD and J integral. The specimens were fabricated by an additive production method - selective laser sintering (SLS). EOS Formiga P100 machine is used, and the material is polyamide PA12. In addition to Pipe Ring Notched Tension specimens, Single Edge Notched Tension (SENT) specimens with identical cross section were also made by the same technique. All specimens were tested on a universal tensile testing machine. A tool specially designed to apply contact pressure to the inner walls in the tension direction was used, simulating the internal pressure. SENT specimens were tested with a standard tensile plate test tool. For determining the field of displacement and strain on the surface of the tested samples that occur during the loading, Aramis GOM 2M optical measurement system was used. Aramis is applied for determination of geometry fracture mechanics parameters: CMOD and CTOD (based on $\delta 5$ concept). In addition to the examination of fracture properties of additively manufactured PA12, the main topic of this work is the development of the non-standard testing procedure, which will be subsequently applied to the specimens cut from metallic or non-metallic pipes. As an important part of this procedure, the calculation of fracture parameters is also considered.

## Acknowledgement

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# #475 Tailored distribution of defects in thin sheets to control their wrinkling

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*membrane* *wrinkling* *defects*

**Abstract** Thin plates are prone to instability phenomena when are exposed to compressive stresses. In particular, wrinkling is a form of instability characterized by the development of corrugated regions where the plate is able to sustain only tensile forces. Wrinkling has been massively studied in the scientific literature in relation to different fields of applications: e.g. in Ref. [1] wrinkled membranes are considered to model the structural behavior of cable-stayed bridges, while in Refs [2,3] wrinkling is studied in relation to biological membranes. Recently, the first two authors developed a robust numerical tool to describe wrinkling in hyper elastic membranes containing cavities of general shapes [4]. The arrangement of voids in tensile membranes has been shown to be a mean for tailoring wrinkle pattern [5]. In the present paper, by making use of the numerical model of Ref. [4] we explore different arrangements and shapes of defects (voids or hard inclusions) to control the wrinkle pattern in a soft membrane under uniaxial tension. An experimental proof-of-concept is carried out using 3D printed bi-phase polymeric specimens. The present work conducted within the framework of the H2020 SIRAMM Project (GA No. 857124) can be relevant in the area of cultural heritage, where a number of artwork types made by natural membranes (e.g., parchment, leather, etc.) are exhibited on either open or closed display within showcases or cabinets. In these microenvironments these natural membranes are subjected to tensile stresses as their ends are clamped at rigid supports as well as to the action of swelling and shrinkage induced by humidity and temperature variations [6,7].

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# #476 Methodologies for the estimation of the LCF-VHCF duplex P-S-N design curves

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*Design curves* *Very High Cycle Fatigue* *Maximum Likelihood*

**Abstract** Probabilistic-S-N (P-S-N) curves are commonly employed to model the fatigue response of specimens and components. They are generally obtained by assuming the statistical distribution of the fatigue life, in order to take into account the randomness that is intrinsically associated with the fatigue phenomenon and the scatter of the experimental data. In industrial applications, starting from the P-S-N curves, the so-called "design curves" or "lower bound S-N curves" are defined for the design of components, in order to ensure a safety margin against possible fatigue failures. The proper estimation of the design curves, especially for experimental datasets with a limited number of available data, is therefore of fundamental importance to prevent possible unexpected fatigue failures, whose effects can be catastrophic.

In the literature, different solutions and strategies are employed to estimate the design curves. For example, the lower 3 sigma (median S-N curve shifted by a factor equal to three times the standard deviation associated with the experimental dataset), the approximate Owen one-side tolerance limit and the double-sided confidence intervals approach are commonly adopted. If the experimental data end with an asymptotic trend (i.e., a fatigue limit), the stair-case method is generally employed. According to the industrial practice, the choice for a specific estimation strategy of the design curve is arbitrary, depending on the internal safety policy and on the application. However, no methodology has been proposed for modelling the design curves in case of failures in the range Low Cycle Fatigue (LCF) - Very High Cycle Fatigue (VHCF), with the experimental data showing a so-called duplex trend, i.e., a first decreasing trend, a plateau and a second decreasing trend ending with asymptote in the VHCF region.

In this work, the Maximum Likelihood Principle is exploited for the assessment of the design curves of datasets obtained through tests in the LCF-VHCF range, with the P-S-N curves showing a duplex trend. Firstly, the model for the P-S-N curves with duplex trend is defined. Thereafter the proposed methodology for the design curves is described and finally validated with experimental and simulated datasets.

# #477 Crack initiation anisotropy in full-ceramic nacre-like alumina

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*Finite Fracture Mechanics* *Anisotropy* *Nacre-like*

**Abstract** Full-ceramic nacre-like alumina (fc-NLA) are ceramic composites made of brittle constituents arranged in a 'brick-and-mortar' microstructure [1]. The bricks are microscale alumina platelets, whereas the mortar is an amorphous glassy phase. The stiffness and strength contrast between the platelets and the secondary phase triggers crack initiation and propagation in the latter. The orientation of the alumina platelets with respect to the loading direction of a given testing sample has a strong influence on the fracture behavior, both in terms of critical stress intensity factor ($K_{IC}$) and of reinforcement mechanisms involved. In one particular orientation, platelet arrangement leads to intensive crack deviation and reinforcement both at initiation and during propagation [2]. For the last decade, most of the work on fracture of fc-NLA focused on such configuration.

Using a coupled experimental-numerical approach within the framework of finite fracture mechanics [3], we proposed to study fc-NLA in two other reference configurations (see Fig. 1). Different tests at the macro- and microscale were conducted. Finite Element Models were used to corollate the experimental result and highlight the different crack initiation mechanisms acting in fc-NLA.

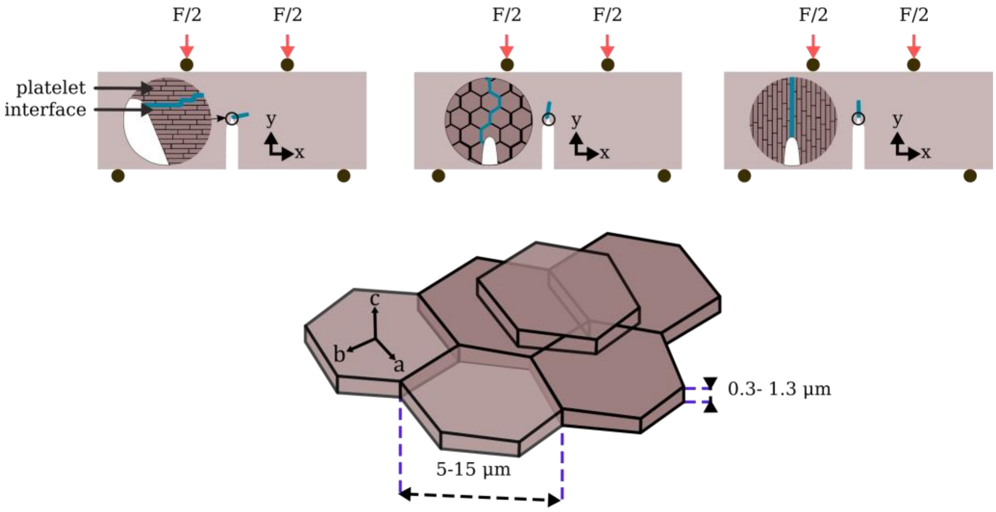


*Figure 1 - fc-NLA with three different platelet orientations. On the left, the extensively studied configuration showing intensive crack deviation. In the middle and on the right, the two reference configurations under study.*

Depending on this orientation, different reinforcement mechanisms are activated. A crack containment mechanism was observed for some configurations, leading to reinforcement at crack initiation. This mechanism alone can lead to stress intensity factor at initiation almost as large as the values observed with configurations exhibiting intensive crack deflection.

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# #479 Study of the Automated Process-Induced Residual Stresses in Multi-Axis Laminates

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*Multi-axis composites* *Residual stresses* *Robotic fibre placement*

**Abstract** The integrity of the composite structures is affected by the manufacturing conditions. Controlling the ply orientation during the manufacturing process plays an important role in defining the induced residual stresses inside the laminate. This work evaluates the generated residual stresses inside multi-axis laminate of carbon fiber reinforced polymers. The samples are manufactured using the robotic fiber placement technique. The residual stresses are measured through the incremental hole-drilling method. Finite element modeling is used to provide the calibration process of the strain measurements. Additionally, microstructure analyses have been performed to show the configuration of the manufactured samples. The effect of the laminate configurations and plies orientations are investigated and compared. The layers' orientations have a considerable effect on the generated stresses.

# #480 Wire to wire contact in fatigue of power cables copper conductors

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*Fretting* *Fatigue* *Copper*

**Abstract** High voltage power cables are composed of a number of concentric layers of wires wound in a helix of pitch equivalent to several diameters, each layer in a direction opposite to that of the previous. During installation and operation in a dynamic application, relative slipping among the wires may occur. In this sense, fretting or wear fatigue phenomena whose magnitude depends on the amplitude of the relative movement and on the contact forces per unit length acting between the wires, can impact the structural integrity of the cable. This study presents the results of fretting fatigue tests on copper conductor wires and compares their performance to the results obtained by testing the sole wire as well as qualitative comparison with the wire surface as extracted from testing of full conductors. The testing was performed utilizing a fretting device specifically designed to reproduce the wire-to-wire contact in the conductor. The conditions of temperature, strain levels and contact force have been limited to the values of relevance with respect to those of interest for the operation of such power cables. The result analysis is supported by scanning electron microscopy investigation of the fractured surface as well as of the surface of the wire-to-wire contact area.

# #481 Impact of conductor assembly indentation on the fatigue properties of copper power cable wires

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*Copper* *Residual stresses* *Fatigue*

**Abstract** The production process of high voltage power cables includes the assembly of the conductor, which is composed of different layer of independent wires wound in helixes of opposite pitch for each subsequent layer. Each wire, which has an initial constant round cross section and is in annealed conditions, is wound around the previous layer and the layers assembled are passed through a calibrated die which compacts the wires together. This process creates periodically spaced indents on the inner side of the wires and work hardens the material in the indented sections. Both the local and global strain distribution related to static loads as well as the fatigue properties of the wires are impacted by such process and its consequent geometrical and material inhomogeneities. In this work, strain-control fatigue results of copper conductor wire are presented. The non-uniform strain distribution caused by the inhomogeneities inferred by their manufacturing process is investigated with the means of digital image correlation. The "indentation" process is modelled with the use of explicit finite elements and the deformation of the virtual specimen obtained is compared with the experimental results.

# #484 Development of a phase field model for elastoplasticity using concepts of damage mechanics

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*Phase Field Method* *Damage Mechanics* *Fracture Mechanics*

**Abstract** The first applications of the phase field method in fracture mechanics were for linear elastic materials under monotonic loading. However, these approaches are not sufficient to correctly reflect the material behaviour under cyclic loads. Therefore, a so-called fatigue degradation was introduced in addition to the usual degradation function in the free energy. These approaches were also extended for ductile materials with elastic-plastic deformations.

There are several approaches to phase field theories for fracture mechanics processes in ductile materials. Phase field models of fracture are in principal gradient enhanced continuum damage models. In the present work an approach based on concepts of non-conventional thermodynamics is adopted, cf. [1]. Accordingly, the existence of an energy flux is assumed, besides the classical heat flux, which is responsible for the damage diffusion. The benefit of this approach is, that damage laws of classical continuum damage mechanics can be incorporated. As a consequence, the evolution law of damage becomes a diffusion equation.

The aims of the present work are as follows: 1) Formulate, within non-conventional thermodynamics, a consistent phase field/continuum damage theory for elastic-plastic material behaviour with isotropic and kinematic hardening. In particular, existing approaches from the literature for cyclic loading will be adopted within this approach. 2) A numerical implementation of the theory shall be developed as a 2-field problem. 3) The basic structure of the model shall be illustrated by examples with homogeneous and inhomogeneous deformations as well as monotonic and cyclic loads.

## References

[1] A. Tsakmakis and M. Vormwald, “Thermodynamics and Analysis of Predicted Responses of a Phase Field Model for Ductile Fracture,” Materials (Basel, Switzerland), vol. 14, no. 19, p. 5842, 2021, doi: 10.3390/ma14195842

# #485 Modeling of AL-6061 aluminum alloy deformation diagrams by machine learning methods

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*AMg6 aluminum alloy* *Deformation diagram* *Machine learning*

**Abstract** There was studied a deformation diagrams of AL-6061 aluminum alloy at various temperatures. Predicting the behavior of nonlinear systems is important. Experimental data have a certain variance that must be taken into account. This gives us a regression problem that can be solved by machine learning. Therefore, with sufficient experimental data, it is advisable to use machine learning methods, namely neural networks and boosted trees in science and technology, where stress-strain diagrams of structural materials is extremely important, in particular in metallurgy, aircraft, railways and more. The neural network method can solve quite complex problems, while the algorithm of boosted trees is similar to the flowchart that is easy to visualize and interpret. Therefore, it is often used to make consistent decisions. The dependences of the experimental deformations on the predicted ones, as well as the dependences of the deformation on the stress (Fig. 1) at temperatures $T$ = 343 та 413°C are constructed by machine learning methods.

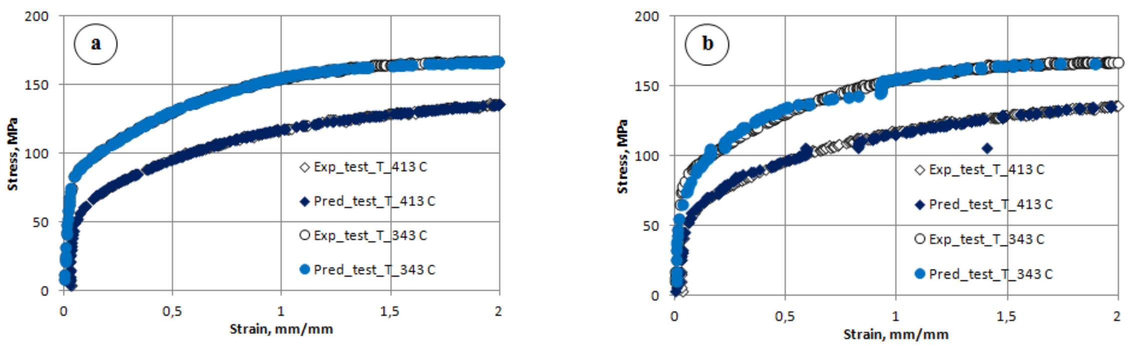


***Figure 1*** *- Stress-strain diagram of AL-6061 aluminum alloy at different temperatures*

Stress-strain diagram of AL-6061 was predicted by methods of machine learning, in particular by neural networks and boosted trees using the experimental data from Jordan S. Weaver et al paper (2016). The constructed model is estimated by means of loss function, which in this paper is selected as the root mean square error (MSE) It was discovered that the method of neural networks gives the least prediction error equal to 0,05%. The errors of the methods of boosted trees is 0,3% in test samples.

The obtained results are in good agreement with the experimental ones.

# #486 Comparative analysis of the influence of higher order terms in Williams' series expansion for different cracked specimens: theoretical approach, photoelastic experiments and finite element analysis

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*Digital photoelasticity* *Williams series expansion* *Higher order terms*

**Abstract** Comparative analysis of the truncated multi-point presentations of the stress field in the neighborhood of the crack tips in different cracked specimens and geometries based on the theoretical fracture mechanics solutions, the digital photoelastic method and finite element method is given. The fracture mechanics problems for cracked geometries having exact analytical solutions are reconsidered. The multi-parameter Williams series expansions of the stress and displacement fields are obtained. The number of terms in the truncated Williams series expansions for different cracked specimens is studied. The estimations of the number of terms in the Williams series expansions needed for the accurate description of the crack-tip stress field is obtained. It is shown that in order to expand the validity domain of the Williams solution, a larger number of terms in the series has to be retained. Digital photoelasticity method is used for obtaining the isochromatic and isoclinic patterns in the cracked specimens with the similar geometries in the isotropic linear elastic material (Figure 1). Stress intensity factors, T-stresses and coefficients of the higher order terms in the multi-parameter Williams series expansion are experimentally determined. The finite element analysis for the cracked plates with the same configurations has been performed. Stress intensity factors, T-stress and coefficients of nine-term asymptotic expansion for the stress field are numerically obtained and are compared with the experimental results. The comparison shows good agreement of experimental and numerical estimations of these fracture mechanics parameters. Very good agreement is shown to exist between the digital photoelasticity method and finite element results confirming the effectiveness of the photoelasticity technique in obtaining the coefficients of higher order terms of the Williams series expansion from the experimental stress field around the crack tip. The comparison of the exact analytical, experimental and numeric solutions shows the importance of the higher order terms in the Williams series expansion.


a b c d

***Figure 1 -*** *Experimental specimens tested: isochromatic fringe pattern of the plate with two collinear cracks under different loads (a-d)*

It is shown that the higher order terms in the Williams series expansion are of fundamental importance in the processing of experimental and computational data.

# #487 Analysis of crack front loading and J-integral evaluation to improve reliability of toughness calculations based on miniaturized CT specimens

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*Finite Element Analysis* *Fracture Mechanics* *Nuclear Reactor Safety*

**Abstract** Structural integrity of the reactor pressure vessel (RPV) is of critical importance to ensure the safe operation of light water reactors (LWRs). Fracture toughness evaluations based on the Master-Curve method (ASTM-E1921) to determine the reference temperature $T_0$ of the ductile to brittle transition has recently gained importance for the integrity assessment of irradiated materials. The reference temperature $T_0$ indexes the median toughness-temperature curve at a toughness value of 100 $MPa.m^{1/2}$ obtained with 1T-size specimens (25.4 mm crack front length). Due to the limited number of surveillance specimens, miniaturization of fracture specimens is unavoidable. However, it is well-known that fracture toughness is specimen size and geometry dependent and intrinsically scattered due to material inhomogeneity. Typically, specimens having a crack front as small as 4 mm are used to characterize the toughness of irradiated specimens. To establish reliable transferability rules of the toughness data from one specimen size to another and to apply the Master-Curve method with confidence when using small specimens, the difference in the structure of the crack tip stress field between large and small specimens has to be well understood and modeled. In this study, the crack tip stresses of two specimen sizes (1T and 0.18T compact tension specimens) were calculated with 3D finite element simulations run over a range of loadings (or equivalently for a range of constraint levels) and at different temperatures in the lower part of the ductile to brittle transition of a structural steel. In addition, 3D J-integral calculations ($J_{cal}$) were performed along the crack front that allow comparison with the standard plane strain experimental determination J ($J_{exp}$) and to evaluate the degree of deviation between these two quantities. As soon as a threshold plastic deformation is reached, a significant deviation is observed between the plane strain and 3D calculations of J. Similarly, the peak stress variation along the crack front and its amplitude are discussed in function of specimen size and loading, and are further compared with those deduced in pure plane-strain calculated in strict small-scale yielding conditions. The threshold plastic deformation is estimated in this work in order to improve accuracy of predicted crack front loading and J-integral profiles.

# #488 Determination of ductile-to-brittle transition temperature of NIOMOL 490K steel welded joints

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*Transition temperature* *Mechanical properties* *Niomol 490K*

**Abstract** This paper is devoted to the ductile–brittle transition behavior of high strength low alloyed (HSLA) structural steel NIOMOL 490K. The steel is designed for welded pressure vessels exposed to dynamic loads, operating at temperatures below zero, and that is why it must have acceptable toughness. Due to its importance for the safety assessment of pressure vessels, a characterization of this steel with Charpy V-notch test in range of temperature between-60 °C and +60 °C was undertaken. Ductile-to-brittle transition curves were generated in the present study by using instrumented Charpy machine and V-notch specimens; notches were located in the parent material, heat-affected zone and weld metal. NDT-temperature and tensile properties in temperature range from -60 °C to +60 °C are presented in this paper. We used different test temperatures to better understand ductile-to brittle transition response than just use either Charpy energy or other related ductility criteria.

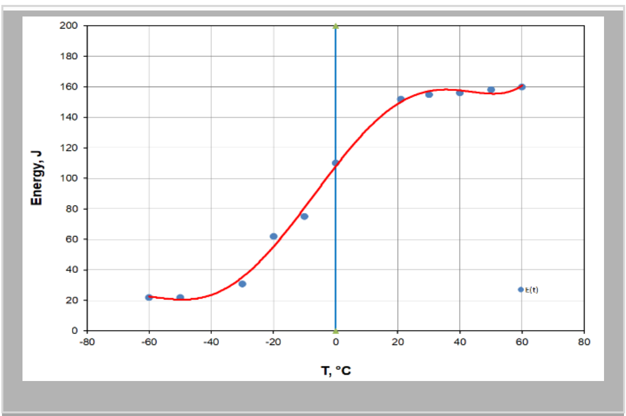


***Figure 1** – brittle to ductile transition temperature curve*

# #489 Vibration fatigue of additive manufactured PLA components

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*Vibration fatigue*     *Additive manufactured PLA component*     *Novel testing methodology*

**Abstract** Up to date, the research on fatigue of additive manufactured (AM) components has received the least attention among studies related to mechanical properties of AM components mostly due to the longevity of experiments multiplied by the large number of influential parameters, related to processing, material, environmental or loading conditions. This study introduces a novel fatigue testing methodology of AM components, which enables simultaneous testing of multiple specimens at significantly higher loading rate by exploiting the specimen's dynamic response when exited with random-signal acceleration.

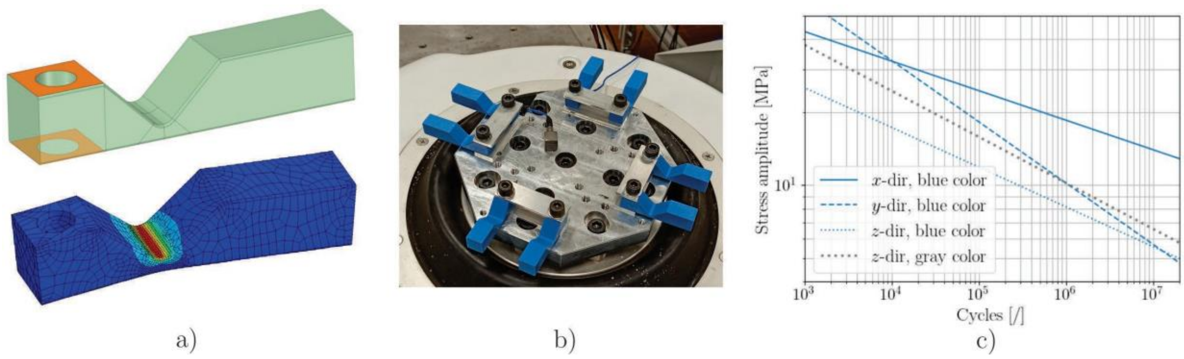


***Figure 1** – a) Specimen geometry with stress mode-shape, b) Experiment setup of 8 specimens, c) Obtained fatigue curves for tested specimen sets.*

The novel methodology is based on the innovative design of specimen geometry (Fig. 1) exhibiting well-spaced mode-shape with distinct fatigue zone, manufacturability by fused deposition modeling in all spatial directions and a possibility of frequency tunning between 200 and 700 Hz. Vibration tests of specimens on electro-dynamic shaker with monitored velocity response combined with individually updated numerical models of specimens result in valid reconstruction of stress PSD on the fatigue zone. By applying frequency counting methods on stress PSD and subsequently minimizing the difference between actual and estimated fatigue life the fatigue parameters were obtained for the specimen set with given influential parameters.

In four specimen sets, tested within this research, the influence of perimeter filament direction, layer direction and colorant were identified on total of 106 PLA specimens. Taking into the account the significant increase of cycling rate, directly related to the specimen's natural frequency, and simultaneous testing of multiple specimens the fatigue test can be performed with proposed method at least 100 times faster compared to classical methods. Hence, the test duration as main consideration of performing fatigue tests on large scale is overcame without imposing any limitations on the range of influential parameters, that can be investigated. What is more, such methodology can be easily adopted to investigate frequency-dependance of fatigue parameters for polymeric materials, and to observe the influence of environmental conditions on fatigue of AM structure (temperature, humidity) with climatic chamber.

# #490 Comparison of lifetimes of stainless steels 304L/4306 and 304L/4307 subjected to ultrasonic fatigue loading

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*Fatigue* *Stainless steels* *High frequency loading*

**Abstract** The contribution brings results of high frequency fatigue tests of the steels S304L/4306 and S304L/4307. The austenitic stainless steels S304L are the most versatile and widely used stainless steels. They are used in food processing, chemical industry, petrochemicals, but also in mechanical and civil engineering. The steel 1.4306 is a more highly alloyed and more corrosion resistant than 1.4307. A new trend in bridge structures is the use of stainless steels for their corrosion resistance and mechanical properties. The bridge structures are loaded cyclically and are designed for decades of operation. For this reason, we have focused on fatigue properties. The results of experimental studies serve as inputs for a reliable assessment of the service life of cyclically loaded structures. Measurements of both steels were performed on ultrasonic fatigue testing systems. Experimental results plotted in the S-N curves are shown in Figure 1. From the results it can be concluded that steel 1.306 shows a slightly higher fatigue resistance than steel 1.4307. The failure in the gigacycle region (around $10^8$ and $10^9$ cycles) only occurs in the case of 1.4306 steel.

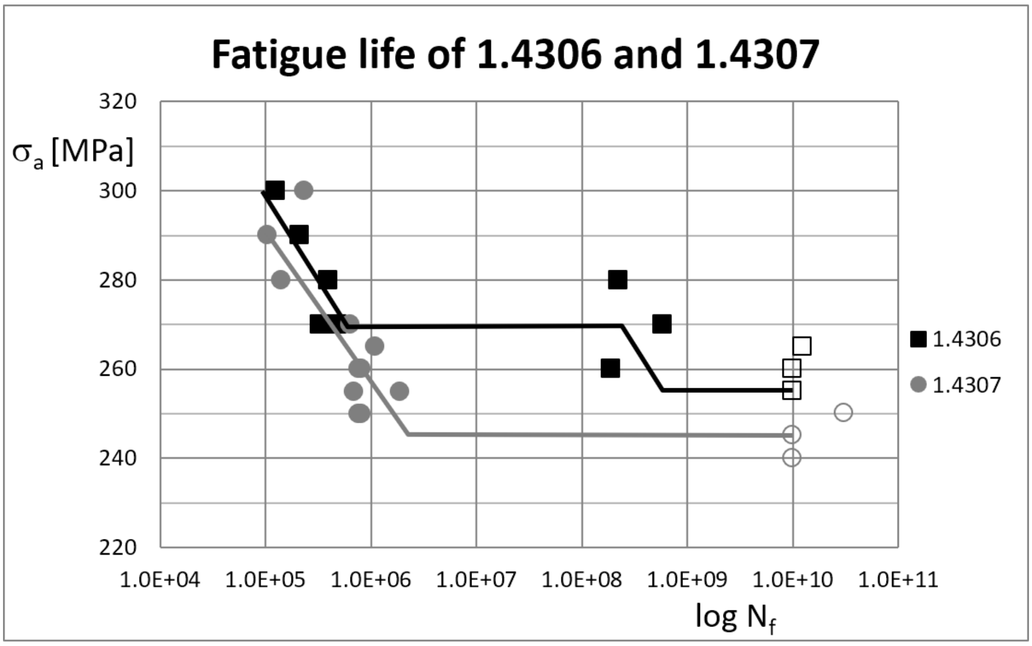


***Figure 1*** *– Fatigue life of studied steels. The empty points correspond to the run-out points.*

**Acknowledgment**: This research has been supported by The Czech Science Foundation: project No. 20-00761S, and by Brno University of Technology: project No. FAST-J-22-7959.

# #491 Creep-fatigue interaction mechanisms of lead alloy for subsea cables sheathing

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*In-situ testing* *Lead* *Fatigue-creep interaction*

**Abstract** Lead alloys are commonly used in as water barrier in subsea cable due to their easy manufacturing, excellent chemical, stability and mechanical ductility. Due to their relatively low melting temperature, lead alloys are prone to microstructural time-dependent evolution phenomena such as recovery, relaxation, recrystallization and creep deformation even at room temperature. The intricate interaction between fatigue and creep significantly increases the complexity toward a reliable estimation and prediction of the service life of subsea cables. Conventional testing covering the full operational range is not practical and the developed damage models inevitably require significant extrapolation. In this sense, an understanding of the dominant damage mechanisms taking place is vital as support to such models. In this work, the fatigue response of lead was investigated using in-situ micromechanical test methods combined with advanced characterization. Pre-fatigued samples were cut into smaller specimens and subsequently subjected to cyclic loading using small-scale in-situ mechanical testing inside a scanning electron microscope (SEM). Deformation behavior and damage mechanisms were revealed with high resolution imaging and discussed in correlation with the dominating time-dependent phenomena. The results provide a deeper insight of the dominant damage phenomena and the necessary input to life estimation calculations and modelling work of the studied alloy system used for cable sheathing. In addition, the current investigation contributes to increase the understanding of mechanisms leading to failure under cyclic motion.

# #492 Effect of mean stress and stress amplitude on the cyclic deformation mechanism and microstructure evolution of Al alloy used for subsea cables using small-scale in-situ testing

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*Al alloy* *Cyclic loading* *In-situ testing*

**Abstract** Subsea cables play a critical role in the global energy grid including interconnectors and a continuously growing offshore energy production. Aluminum sees an increasingly important role thanks to its high relative conductivity compared to weight and material cost. In addition the technological footprint of aluminum conductors is still not completely exploited and research-based alloy development can significantly increase the functional and mechanical properties of such conductors; while the impact of alloying and thermal conditioning on aluminium conductors monotonic response is well documented within today's standardized cable testing, the impact on the conductors' cyclic and time dependent properties is less understood. This becomes more and more important as the trend of the industry in the last years is moving toward designs in which the conductor may also become a load bearing component in the cable system. In this context, this works aims to understand the cyclic loading behavior and damage mechanisms of aluminium alloys used for subsea cables through full- and small-scale in-situ mechanical testing combined with advanced scanning electron microscopy (SEM) characterization techniques, so to obtain a detailed insight into the physical mechanisms of the material's mechanical behavior. Preliminary results show a clear link between specific microstructural features in the material from which damage is initiated and the cyclic loading parameters such as the mean stress and the stress amplitude. This opens up to possibility to better target alloy development beyond just conductivity and monotonic strength to allow higher installation depth and/or offer pathways to new cost-efficient cable designs.

# #493 Experimental and Numerical Characterization of Ductile Fracture Properties of EN AW 5183 WAM Profile

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*WAM* *Ductile Fracture* *GISSMO*

**Abstract** A hybrid experimental-numerical approach was employed to investigate the ductile fracture properties of EN AW 5183 WAM (Wire-arc Additive Manufacturing) profiles. The experimental testing program consists of specimens cut from the WAM profiles which correspond to different stress triaxialities ranging from simple shear up to equi-biaxial tension.

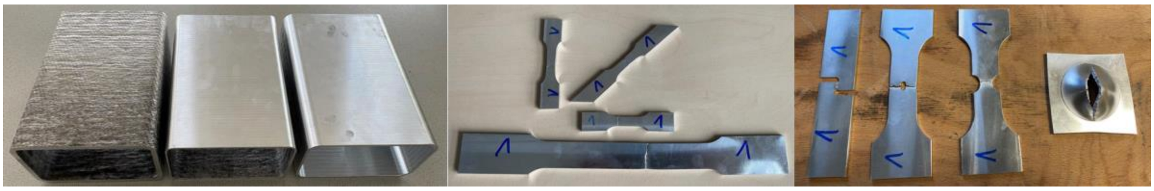

***Figure 1** – WAM profiles (left), specimens for fracture characterization (middle and right)*

The stress state and Lode parameter dependent Hosford-Coulomb fracture model combined with the phenomenological damage model GISSMO in LS-DYNA was calibrated based on the specimen tests.

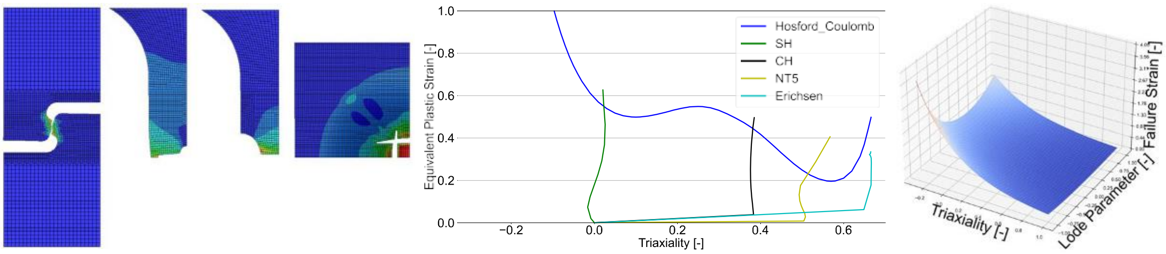


***Figure 2** – FE mesh of the coupons (left), Calibrated Hosford-Coulomb model for shell element (middle), Calibrated Hosford-Coulomb model for solid element (right)*

Finally, the WAM profiles were crushed under quasi-static axial load to investigate their crashworthiness. FE-simulations of the crush tests were carried out using the calibrated fracture models. The experimental data and simulation results were in reasonably good agreement.

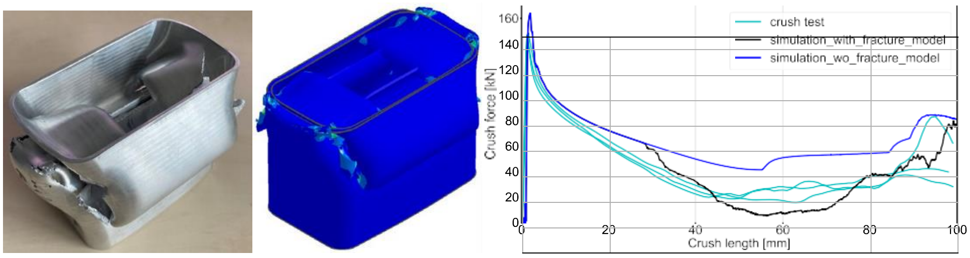


***Figure 3** – WAM profile after crush test (left), Simulation of the crush test (middle), experiment vs. simulation (right)*

# #494 Hydrogen-induced transgranular to intergranular fracture transition in bi-crystalline nickel

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*Hydrogen embrittlement* *Intergranular fracture* *Molecular dynamics*

**Abstract** For polycrystalline materials, hydrogen could influence the dislocation behavior and induce intergranular fracture. However, the nanoscale interaction behaviors and underlying mechanisms remain unclear. By uniaxial straining of bi-crystalline nickel with a Σ5(210)[001] and Σ9(1-10)[22-1] grain boundaries, a transgranular to intergranular fracture transition facilitated by hydrogen is elucidated by atomistic modeling, and a specific hydrogen-controlled plasticity mechanism is revealed. Hydrogen is found to form a local atmosphere in the vicinity of grain boundary, which induces a local stress concentration and inhibits the subsequent stress relaxation at the grain boundary during deformation. It is this local stress concentration that promotes earlier dislocation emission, twinning evolution, and generation of more vacancies that facilitate nanovoiding. The nucleation and growth of nanovoids finally lead to intergranular fracture at the grain boundary, in contrast to the transgranular fracture of hydrogen-free sample.

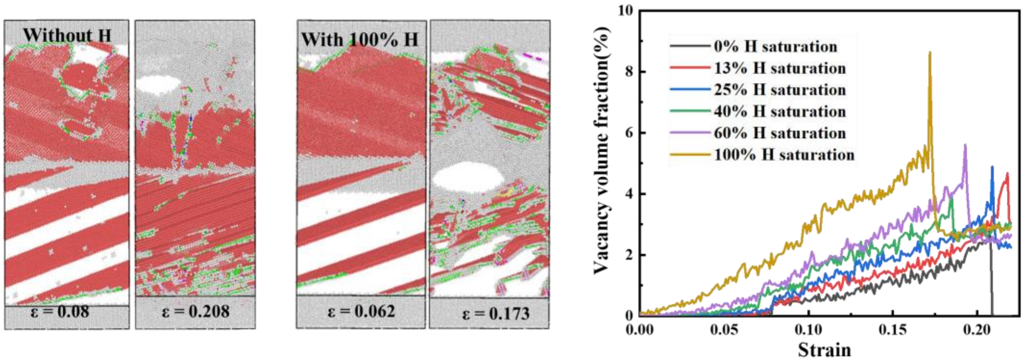


***Figure 1*** *– The schematic of Hydrogen-induced transgranular to intergranular fracture transition.*

# #495 Crack path direction analysis in plane-strain fracture toughness assessment tests of quasi-brittle PLA polymer and ductile PLA-X composite

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*Fracture toughness* *PLA polymer* *PLA-X composite*

**Abstract** Plane-strain fracture toughness is one of the main parameters in linear elastic fracture mechanics and its purpose is to show the material capability to withstand load while having a defect. Main validity aspect for such an assessment is to provide a wide enough crack front to enable plane-strain condition. Nonetheless, in FDM (Fused Deposition Modeling) polymers, due to structural anisotropy caused by material properties and Additive Manufacturing (AM) process parameters, more validity aspects must be met. During the plane-strain fracture toughness test a crack must follow a straight line from initiation cite up to the point of structural failure. For such a purpose a DIC (Digital Image Correlation) device can be used for crack path direction analysis. Plane-strain fracture toughness assessment is conducted according to the ASTM D5045-14 standard for testing of polymer materials. Tests are performed on SENB (Single Edge Notched Bend) specimens, made from two similar polymer materials: quasi-brittle PLA and ductile PLA-X composite. Specimens are manufactured with four different AM process parameters, i.e., layer height, infill density, printing orientation and one batch was dried before testing. Testing is conducted using 3-point bending test fixture on universal testing machine, with DIC dual-camera device placed ahead of the machine in order to capture full-field deformations of front SENB specimen surface (Fig. 1).

***Figure 1** – Plane-strain fracture toughness test setup with DIC dual-camera device.*

# #496 A modelling framework unifying hydrogen enhanced plasticity and decohesion

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*Hydrogen embrittlement* *Complete Gurson model* *Plasticity and decohesion*

**Abstract** A generic, versatile and unified platform for the continuum-level simulation of hydrogen embrittlement (HE) is proposed. The complete Gurson model (CGM), designed to predict ductile failure by voiding, is extended to the CGM$^+$ by incorporating a decohesion failure criterion. Hydrogen enhanced plasticity is accounted for through acceleration of the voiding process while hydrogen induced decohesion is realized by a degradation of the decohesion threshold. In such way, hydrogen induced synergistic action of plasticity and decohesion is unified in one predictive model, referred to as H-CGM$^+$. Both implicit solver and explicit solver are established for the H-CGM$^+$ model. Specifically, the explicit subroutine for hydrogen diffusion (VUMATHT) is developed for the first time. Coupled mechanical-diffusion analysis in a complex geometry such as microstructure-based model can be conducted with explicit solver. The interplay between plasticity-dominated and decohesion-dominated failure modes driven by varied conditions, i.e. hydrogen concentration, trapping, and material's microstructure are well captured. The platform may serve as a basis for interpretation of laboratory experiments and enable the transferability of the laboratory results to the integrity assessment of engineering components in hydrogen environment.

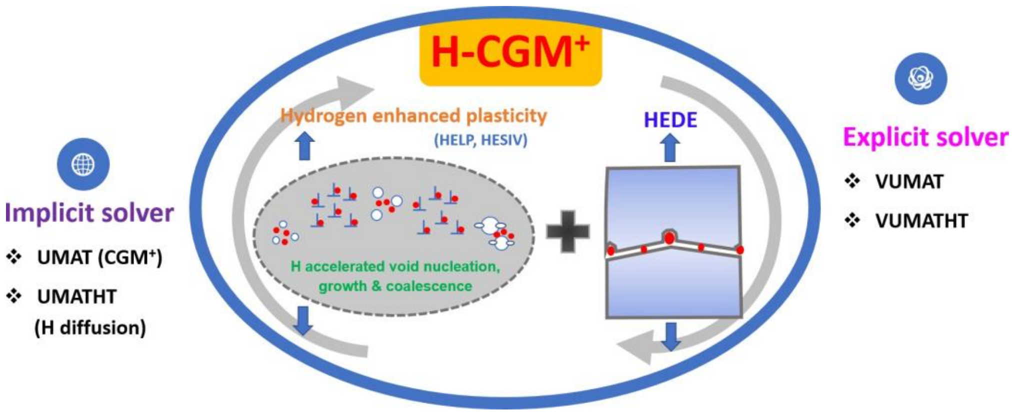


***Figure 1** – The schematic of H-CGM$^+$ platform.*

# #497 Effect of reinforcement parameters on the impact resistance of cementitious composites for vehicle restraint systems

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*Impact resistance* *Fibreconcrete* *Restraint systems*

**Abstract** The presented study investigates the dynamic resistance of cement-based large-format elements with various types of reinforcement and retrofitting. Both inner and outer reinforcement has been assessed. The effect of matrix type (low, high, and ultra-high-strength), amount of steel fibres, and ribbed reinforcing steel on impact toughness has been evaluated. The influence of an additional polymer-based layer to increase impact resistance level has also been investigated. The effectiveness of each reinforcing method has been compared. An instrumented large-scale device (700 J) operating on the principle of a Charpy hammer with an integrated force sensor has been used to determine the impact toughness. The results show that ribbed reinforcing steel increases the impact toughness more effectively than the fibre reinforcement and additional polymer layer. However, fibers significantly reduce fragmentation, especially at a higher concentration of 2.5 vol%, contributing to the overall higher impact resistance of the elements and their safety in practical use. The test results also show a significant effect of the matrix type, with the most increased impact toughness achieved when using a high strength matrix. The addition of an antifragmentation polymer layer then provides a further increase in impact toughness. The results also indicate that similar resistance capacity can be achieved using different reinforcement combinations, which is crucial for designing the material composition with the optimal performance/cost ratio.

The presented research is a part of the development process of the restraint system for stopping trucks. The data obtained has been used to create the elements with suitable material composition, which have subsequently been successfully verified by numerical simulations and real tests.

# #498 Effect of production technology on high strain rate characteristics of Reactive Powder Concrete

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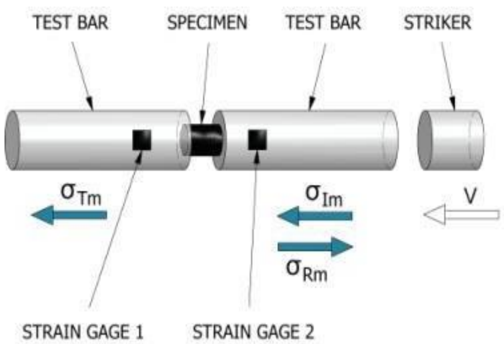
*RPC* *SHPB bar* *High strain rate*

**Abstract** This paper presents an experimental study evaluating the effect of mixing technology and curing conditions on the high strain rate compressive behavior of Reactive Powder Concrete (RPC). In total, eight sets of specimens were prepared with identical composition, based on Aalborg Portland cement 52,5R, fine sand with a grain size up to 0,5 mm, silica fume, micronized quartz, superplasticizer and water. Two different mixing conditions were tested: 1) Mixing under normal pressure, 2) Vacuum mixing. Four curing conditions were adopted: 1) Curing in water at an ambient temperature, 2) Curing under 5MPa pressure 3) Curing under hydrothermal conditions et 190°C/40 hours 4) Curing under hydrothermal conditions 180 °C/8 hours.

Split Hopkinson pressure bar (SHPB) equipment was used to determine the cementitious composite behavior at compression at strain rates up to 1600 s-1 (see the scheme in Figure 1 left). For the SHPB tests, the cylindrical specimens with a diameter of 15 mm and length of 6.5 mm were prepared by waterjet cutting (see Figure 1 right) from the slab.



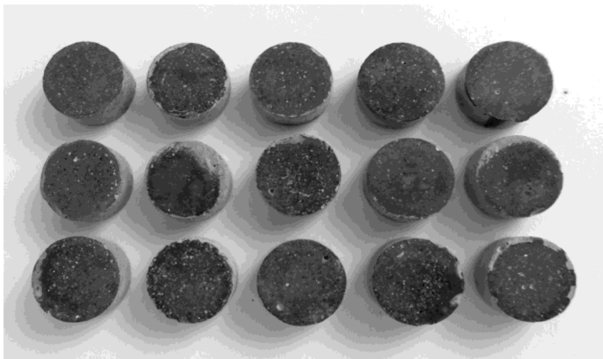



**Figure 1** Scheme of the Split Hopkinson pressure bar device (left) and specimens to be tested (right)

Quasistatic tests were also performed (compressive and flexural strength) as well, and ratios of these properties at high strain rates to their counterparts at static loading were compared. The dynamic increase factors were calculated. Peak stress values, critical compressive strain, and post-peak behavior vary for specimens prepared in different regimes, which allows finding the optimal production technology for high strain rate impacted structures.

The results show the influence of mixing procedure and treatment regimes on the resulting behavior of the material at a high strain rate. Vacuum mixing reduces the pore content in the composite, which is accompanied by a significant increase in peak stress values at both quasistatic and high strain rate regimes (about a 25% increase). Further increase in peak stress values is then achieved by hydrothermal treatment, with higher values connected with higher temperature and dwell time. The pressure developed at the first stage of the curing period also improves the mechanical parameters, but to a lesser extent than vacuum mixing.

# #499 Fatigue-life estimation for non-stationary excited structures

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*Fatigue life* *Non-stationarity* *Narrowband*

**Abstract** In case of random loading, the vibration fatigue is obtained in the frequency domain using the spectral methods, where fatigue-life estimation is based on the assumptions of stationarity and Gaussianity. However, this assumption is not always justified and some considerations should be made to extend the applicability of spectral methods. For this purpose the transmission of non-stationarity trough the structure is researched.

A method for a fatigue-life estimation for non-stationary excitation is proposed; the method is based on the short-time spectral narrowband method, where the short-time width was found to be related to the structural dynamics (i.e., natural frequency, damping) of the excited structure. A correction factor for the short-time narrowband method is defined to account for the nonstationarity; a flowchart in Fig. 1a) summarizes the proposed short-time fatigue-life estimation.

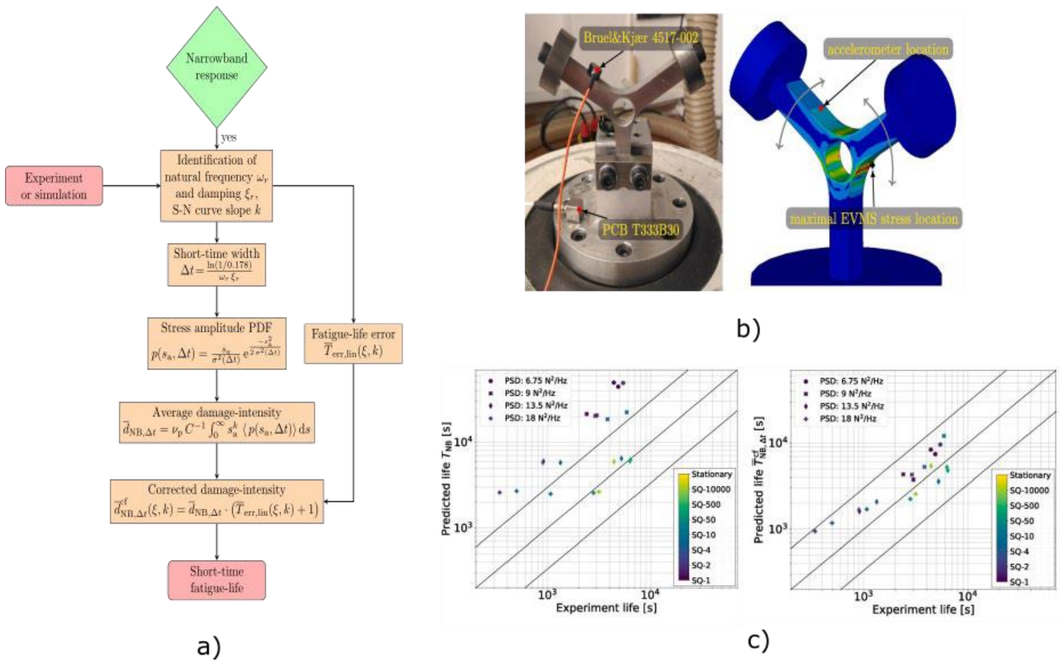


***Figure 1** - Short-time fatigue-life; a) flowchart, b) experimental setup and FEM model, c) experimental and numerically predicted fatigue life.*

A numerical test case and a real experiment were conducted, as depicted in Fig. 1.b). Y-shaped sample was exited using electro-dynamic shaker over 4-th natural frequency to ensure narrowband response, then the stress time-history was obtained based on a numerical FEM modal model. With the proposed method a significant accuracy increase for fatigue-life estimation at non-stationary and non-Gaussian excitation is obtained, as shown in Fig. 1.c).

# #500 Visualization of fractographic signs of operational degradation of heat-resistant steel for estimating its actual structure-mechanical state

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*Heat-resistant steel* *Fractographic signs* *Brittle fracture resistance*

**Abstract** Operational factors contribute to the occurrence of critical damages in elements of thermal power equipment as a necessary precondition of their failure. Peculiarities of macro and microfracture of pipes of steam pipelines, as well as the fracture surfaces of laboratory specimens, cut out from the operated metal; indicate the intensity of steel damage. Fractographic analysis, which is used to find out the causes of failure of structural elements, is increasingly being used to assess the actual technical state of operated steels. Established fractographic features concerned with structural changes in the metal during long-term operation make it possible to judge the current state of critical objects.

Fracture surfaces of specimens of the steel 15H1M1F long-term (approx. $2 \cdot 10^5$ h) operated on the main steam pipelines of a thermal power plant have been analysed after their mechanical testing. Fractographic analysis showed some distinctions resulted from different number of shutdowns (501 and 576) of power units during their operation. After impact toughness and fracture toughness tests, as expected, the fracture surfaces of the steel subjected to more shutdowns have less area of ductile (subcritical) fracture in the vicinity of notch or pre-crack and more intergranular fragments against the background of typical transgranular relief in the zone of spontaneous fracture. These features are concerned with more intensive degradation of the steel after more shutdowns of power units. It can be explained by a larger pre-fracture zone in impact specimens and, accordingly, the possibility of a greater deviation of the crack from its main path, involving the boundaries of dozens of grains with operational damages. In contrast, pre-cracked specimens for fracture toughness evaluation have the narrower pre-fracture zone, therefore, there is significantly less grain boundaries weakened by degradation on the crack path. Some areas of intergranular fracture against the background of a classical, as a whole, transgranular fatigue fracture were also found at the fracture surfaces of the operated steel after fatigue tests, namely, in the near-threshold region of the crack growth. They are associated with grains encountered along the path of fatigue crack propagation, the boundaries of which were damaged as a result of creep during long-term operation of the steel on steam pipelines.

Based on fractographic research of the long-term operated steel, the area of intergranular fragments in the unit area of the fracture surfaces is proposed as a quantitative fractographic indicator of changes in its structural and mechanical state due to degradation. The mechanical characteristics of brittle fracture resistance of the steel are consistent with the proposed fractographic indicator of the metal state.

# #501 Development of a stabilized fracture test on brittle material: proof of concept with a brittle polymer

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*Stable crack growth* *R-curve* *Compact tension type geometry*

**Abstract** Based on a stability criterion, known from the literature and involving the mechanical stiffness notion, a numerical analysis based on the Virtual Crack Closure Technique (VCCT) was implemented with the finite element software Abaqus. In doing so, fracture tests in the opening mode (mode I), which is considered to be the most critical mode from a material point of view, were carried out. The aim of the numerical study was to show the influence of various parameters such as the part geometry (CT/DCT/TCT), the notch length, the notch width and the piece scale factor on the crack growth stability. Results consistent with those of the literature showed the strong influence of the notch width on the mechanical system stability. The larger the scale factor and notch length, the more stabilized the system will be. It would also appear that TCT geometry is more suitable to the crack growth stabilization.

To converge towards brittle inorganic materials (ceramics), a proof of concept has been formalized with polymethylmethacrylate (PMMA) which has regularly served as model material for studying material with brittle linear elastic behavior. Thanks to numerical studies, stabilized fracture tests were performed. From these, the resistance curve of PMMA, commonly known as R-curve, was obtained for the different « compact tension » type geometry simulated with Abaqus. From these fracture tests, material data such as the fracture energy and the crack growth rate were thus determined.

Lastly, the mechanical response of the simulated structure was compared to the one experimentally obtained with all tested geometry. Created digital twin substantiate the crack length obtained by image analysis and the experimental R-curves.

A small detailed description of the microstructure and fracture surfaces at different scales of analysis was also carry out to understand the surface creation mechanisms.

# #502 Pecularities of fatigue cracks growth in steel and composite sucker rods

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*Sucker rods* *Fatigue cracks growth* *Steel and composite*

**Abstract** To predict the fatigue life of sucker rods, it is important to take into account the effect of technological environments under various loading schemes on the conditional fatigue limit of steels used for their manufacture (in particular, such as steel 20Kh2M), and compare these properties with modern materials for the manufacture of so-called hybrid sucker rods (with metal heads and fiberglass rod) as prototypes of steel elements of oil- producing equipment.

Specimens from pump rods with technological or operational defects were tested for fatigue life-time in aggressive technological environments. It has been established that the fatigue life-time and fatigue endurance of pump rods decrease with an increase in their diameter. So, with a test base of $10^7$ loading cycles, the endurance limits of rods with a diameter of 19, 22, and 25 mm were 95, 85, and 80 MPa, respectively. It was shown that technological defects practically did not affect the life-time of the rods. Minor differences were associated with the scatter of the fatigue characteristics of the metal. Defects formed in rods during their operation in wells have a more noticeable effect on their life-time under variable loads. It was found that the resource of rods with a diameter of 19 mm decreased faster compared to rods with a diameter of 22 mm in the presence of operational defects of the same depth in both rods. This is due to the greater sensitivity of smaller diameter rods to defects.

According to the curves of the crack growth rate in specimens made of rods with a diameter of 22 mm, it was found that the critical state (according to the jump in the crack growth rate) is reached if the crack length along the perimeter of the rods is within 15...16 mm, and its depth is 4 .5 5.6 mm. Such cracks were fixed at a stress range of 100 MPa, which is commensurate with the operating loads of the rods. For rods of other standard sizes, the critical crack depth, which preceded the almost spontaneous destruction of the specimens, was 3...4, 4...5 and 5. 6 mm for rods with a diameter of 16, 19 and 25 mm, respectively.

Recently, pumping rods made of polymer composites have been used in oil production to reduce the harmful effects of aggressive environments. According to the test results, it was found that fiberglass sucker rods have higher fatigue endurance characteristics in aggressive environments than steel ones, and this advantage is manifested at more than $(2\ldots5)\cdot10^6$ loading cycles. Comparative experimental studies of full-scale steel and hybrid sucker rods have been carried out. The dependence of the incubation period before the appearance of the first visible crack in the hybrid rods is established and it is shown that it increases from 0.4 to 0.85 with an increase in load from 110 to 175 MPa. Whereas the part of the spent resource before the appearance of cracks in steel rods was much less and varied within 0.18. 0.4 with an increase in load from 100 to 150 MPa. The crack growth rates in both steel and composite rods at the stage of their subcritical growth varied within $10^{-9}...10^{-8}$ m/cycle. It is shown that with an increase in the load range, the length of the largest of the recorded cracks decreased in fiberglass and hybrid rods from 42. 45 mm to 12 mm.

# #503 Evaluating the size effects on fatigue life of 42CrMo4+QT steel using a statistical S-N model with highly-stressed volume and surface

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*Size effects* *Highly-stressed volume and surface* *Fatigue model*

**Abstract** Full-scale fatigue tests of engineering components are generally time-consuming and costly, and often require special-purpose equipment. Therefore, fatigue tests are usually carried out by small-scale specimens and the relationship between full-scale components and small-scale specimens fatigue strength is established by an empirically-based geometrical size effect.

This paper evaluates the size effects on fatigue strength of 42CrMo4+QT steel by a statistical S-N model and stress-based methods. Solid and hollow unnotched cylindrical specimens with various diameters are tested under push-pull constant amplitude fatigue loadings. The obtained fatigue data are analyzed by a statistical S-N model (Castillo et al. fatigue model). To estimate the parameters of the model, a non-linear optimization problem is solved. Finite element analysis is also performed to obtain the highly-stressed volume (HSV) and surface (HSS) of specimens.

The statistical model shows a good fit when applied to data from solid (A1-A4) and hollow (A5-A8) specimens, see ***Fig. 1***. In both cases ***Fig. 1***a) and ***Fig. 1***b), the ratio between stress amplitude of one S-N curve to another changes considerably with cycles to failure, e.g. $\sigma_{a,A1}/\sigma_{a,A4} = 1.15$ when $N_f = 10^4$ instead $\sigma_{a,A1}/\sigma_{a,A4} = 0.98$ when $N_f = 10^6$. The HSV and HSS increase from set A1 to A4 in the case of solid samples and from A5 to A8 in hollow samples. By comparing the HSV or HSS with parameters of the model, common relationships between them are suggested. This relation allows best-fitting expressions to be proposed for all parameters. Therefore, the parameters can be estimated from any other value of HSV or HSS of unnotched specimens (42CrMo4+QT steel) under push-pull. The estimated parameters can provide fatigue models that are easy to implement without the necessity on non-linear optimization.

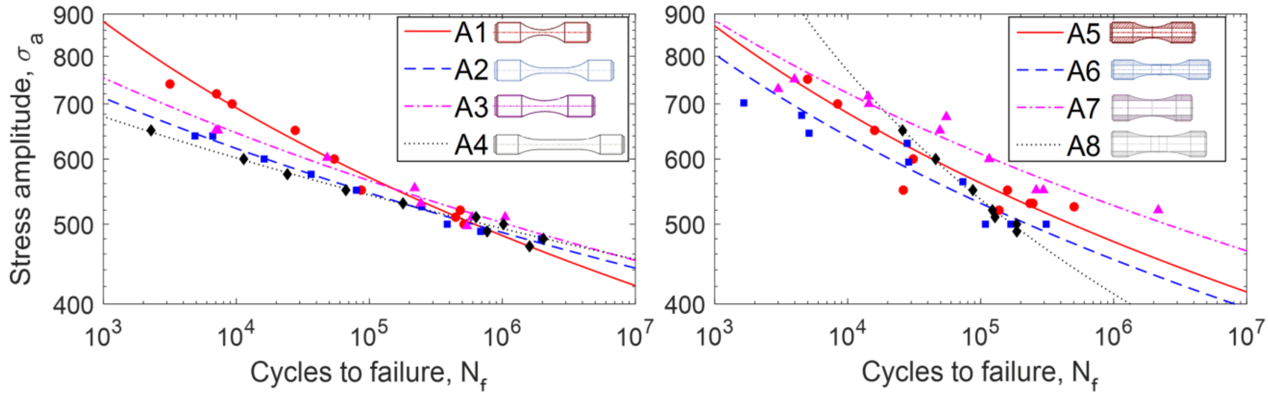


***Figure 1** – S-N model applied to data from unnotched 42CrMo4+QT steel specimens: (a) solid specimens (A1 to A4) and (b) hollow specimens (A5 to A8).*

# #504 The influence of anisotropy on vibration behavior of S600Mc sheet metal

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*Anisotropy* *Vibration* *Finite element analysis*

**Abstract** Sheet metals anisotropy is the directional dependence of mechanical properties. It is a critical factor that must be considered when using numerical simulation to predict any manufacturing process involving plastic deformation [1]. Sheet metals demonstrate anisotropic plastic behavior due to crystallographic texture caused mainly by progressive rolling steps [2]. Cold bending of steel sheets is a widely used manufacturing process in the automotive industry due to its cost efficiency, and by avoiding line heating, the oxidative process of steel is thus avoided. The primary application of sheet metal in the automotive industry includes doors, fenders, bumpers, roof panels, and seat frames.

In this paper, test specimens were laser cut at orientations θ = 0°, 45°, and 90° to the rolling direction. The specimens were subjected to forced vibration on an electromechanical shaker, Figure 1, and the frequency response amplitude was measured using accelerometers. Natural frequency and Q-factors were discussed. Experimental data are used for viscous damping coefficients (alpha and beta) for each direction of the specimen. The measured coefficients are then used to validate the finite element numerical models for each specimen type.

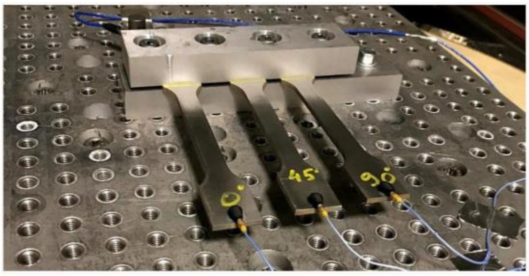


***Figure 1** – Vibration test setup*

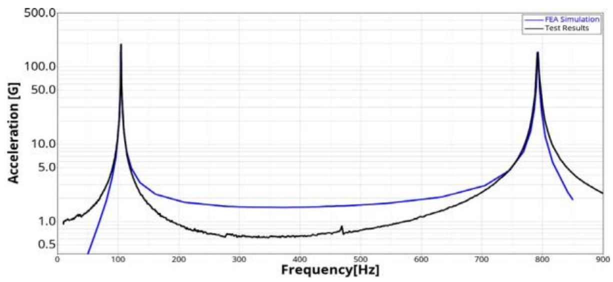


***Figure 2** – Frequency Response Functions:* Experimental *test vs. numerical model*

The results show the level of dependency between the structural damping and anisotropy of the laminated sheet metal and the influence on the high cycle fatigue performance.

[1] I.-I. Ailinei, S.-V. Galatanu1, L. Marsavina, Influence of anisotropy on the cold bending of S600MC sheet metal, Engineering Failure Analysis, SI: VSI: ICEAFVI, https://doi.org/10.1016/j.engfailanal.2022.106206, 2022.

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# #505 The interaction of hydrogen with microstructural defects studied by internal friction

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*Hydrogen-defect interactions* *Internal Friction* *carbon-vacancies*

**Abstract** Understanding of the interactions of hydrogen with microstructural defects is of major importance for the mitigation of hydrogen embrittlement. Several current mechanisms for hydrogen embrittlement identify the hydrogen-dislocation interaction as the detrimental one. However, recently interest has also been raised towards the action of vacancies and their interactions with hydrogen. Moreover, other interstitials present in steel, such as carbon, are known to interact with these defects as well. Consequently, the carbon distribution might strongly influence the hydrogen defect-interactions.

Therefore, in this work an ultra-low carbon steel is subjected to various thermo-mechanical treatments, resulting in specific defect concentrations and carbon distributions. These microstructural conditions are characterized in detail via positron annhiliation spectroscopy (PAS) measurements, transmission electron microscopy (TEM) and internal friction (IF) experiments. A full overview of the hydrogen-material interactions is obtained by thermal desorption spectroscopy (TDS) as well as IF measurements on electrochemically hydrogen charged samples. Information on the dislocation structure and density in the samples is obtained by TEM. While the presence of all open volume defects, both vacancy clusters and dislocations, is evaluated by PAS. The IF technique characterizes the carbon distribution in the material as well as to evaluate the interstitial-dislocation interactions. Moreover, the IF spectra of hydrogen-charged samples provide additional in-depth information on the hydrogen-defect interactions, which could be linked to the TDS spectra.

Hydrogen trapping in the cold rolled steel is dominated by dislocations. Moreover, the hydrogen-dislocation interaction results in an additional relaxation peak in the IF spectrum. Recovery annealing results in a strong decrease of the trapping contribution of the dislocations in the TDS spectrum as well as the annihilation of the relaxation peak, despite the dislocation densities being similar. This could be attributed to the dissolution of meta-stable kink pairs and small carbon-vacancy clusters. Dissolution of these clusters causes additional carbon segregated at the dislocations, consequently reducing the hydrogen trapping capacity. Further investigation of the influence of the carbon distribution was obtained via redeformation (tensile or torsional) of recovered and recrystallized samples. Interestingly, the relaxation peak could only be reintroduced under specific conditions. Hence carbon is considered to play an important role in the generation of defects, and as such influences the hydrogen ingeractions in the material. The large vacancy clusters produced during the cold rolling were able to act as strong trapping sites. Hydrogen release from these vacancy clusters, resulting in a small higher temperature peak in the TDS spectrum, is related to dissolution of the clusters rather than unbinding.

## #506 Effect of recycling powder on the fatigue properties of AM Ti6Al4V

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*Fatigue properties* *Additive Manufacturing* *Recycling powder*

**Abstract** Additive manufacturing (AM) techniques offer significant advantages with respect to conventional manufacturing (CM) ones such as the realization of highly customized components both dealing with their geometry and their mechanical properties. An important advantage of AM is the significant reduction of wasted material with respect to CM. However, AM techniques, such as the powder bed fusion, involve during the production an amount of powder higher than that needed to realize the final component even if the excess of powder in not interested by the melting process and can be recovered and used again. However, it is obvious to expect that the new powder feedstock that include this reused powder has different morphology characteristics since it has been subjected to a thermal history in the building chamber. These changes in the material feedstock can results in a different morphology of defects and consequently in different fatigue properties even for AM components realized with the same design geometry and same process parameters. In the present study, the effect of the use of recycled powders on the fatigue properties of AM Ti6Al4V has been investigated by considering specimens realized from virgin powder and recycled powder. The specimens fracture surfaces are investigated to correlate the effect of the powder on fatigue properties with the effect on the defects' morphology.

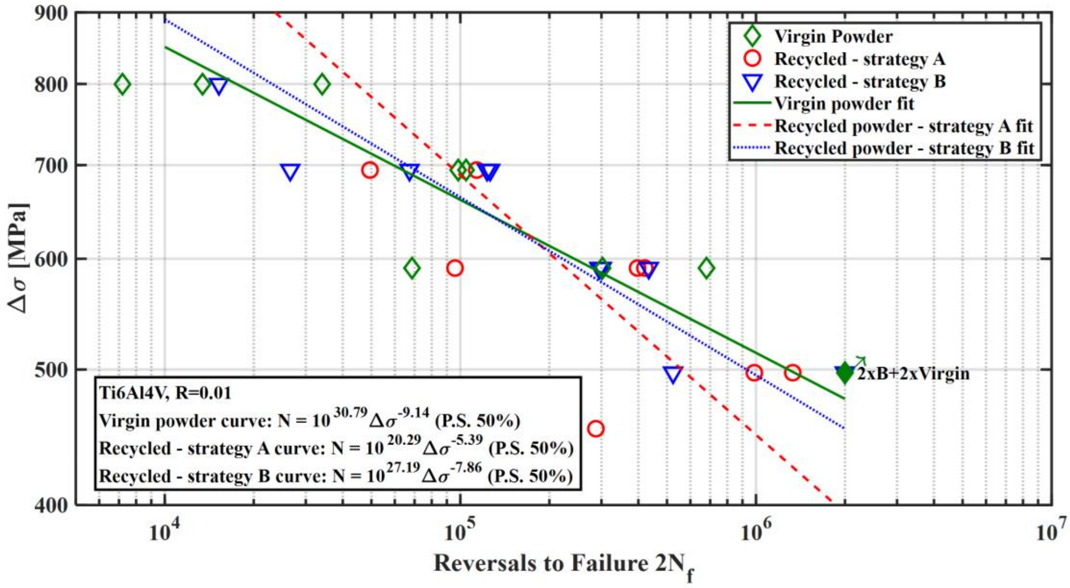


***Figure 1*** *– Stress vs Cycles to failure for Ti6Al4V AM specimens realized using virgin and recycled material feedstock*

# #507 Fatigue life of cable sheathing manufactured by longitudinally welding and forming

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*Copper alloys* *Residual stresses* *Laser welding* *Fatigue*

**Abstract** The introduction of floating wind power plants creates the necessity of the development of dynamic subsea cables. High voltage cables designed to transport produced power from offshore plants to shore, commonly referred to as “export cables”, do not exists as of today due to lacking in legacy static high voltages subsea cables. This puts an extreme cost premium on the already planned commercial floating wind parks. The realization of such cables requires the introduction of radial water barriers that can tolerate the significant mechanical cyclic loads without losing its protective function. This work presents the characterization of the fatigue life of a novel water barrier manufactured by longitudinally welding and forming of a copper-based alloy. Finite Element modelling and Digital Image Correlation are used to understand the effect of the imposed cyclic strain on the weld under fatigue testing at elevated temperatures designed in line with the expected cable operation. Fatigue $\Delta\varepsilon$-N curves are established on the basis of both load- and strain-controlled testing with emphasis on the impact of accumulated plastic deformations originated from the cable manufacturing process.

# #509 Mechanical behavior of Inconel 718 manufactured by high-productivity rate SLM process

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*Fatigue strength* *SLM* *Surface roughness*

**Abstract** Inconel 718 is widely employed for elevated temperature applications, where the optimized shapes, internal cooling channels, or lattice structures, allowed by the Selective Laser Melting (SLM) technology, can introduce significant enhancements in terms of component mechanical and thermal properties, machining costs and scrap reduction.

The productivity rate of the SLM process is known to be a limiting factor for the industrial spread of the technology. Its enhancement can play a crucial role, as long as it doesn't significantly affect the fatigue performances of the component.

In the present work, it is presented the development of SLM process parameters aimed at enhancing the productivity rate, while preserving the vertical process resolution, and the experimental assessment of the effects introduced on the static and cyclic mechanical properties. Based on a previously developed and validated analytical model of the material SLM feasible region, two sets of process parameters were devised to increase by 50% the process productivity rate. For each process parameters set, tensile and High Cycle Fatigue (HCF) tests were carried out on vertically built round specimens, in the as-built and aged material conditions, both featuring the as-built surface. Metallographic analyses were carried out to investigate the microstructural properties or the presence of internal defects, i.e. porosity, lack of fusion, and hot tearing cracks, produced by each set of process parameters. The surface quality was also investigated in detail through optical microscope analyses and profilometer measurements. Fractographic analyses were used to identify the nucleation region and the crack propagation features, as well as the presence of the defects in proximity to the fracture onset.

Despite the increase in the material porosity and surface roughness, in the case of the most promising process parameters set, the fatigue strength was reduced only by 4% both in the as-built and aged conditions, Figure 1. The data were finally investigated in the framework of the $\sqrt{area}$ method developed by Murakami, which resulted in effectively estimating the fatigue behavior of the investigated specimens for all the tested sets of SLM process parameters

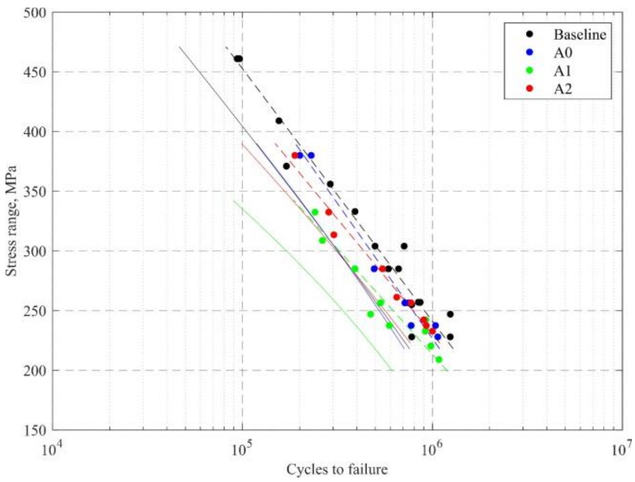


***Figure 1** – Wöhler curves for the baseline, A0, A1, and A2 process parameters set*

# #510 On the influence of additive manufacturing defects on the energy absorption capability of a lattice structure

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*Lattice structure* *Additive Manufacturing* *Energy absorption*

**Abstract** In recent years, the development of additive manufacturing (AM) processes has made possible the production of components consisting of lattice structures with enhanced mechanical performance. Previous studies have shown that the energy absorption capability of lattice structures, in absence of defects, is significantly higher than that of standard structures made of the same material. However, actual lattice structures made with AM processes are characterized by a high defectiveness that can significantly affect the mechanical response and that must be thus considering when designing a lattice-based component.

In this work, the influence of AM defects on the energy absorption capability of a lattice structure made of carbon nylon has been numerically investigated. In particular, defects that have been considered are: i) the variation of the diameter of the beam with respect to the nominal value; ii) the presence of lack-of-fusion portions of material within the beams. The defects have been randomly disposed in the unit cell and different defect populations have been then simulated. Transient nonlinear finite element analyses of the lattice structure subjected to compression tests have been performed in LS-Dyna environment. The numerical model has been validated with experimental data collected in a previous published work [1]. Results have shown that both beam diameter variations and lack-of-fusion portions affect the absorbed energy although with different severity. Further, the increasing degradation of the absorbed energy with the increasing numerosity of the defects confirms the necessity of accounting for these defects when designing lattice-based energy absorbers.

[1] C. Boursier Niutta, R. Ciardiello, A. Tridello, "Experimental and numerical investigation of a lattice structure for energy absorption: application to the design of an automotive crash absorber", Polymers, 2022, 14.

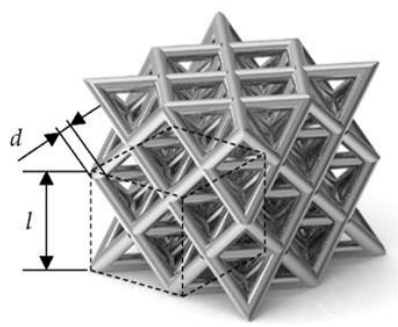


***Figure 1*** *– Lattice structure retained in this study with the unit cell geometry highlighted.*

# #511 Corrosion of austenitic stainless steels and nickel-based alloys in concentrated phosphoric acid at elevated temperatures

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*Corrosion* *Phosphoric acid* *Nickel-based alloy*

**Abstract** The corrosion sensitivity of several austenitic stainless steels (316L, 316Ti, sanicro28, sanicro35) and nickel-based alloys (hastelloy G30 and hastelloy G35) was determined at elevated temperatures in food grade phosphoric acid (FGPA). The materials were submerged in a harsh environment of >85 wt% FGPA in a temperature range of 100-170 °C. The main aim was to understand the corrosion mechanisms occurring in such environment and define the temperature range for which corrosion is within acceptable limits for these materials. Moreover, the role of a material's chemical composition on the corrosion resistivity in phosphoric acid was experimentally elucidated. The corrosion sensitivity was determined by weight loss measurements, scanning electron microscopy (SEM)(imaging of the corroded surfaces) and energy dispersive X-ray spectroscopy (EDX)(chemical analysis of the surface). Furthermore, the effect of phosphoric acid purity, phosphoric acid concentration and solution stirring on the corrosion resistance of sanicro28 was studied. Finally, an evaluation of the effectiveness of magnesium as a corrosion inhibitor in FGPA was performed.

The high concentrations of alloying elements in the selected metals allow them to form a protective passive surface film, which inhibits further oxidation. Depending on the stability of the passive film, materials will be corrosion resistant up to higher temperatures. Alloys with an increased molybdenum content showed a higher general and pitting corrosion resistance up to 140 °C. Moreover, copper alloying resulted in a relatively improved corrosion resistance at higher temperatures.

The pitting resistance decreased with increasing impurity concentration of the phosphoric acid. Strongly concentrated phosphoric acid (95 wt% phosphoric acid) led to a considerably lower corrosion rate compared to 85 wt% phosphoric acid. Flow in the acid solution had a considerable influence on the corrosion rate of sanicro28 as erosion corrosion occurs synergistically with acid attack. Finally, magnesium showed potential as a corrosion inhibitor as magnesium phosphates formed on the surface.

# #512 Stress distribution at the crack tip and the dog bone model of the plastic zone measured by synchrotron

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*Plastic zone* *Fatigue crack* *Synchrotron*

**Abstract** Crack tip propagation under static and cyclic loading is driven by the local stresses at the crack tip. In thin parts and in thick parts the description is quite simple due to plane stress and plane strain states respectively. However, in between, there is a mixed mode of plane stress and plain strain which has an important influence on crack propagation or materials parameters like fracture toughness given by the critical stress intensity factor which is constant parameter for thick specimens or construction parts only. The reason is the different amount of plasticity for plane stress and plane strain. That results in a complex 3D shape of the plastic zone, which is known as dog bone model (Fig. 1). This idealized model has been proofed in principle by FEM calculations whereby some differences between the model, resulting from the calculated stress 3 D stress states by isotropic continuum mechanics and FEM calculations for materials with real mechanical constants. Therefore, in our work the plastic zone was measured by depth sensitive 3D synchrotron stress measurements for AW7075 at the EDDI-Beamline of BESSY (Berlin). Due to the low but not negligible absorption of the x-rays, the surface area of the plastic zone could be measured only however, this is the interesting part while in the middle there is the plane strain state. Some differences between the model and the experimental results were found straight below the surface (Fig. 2) and will be discussed.

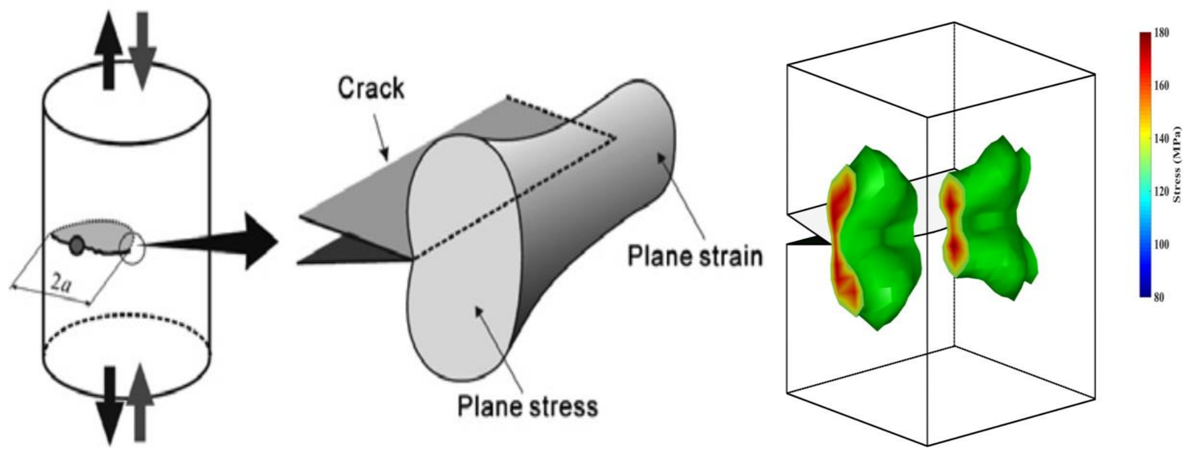


**Fig. 1:** Schematic image of plastic zone at a crack tip, in this case of a penny shape surface crack (from [1], left and middle) and iso-surface of $\sigma_{22}$ at the 130 MPa (ratio: 1:1:30, right).

[1] Y. Murakami, S. Matsuoka, Eng. Fract. Mech. 77 (2010) 1926–1940

# #513 Optimization of nanocrystalline, ultra-fine grained and bimodal nickel according to mechanical properties

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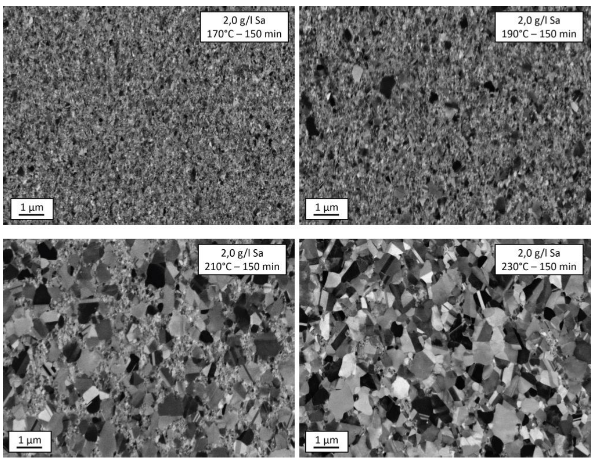
*Nanocrystalline nickel* *Pulsed electro deposition*

**Abstract** The aim of the work was to optimize the production and characterization of nanocrystalline (nc), bimodal and ultrafine grained (ufg) nickel. The material properties have been investigated with focus on microstructure, mechanical properties and thermal and mechanical stability.

The material was prepared by pulsed electro deposition. Layer thicknesses up to 2 mm with very homogeneous properties over the thickness have been produced. In order to characterize the nc microstructure as well as its thermal and mechanical stability, high resolution measurement methods such as electron backscatter diffraction (EBSD) and transmission Kikuchi diffraction (TKD) in scanning electron microscope were used and optimized. Nc, bimodal and ufg microstructures could be specifically adjusted by selecting suitable amount of additives and heat treatment parameters. The mechanical stability was investigated especially under cyclic loading. For this purpose, a method based on ASTM 674-13 was developed to investigate crack growth.

The nc microstructures show the best mechanical properties. By means of atom probe tomography the reduction of strength and ductility of the bimodal and ufg microstructures could be attributed to grain boundary embrittlement caused by sulfur containing additives and heat treatment. As a consequence, approaches were discussed, and experiments were presented to increase the stability of nc metals. In addition to the use of additives, a specific „grain boundary engineering“ or the incorporation of ceramic nanoparticles into the metallic matrix should be mentioned here.



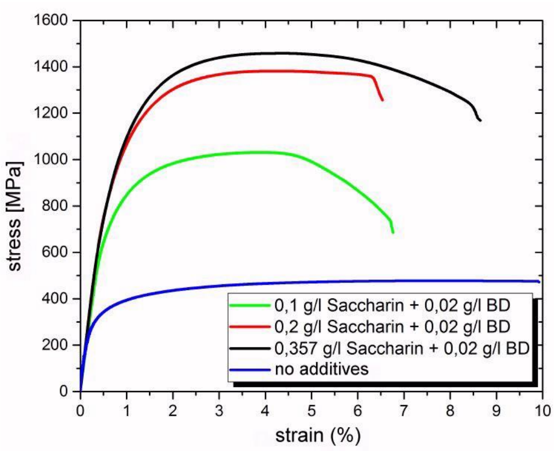




***Figure 1*** *– SEM images of different nc-ufg bimodal micro-structured nickel samples after different heat treatment times at the same temperature.*

***Figure 2*** *– Stress-strain curve of differently micro-structured nickel specimens produced with different amounts of additives.*

# #514 On the Formation of Zirconium Hydride Platelets

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*Hydrogen Embrittlement* *Zirconium Alloys* *Phase Field Modelling*

**Abstract** Zirconium hydrides obtain a platelet-shaped morphology in hexagonally close-packed zirconium. The obtained orientation of the platelets is balancing between being perpendicular to the stress field and the advantage of occupying a preferred crystallographic plane of the zirconium, the so-called habit plane. The ambition of the study is to predict the preferred orientation and to study the processes leading to the final result. The governing partial differential equations are obtained by minimising the free energy, with contributions from the kinetic energy of the diffusion, the elastic energy and the energy required to form the hydride. The material model considers elastic-plastic deformation. The study finds that the platelets are assuming an ellipsoidal shape. Further, the habit plane is close to its basal plane. The orientation may be detrimental to the structural integrity whereas the hydride is very brittle. Especially so since the orientation of the crack mimicking platelet often end up close to perpendicular to a tensile load.

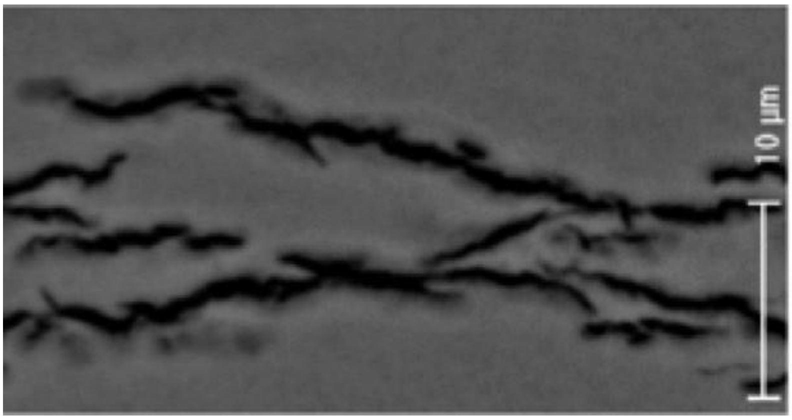


***Figure 1 -*** *Typical cluster of zirconium hydride platelets*

# #516 Cold Pressure Welding of aluminium: conventional and FIB-assisted microscale techniques

Ambra Celotto[1], Øystein Grong[1,2], Randi Holmestad[3], Jørgen A. Sørhaug[3], Jan Torgersen[1], Per Erik Vullum[3], Di Wan[1], Filippo Berto[1]

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*[3]Department of Physics, NTNU, Høgskoleringen 5, 7491 Trondheim, NO*

*Microscale welding* *Focused Ion Beam* *In-situ studies*

*Electron microscopy* *Solid-state welding* *Aluminium alloys*

**Abstract** Cold Pressure Welding (CPW) is an example of a solid-state welding method whose resulting joints are generally characterized by a high metallurgical efficiency. The pieces to be coupled, typically wires or thin plates, are put in close contact under a certain pressure and achieve bonding by severe plastic deformation and surface expansion. These are two of the many phenomena contributing to bond formation in the HYB process (Hybrid Metal Extrusion and Bonding), which is a cold-welding technique patented by researchers of the group.

To better investigate the bonding mechanisms happening during HYB welding, CPW has been taken as a *simplified* model for reproducing and monitoring HYB at the microscale. Therefore, a CPW-inspired technique has been developed and optimized for the microscale by means of a Focused Ion Beam microscope. By employing a tailored setup of the instrument, it was possible to recreate CPW bonding conditions between two aluminium pieces: an AA1070 aluminium plate as Base Metal (BM) and an AA6082 wire used as Filler Metal (FM) (Figure 1). Cross-sections of the resulting axisymmetric V-shaped micro-joint were investigated by high resolution SEM imaging and compared with reference CPW samples. EDS analysis highlighted the presence of implanted gallium particles and a relatively thick oxide layer at the materials interface, which being both detrimental for the joint mechanical properties have worked as guide for further technique improvements. Moreover, a variation of the setup was employed to perform an in-situ experiment that allowed to observe the on-going process, giving useful information on the deformation flow of the surfaces put in contact. A plan for future micro-mechanical testing is shown and discussed.

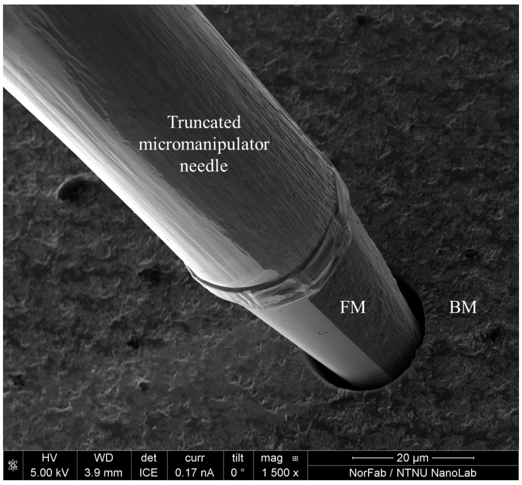


***Figure 1 –*** *Microscale welding operation in a Focused Ion Beam (FIB) microscope: the Filler Metal (FM) is fed inside a hole drilled in the Base Metal (BM) by means of the FIB micromanipulator needle*

# #517 Structural Integrity Calculations for Ageing Large Scale Systems

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*Structural Integrity* *Fracture mechanics* *Material Ageing*

**Abstract** Large-scale structures, such as bridges, dams, and high-performance systems (e.g. power and chemical plants, ships, etc.) have a limited lifetime, mainly due to ageing of their structural materials. Ageing also causes structural materials to become more susceptible to failure under decreasing overloads, therefore fracture mechanics is an essential part of structural integrity calculations. The objective of Structural Integrity is to assure the fail-safe operation of engineering systems during their entire service lifetime. The service lifetime of a system is predicted by complex Structural Integrity calculations, the effectiveness of which depends on the predictive capability of the underlying computational tools built around the theoretical core of the relevant phenomena. State-of-the-art Structural Integrity calculations for industrial applications are largely based on internationally accepted standards and guidelines, which bear footprints of hundred-year-old ideas encoded within them. Although application of the latest achievements of experimental methods (e.g., destructive, nondestructive material testing methods) and information technology (data acquisition systems, high performance computing) highly contributed to improving the accuracy of Structural Integrity computations of large-scale pressure vessels, predictive power of the standard-based analysis methodology has not improved significantly (e.g. the load history effects are poorly described by these calculations). From theoretical point of view, these methodologies are mainly based on the widespread thermal-stress approach –essentially based on the Duhamel-Neumann model– and fracture mechanics. During fracture mechanics calculations, global approaches of fracture play a prominent role. Beyond that, their ability to predict vessel's behavior after long-term operation is largely limited by the strong dependence of the analysis methodology on the empirical models correlated to the behavior of structural materials and their changes during material ageing.

There are various attempts, to overcome the limitations of current Structural Integrity computation methodologies of large-scale pressure vessels, but these days, the results of different research and development activities do not form a coherent system yet. Currently, research is being conducted in the Centre for Energy Research with the aim, to develop a new, generalized methodology for future Structural Integrity calculations of large-scale systems with integrated ageing computations. The long-term research goal is to incorporate more general constitutive models of structural materials, able to describe ageing more adequately than current constitutive models, into computational methods. According to our previous results, the reliability of the computational methodology should be based on more general –philosophically and scientifically deeper– principles than those found in the standard analytical methodologies used today. We propose an enhanced thermodynamical framework designed as a core theory to be applied at the development of methodologies and models for future Structural Integrity computations on research level, and a theoretical frame for industrial models.

The starting point is modern, non-equilibrium thermodynamics, augmented with transformations derived from the system's finiteness, the corresponding stability constraints, and the resulting conditions on the changes of all these. The resulting theoretical framework is a tightly coupled model that can account for the simultaneous occurrence of thermal and mechanical interactions and also their effects on aging in globally inhomogeneous solids. As a by-product, governing relations for thermomechanical fracture are derived in the form of a generalized *J*-integral. Since the model is based on very general principles and assumptions, without specifying restrictions on material behavior, the framework seems to be an adequate tool serving to derive complex, application-oriented, thermodynamically consistent damage and fracture models for much wider class of materials than existing models do. The most recent results show that a phenomenological model of material ageing, based on modern thermodynamics, can be constructed, suitable to describe the increasingly brittle behavior of structural materials as they age. The significance of this approach is that it may pave the way for a more systematic modelling of ageing materials in future, fracture/damage-mechanics based computations, which is an increasingly pressing need in digital twin-based systems. The presentation will also include the basic considerations of the ageing model.

# #519 Finite element modelling of creep crack growth in P91 steel weldments

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*Finite Element Method* *Creep Crack growth* *P91 steel*

**Abstract** The method implemented in this study is the modified nodal release in the crack path assuming a straight-line crack path for incremental increase. Creep crack growth simulations were carried out using the finite element program ABAQUS. 2D FE analysis were performed to calculate the $C^*$-parameter for parent metal (PM), weld metal (WM) and heat affected zone (HAZ) of P91 steel welded joints. Due to the symmetry of CT-models, only one-half of PM, WM and HAZ were considered, the FE mesh mainly consists of 2D, (CPS8R) an 8-node biquadratic plane stress quadrilateral, reduced integration, the element size nearest to the crack front of 0.123 mm, to provide adequately accurate results. The procedure followed is to divide the crack front into nine cracks over nine steps. For total $\Delta a$ =

4.5 mm by increment of 0.5 mm for each crack at mesh size of 0.1 mm, $C_t$-integral was calculated for each step starting at step 2. The results obtained by using described procedure show relatively good agreement between experimental results and 2D plain stress FE simulation, and are encouraging for further investigations.

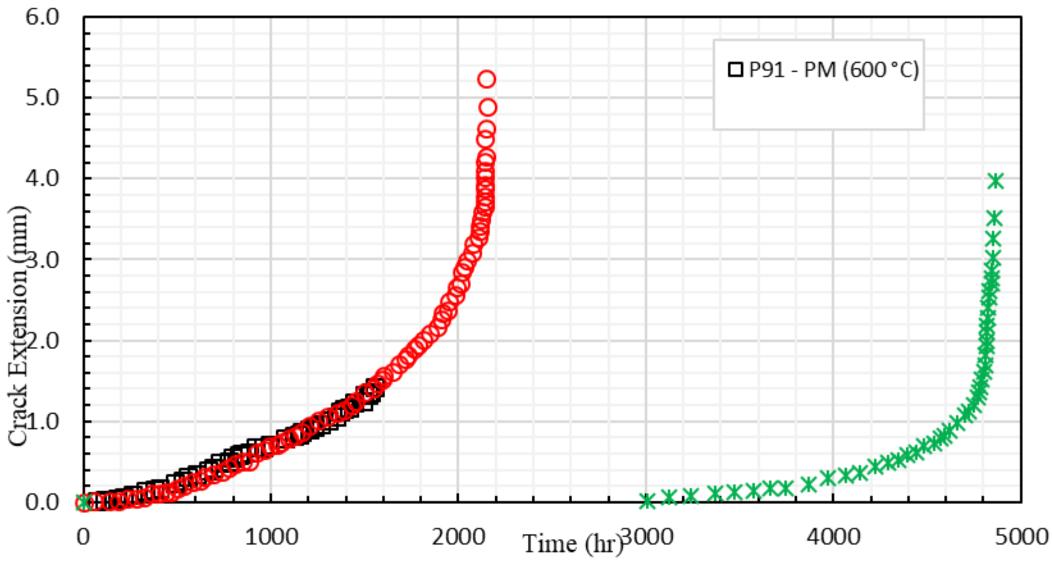


*Figure 1 - FEM analysis – stress distribution*

# #520 Effect of temperature and specimen orientation on Charpy impact toughness

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*Steam pipeline* *Heat-resistant steels* *Charpy impact test*

**Abstract** Steel grade 14MoV6 3 is used for manufacturing of boilers and steam pipelines designed for steam temperatures up to 540°C. This paper presents the experimental analysis which included impact toughness test. The analysis resulted in impact energy values, and their respective components, crack initiation and crack propagation energy, and represents the initial stage of extensive research involving the behavior of 14MoV6 3 steel. The goal was to determine the effects of temperature (room vs. elevated), as well as the effects of specimen orientation with regards to the rolling direction, on the impact toughness and the relation between its components.

# #521 Numerical Simulation of 14MoV6 3 steel CT-Specimen Fracture Behavior

Bojana ZEČEVIĆ1, Aleksandar GRBOVIĆ2, Ana MAKSIMOVIĆ1, Simon SEDMAK3, Ljubica MILOVIĆ 3 and Vujadin ALEKSIĆ5

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*Steam Pipeline* *CT-specimen* *Finite Element Method*

**Abstract** Steel grade 14MoV6 3 is used for manufacturing of boilers and steam pipelines designed for steam temperatures up to 540 °C. This paper presents the numerical simulation of CT-specimen, using the finite element method. The analysis was performed using ABAQUS software, and represents the initial stage of extensive research involving the behaviour of 14MoV6 3 steel. The goal was to simulate the real experimental conditions, including boundary conditions and loads, which were defined in accordance with relevant standards, and to obtain representative results. The temperature dependent mechanical properties needed for the simulation of plastic behaviour of such specimens under tensile loads were obtained from the experimental data and the literature.

# #522 Experimental Analysis of Pressure Vessel Welded Joint $J_R$ Curves

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*Keywords: Welded joint Surface axial crack Finite element analysis*

**Abstract** In order to estimate the integrity of the welded pressure vessel containing a crack, the behavior of specimens exposed to tensile loading, at -40 *°C* testing temperature, is experimentally analyzed. The specimens were made of low-alloyed steel NIONIKRAL 70, welded by SAW welding method. Surface notches were machined by the electro-erosion method in the parent material, heat affected zone and weld metal.

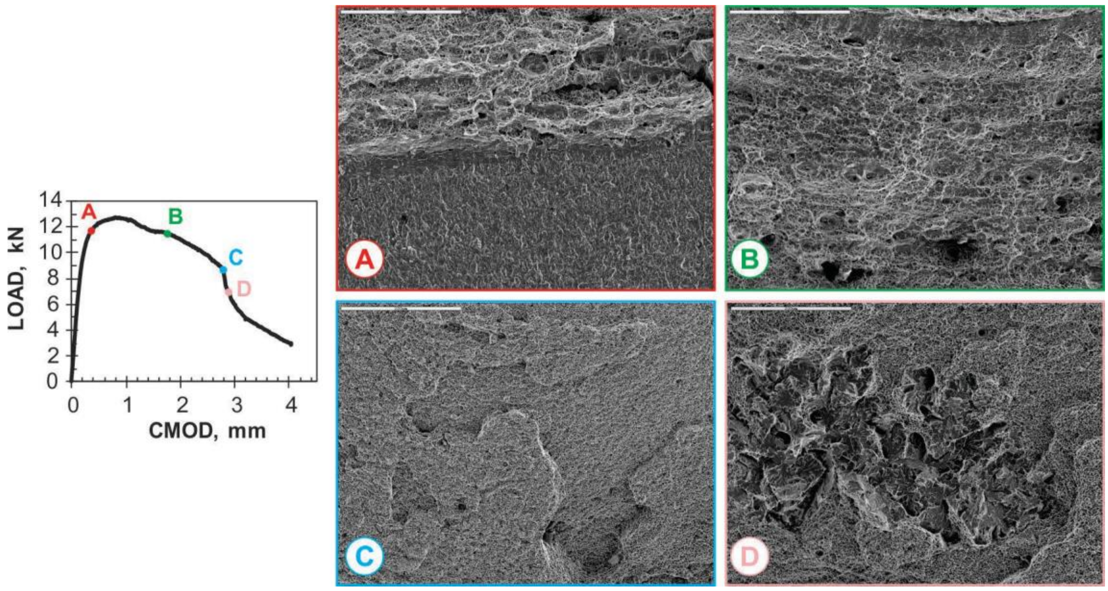


***Figure 1*** *- Load vs. CMOD curve for HAZ tested at -40 °C*

# #523 Determining the cause of incorrect work of bumper paint robot reducer

Taško Maneski[1], Vesna Milošević-Mitić[1], Ljubica Milović[2], Miloš Jovanović[1], Nina Andjelić[1], Ana Petrović[1]

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*Load-bearing structure* *Vibrodiagnostic* *Dynamic behaviour*

**Abstract** Industrial robots are used for jobs where high precision and productivity are expected, and one of the most reliable methods for monitoring their work is the vibrodiagnostic method. It also serves as a diagnostic method to determine the cause of failures. When analyzing the operation of industrial robots, their connection with the supporting structure is also very important.

This paper presents the process of diagnosing the state of the structure with bumper painting robots, after the failure of the robot motion reducer. To analyze the causes of the failure, a numerical-experimental analysis was performed, which included: (1) static calculation of construction deformations by applying FEM, (2) dynamic calculation of eigen oscillation forms, (3) determining transfer function in the frequency domain and dynamic reinforcement factors and (4) measuring dynamic displacement and acceleration. When the supporting structure has very low eigenfrequencies, it cannot accept inertial forces when moving the robot and large deformations and resonant behavior occur. Vibration measurements showed that the robot's natural frequencies are 3.5 ÷ 9.5 Hz.

Within the static analysis, the stiffness of the structure was calculated. Within the dynamic analysis, the eigenfrequencies and amplitudes of the main oscillation forms are determined. Dynamic analysis has shown that the behavior of the structure is very unfavorable because 20 eigen-oscillations have a frequency less than 17 Hz, and only five of them represent local oscillations of parts outside the working space of the robot. The determination of the transfer functions showed that the dynamic gain factor in all three directions of the excitation force is extremely large, while the corresponding frequencies are 5 ÷ 20 Hz. As part of the experimental analysis, accelerations and displacements at the locations of existing robots that exceed the standard acceptable limit were measured.

It was determined that the main problems that needed to be remedied were the rigidity of the supporting structure and substructure for supporting the robot in the horizontal plane and eliminating the omissions observed during the visual inspection. Only a partial relatively fast repair was done on the structure, without performing major interventions, but so that the displacements at the places where the most critical painting robots are supported were significantly reduced.


***Figure 1 -*** The supporting structure of the bumper painting robot

# #524 A finite fracture mechanics approach to thin structural silicone adhesives

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*Finite fracture mechanics* *Silicone adhesives* *Adhesive Bondings*

**Abstract** The present study investigates in the failure of adhesive bondings with thin structural silicone sealants. Prior to the failure analysis, mode I and III fracture toughness of the adhesive are determined. Additionally to classical double cantilever beam tests, a new experimental test design for out-of-plane loading of thin adhesive layers is employed and a theoretical framework explicitly allowing for large deflections is developed. Numerical investigations of this innovative test design are performed to validate the methodology of the evaluation.

The material properties found combined with a novel equivalent strain model allow for the application of finite fracture mechanics, where crack nucleation is predicted only if both conditions are fulfilled simultaneously. The numerical investigation of point connectors of two circular metal adherends bonded with thin structural silicone adhesives under tensile loading are performed with adequate hyperelastic constitutive laws that capture volumetric softening owing to the formation of cavities. The predicted onset of cavitation and ultimate failure loads are in good agreement with our experiments. The proposed model provides initial crack lengths that allow for the derivation of simple engineering models for both initial designs and proof-of-statics while simultaneously extending the range of usability of the structural silicone compared to standardized approaches.

# #525 Fatigue and fracture properties of concrete mixtures with various water-cement ratio

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*Concrete* *S-N curves* *Fracture properties*

Concrete elements used as a civil structure are usually made of a cement-based matrix and natural aggregates (such as sand, gravel, crushed stone, etc.). Three different concrete mixtures were prepared for these tests. The first is a common reference concrete with water-cement ratio w/c = 0.50 and a cement dosage of 450 kg/m$^3$. At the age of 28 days, this concrete shows cube compressive strength of 45.0 ± 0.4 MPa and flexural strength of 7.1 ± 0.2 MPa. The second concrete contains also 450 kg cement but w/c= 0.40, which means this concrete represents the boundary between usual and high-performance concrete (HPC). Its compressive strength was 69.1 ± 1.0 MPa and its flexural strength 8.2 ± 0.5 MPa. The third concrete is HPC with w/c = 0.30 and cement dosage 450 kg/m3. In this case, compressive and flexural strengths were 78.6 ± 0.7 MPa and 9.6 ± 0.5 MPa, respectively. This contribution introduces and compares fracture mechanical properties obtained from static and fatigue tests for three kinds of concrete. The focus was set on the bulk density, flexural and compressive cube strength, fracture toughness and fatigue properties (S−N − Wöhler curve). All of these tests are important for a practical application in the design of precast concrete structures.

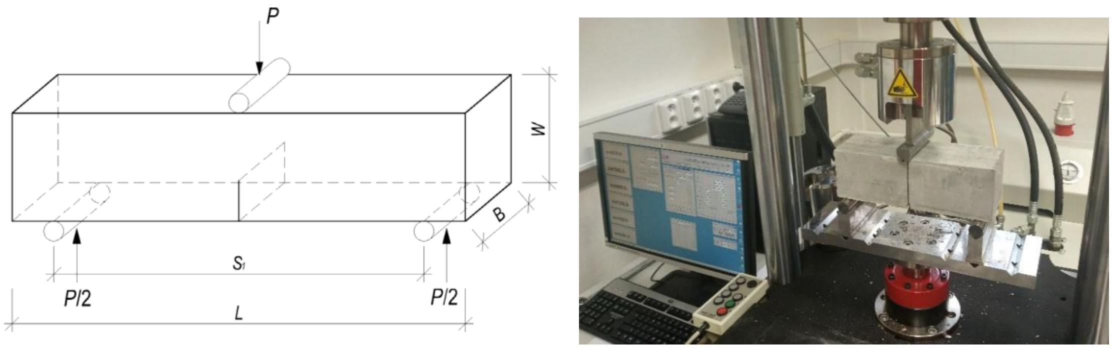


***Figure 1** – Sketch of a fatigue specimen and experimental set up for fatigue measurement.*

**Acknowledgement**

This outcome has been achieved with the financial support of the Czech Science foundation project No. 21-08772S - Influence of Self-Healing effects on structural fatigue life extension of structures made from high performance concrete (InShe) and mobility project No. 8J22AT008 - Mechanical fracture quantification of role of hemp fibres on self-healing processes in selected composites (KvaRK).

# #526 Experimental investigation of adhesion strength of dental ceramic to Ti6Al4V alloy fabricated by milling and selective laser melting

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*Ti alloy* *Selective laser melting* *Dental ceramic* *Adhesion strength*

**Abstract** The aim of the present paper is to investigate the bond strength of dental ceramic to Ti6Al4V alloy fabricated by milling and selective laser melting (SLM). The adhesion strength is studied by 3-point flexural test of samples with porcelain coating according to EN ISO 9693. Two groups of specimens are manufactured by milling and SLM. Four different surface treatments are used before porcelain application - no surface treatment (control), sandblasting and application of bonding agent on untreated and sandblasted surfaces. The coating of leucite-reinforced glass-ceramic is manufactured on the one side of the samples according to the manufacturer's instructions. It is established that the surface roughness of the SLM samples is about 8 times higher compared to the milled. Sandblasting increases 2 times the roughness of the milled samples, but decreases that, produced by SLM, with 11%. Adhesion strength of the ceramic to the SLM samples is higher in comparison to the bond of the milled samples. Sandblasting leads to increasing the bond strength of the milled samples but to decreasing that of the SLM ones. The highest is the adhesion strength of the two groups in combined surface treatment – sandblasting and application of bonding agent.

# #527 Analysis of the ERR for a transverse crack in cross-ply laminates due to residual thermal stresses and its application in the coupled criterion

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*Residual thermal stresses* *Cross-ply laminates* *Eshelby's procedure*

**Abstract** In the study of transverse cracking in cross-ply laminates in the presence of residual thermal stresses under the assumption of generalized plane strain [1], ERR for a transverse crack was very accurately computed by the BEM. Two partial problems were considered: the 1st problem of the laminate with a transverse crack subjected to a uniform imposed strain, and the 2nd problem of the same laminate subjected to the null imposed strain and a uniform temperature change in the whole laminate. For a particular case studied in [1], it was revealed that the dimensionless ERRs computed by the BEM for these two partial problems were apparently coincident. The present works tries to prove by applying the well-known Eshelby's sequence of imaginary cutting, straining and bonding operations [2] that these dimensionless ERRs are coincident in general. Finally, the obtained ERRs values are used in the Coupled Criterion of Finite Fracture Mechanics to predict the failure strain in cross-ply laminates in the presence of residual thermal stresses.

### Acknowledgements

The research was conducted with the support of Spanish Ministry of Science, Innovation and Universities: PGC2018-099197-B-I00. Consejería de Transformación Económica, Industria, Conocimiento y Universidades, Junta de Andalucía: P18-FR-1928, US- 1266016. European Regional Development Fund: PGC2018-099197-B-I00, P18-FR-1928, US- 1266016. The authors also acknowledge the funding received from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 861061 – Project NEWFRAC.

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# #528 Analysis of the material properties in the vicinity of the bi-material interface made by the laser cladded protective layer on the S960

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*Fracture mechanics* *Laser cladding* *High Strength Steel*

## Abstract

**Abstract** In technical practice, structural elements are used that are formed by combining layers of different metallic materials. These material combinations are created with regard to the required function either during the design of the structural construction or during its renovation and repair.

High Strength Steel (HSS-S960) is a very frequently used material for the production of structural components because of the advantageous strength-to-weight ratio. The application of various coatings on the HSS substrate may cause change of the properties, residual stresses and initiate a potential formation of surface concentrators.

*Figure 1* - *Example of preparation of the bi-material interface made by the laser cladded protective layer on structural steel.*

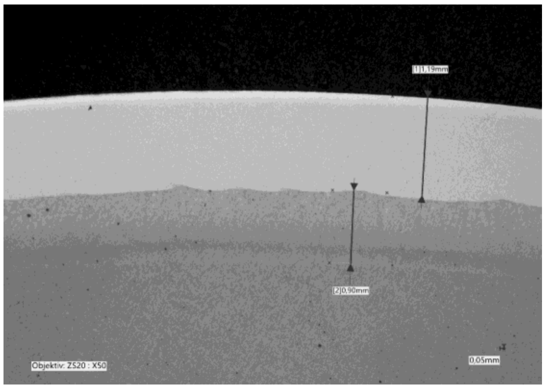

*Figure 2* - *Example of detail of a 50× zoomed interface made from a structural steel with a hard chrome layer.*

As a part of the experimental campaign, test samples have been created. High strength steels S960 were used as the base material and layers of the additional material were deposited on these base materials using laser cladding (particularly, aluminum bronze and hard chrome were selected). Different parameters of laser cladding technology (size of the layer, temperature, feed rate, powder ratio, carrier gas velocity and flow rate) were varied during the process. By this approach we resulted a wide range of samples with different structure and properties.

Vickers microhardness tests were performed on selected samples to determine the change in mechanical properties. The interphase between laser-cladded metal layer and steel substrate, including the heat-affected area, was analyzed by electron microscope.

## Acknowledgment

This research has been supported by projects No.: 21-14886S - Influence of material properties of high strength steels on durability of engineering structures and bridges and FAST-S-22-7881 - Initiation and propagation of cracks in corrosion of high-strength steels.

# #530 Influence of corrosion environment on the fatigue crack growth of 17- 4 PH steel specimens made by SLM

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*Corrosion* *Fatigue crack growth* *SLM*

**Abstract** Selective Laser Melting (SLM) and in general the additive technologies potentially offer to designers and technologists numerous advantages such as the reduction of the lead-time of new product and the possibility of producing any kind of complex shape. The performance of these components under cycle loading is influenced by porosities, residual stresses, heat treatments, corrosion environments etc. In particular corrosion environments can influence the fatigue crack propagation. In this paper fatigue crack propagation behaviour of 17-4 PH steel made by SLM under corrosion environments are presented. The tests were carried out using standard 5 mm thick compact specimens C(T) tested at R= 0.1 and with frequency in the range 1÷10 Hz under NaCl solution and in air. The main objective was to study the effect of the environment solution on da/dN-ΔK curves and on the fatigue failure mechanisms.

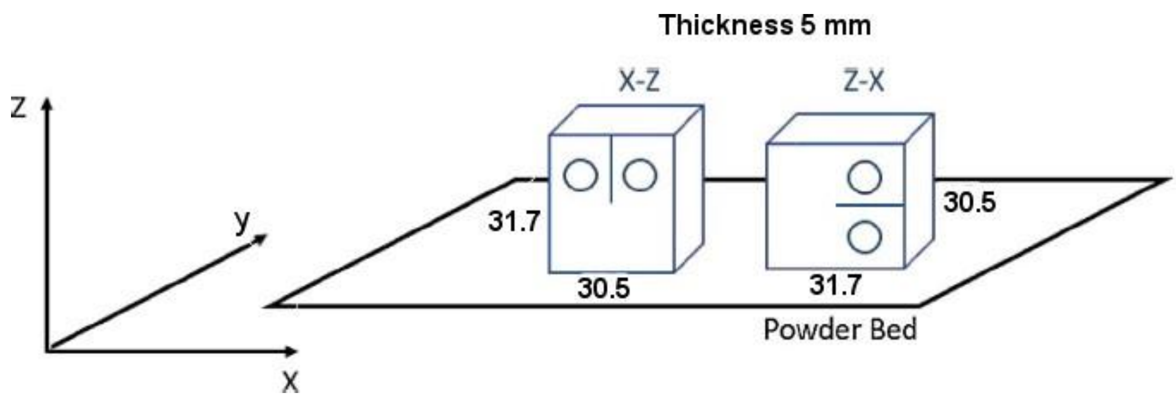


***Figure 1** – Case of study*

# #531 Role of stress and thermally -induced martensite transformations on fatigue crack growth in NiTi alloys

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*NiTi Shape memory alloys* *Fatigue crack growth* *Digital image correlation*

**Abstract** Fatigue crack growth nickel-titanium based (NiTi) shape memory alloys (SMAs) was systematically analyzed under different thermo-mechanical loading conditions. In particular, isothermal fatigue tests were carried out at different values of the testing temperature, with the aim of analyzing the effects of near crack tip stress-induced transformation phenomena and related thermo-mechanical coupling effects on the fatigue crack growth rate. Furthermore, both austenitic and martensitic materials were tested to capture the effects of stress-induced martensite and martensite reorientation mechanisms, respectively. Fatigue crack growth experiments were carried out by using eccentrically loaded single edge tension (ESE(T)) specimens and near crack tip displacements were captured by using digital image correlation (DIC) techniques (see Fig. 1). A special fitting procedure, based on the William's solution, was also used to estimate the effective stress intensity factor range (SIF) from the DIC displacement field. Results highlighted the marked effects of near crack tip transformation mechanisms and related thermo-mechanical couplings on the fatigue crack growth in NiTi SMAs.

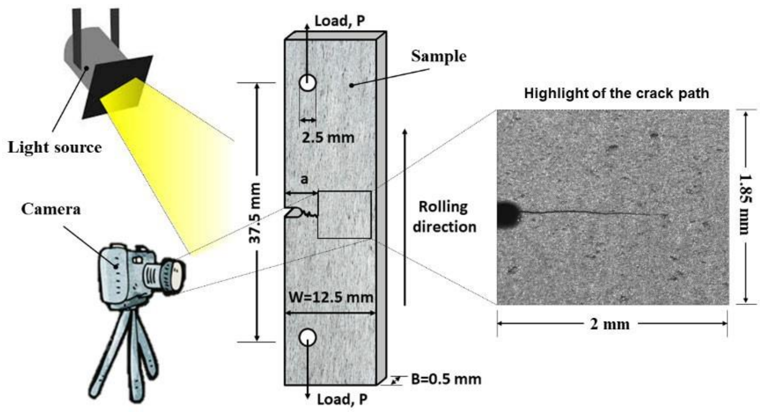


***Figure 1:*** *Eccentrically loaded single edge crack (ESE) specimen and experimental setup*

# #532 Modeling of Delamination in CFRP Beams with Elastic Couplings

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*delamination* *composite* *couplings*

**Abstract** The field of applications of composite laminates in contemporary engineering could be extended with usage of coupled layups. For the purpose of fracture toughness determination the standardized procedures can be used, such as ASTM D5528, ISO 15024, ISO 15114, ASTM D7905, by introducing additional parameters for the data reduction schemes. The finite element (FE) simulations can be helpful in proper design of the coupled experimental specimens. In particular, distributions of the strain energy release rate along the front of delamination obtained numerically can be helpful in mode separation problems. The virtual crack closure technique (VCCT) was used in the simulations performed with the Abaqus FE software together with the Reeder Law as the fracture criterion because of its capability to describe the three separate fracture modes, as well as the mixed modes. The study revealed possible difficulties in direct application of the standardized methods for delamination resistance assessment. The numerical outcomes are now being verified in laboratory tests with specimens of different couplings/delamination interfaces, as well as in various test stand configurations, ex. DCB, ENF, ELS. The project/research was financed in the framework of the project Lublin University of Technology-Regional Excellence Initiative, funded by the Polish Ministry of Science and Higher Education (contract no. 030/RID/2018/19).

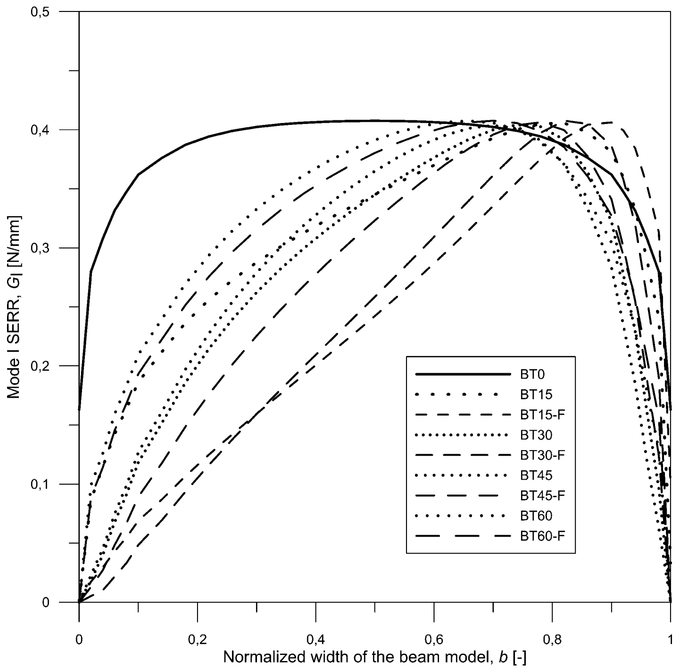


***Figure 1** – Mode I SERR distributions along delamination front in bending-twisting coupled laminate beam model*

# #533 A variational approach to Paris-type fatigue law

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*Fatigue* *Paris's law* *FEniCSx*

**Abstract** Fatigue is one of the most critical and less predictable phenomena in nature, affecting the mechanical behavior of materials. As shown in [1], the most common approaches to describing fatigue have a phenomenological origin. These models can vary in shape and parameters depending, not clearly, on the geometry of the sample, loading, and environmental conditions. The most celebrated one dates back to 1963 when Paris and Erdogan proposed a power law that gives the rate of growth of a crack provided: i) the range of the stress intensity factor over a cycle of solicitation, ii) a material coefficient, and iii) the exponent at which the stress intensity factor range is subjected. The latter two must be determined through an experimental campaign.

This work is based on the seminal deduction of Marigo and co-workers presented in [2-3]. Here, they propose a variational formulation able to describe the propagation of the crack in a brittle manner, recovering the Griffith model and the fatigue phenomenon, retrieving the models of Paris. In particular, this approach is based on the least energy principle where the total energy of the structure, to be minimized, is the sum of the elastic energy and a dissipation potential, taken as a power function of the newly created crack surface.

We present a finite element numerical implementation of the model mentioned above via FEniCSx [4], an open-source computing platform for solving PDEs. In these numerical experiments, it is possible to appreciate the initiation and subsequent propagation of a crack in a pre-notched sample where the imposed cyclic loading conditions permit obtaining both standard pre-assigned crack paths (e.g., straight-line) and less trivial crack paths.

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# #534 On the key role of crack surface area on the lifetime of arbitrarily shaped flat cracks

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*Fatigue crack propagation* *Perturbation method* *Damage tolerance*

**Abstract** Accurate fatigue lifetime prediction is a central element in many industries. Often, a damage tolerant approach is used to ensure that some given imperfections are safe. In this context, these lifetime predictions are frequently made using simplified crack geometries leading to costly conservatism. In particular for a closed crack front, a circular or elliptical crack enclosing the real defect is generally used leading to an underestimation of the real lifetime. Using an iterative perturbation method to simulate the fatigue growth of many tensile complexly shaped cracks, we show that in the absence of any additional complexity, (i) the front quickly becomes circular; (ii) its evolution with the number of loading cycles can be obtained analytically using a circular crack of same area as the original distorted defect. In practice, it means that replacing a complex crack front shape with this simple, analytically solvable configuration is an effective way to improve predictions and that it is not useful to invoke more complex shapes such as elliptical cracks. These take-home messages are illustrated by an example from the aviation industry.

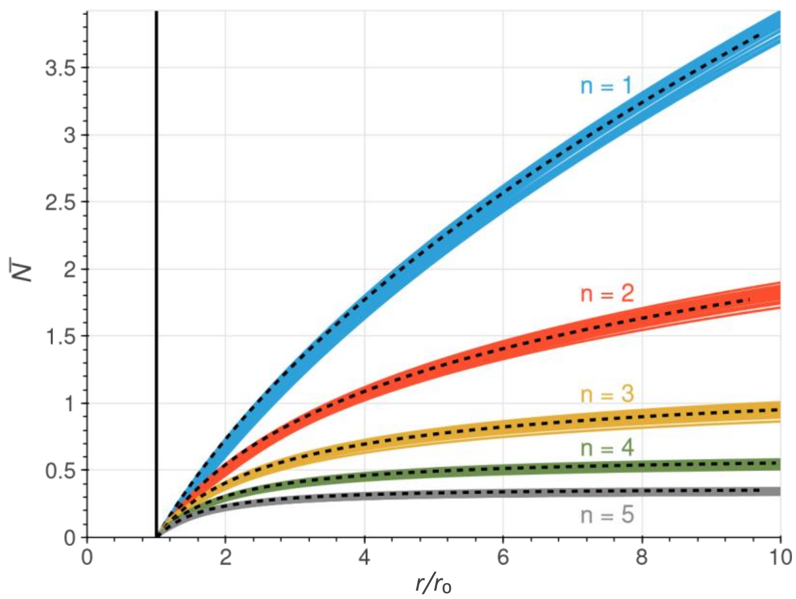


***Figure 1*** *– Whatever the initial crack shape the number of cycles N necessary to reach a crack of surface area $r^2$ is the same than for a circular crack of same area.*

# #535 Friction effects in uniaxial compression of concrete cylinders

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*concrete* *friction* *compression*

**Abstract** Experimental testing of concrete samples is of crucial importance both when designing a concrete mixture and when obtaining material properties of existing structures. External factors, such as the configuration of the experiment may play an important role and potentially influence the results.

When it comes to compressive testing of concrete, one such factor is the friction between loading platens and the specimen. It has been shown that friction directly influences the failure mechanism of specimens and the resulting compressive strength. The phenomenon is most prominent with specimens of low slenderness ratio, gradually fading as the slenderness ratio grows. Understanding the phenomenon is paramount for the correct interpretation of experimental results.

The contribution illustrates and describes the different mechanisms of failure during compressive testing of concrete cylinders of various slenderness ratios using different friction boundary conditions on the specimen-loading platen contact. The study compares experimental data and numerical results. The model of the specimens is formulated as a Lattice-Discrete Particle Model, which is a model considering the explicit representation of mineral aggregates and thus allowing for a detailed study of crack formation.

# #536 Fatigue life prediction of 6060 extruded aluminium

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*Fatigue* *Life prediction models* *Aluminium*

**Abstract** The fatigue limit stress prediction models make it possible to determine the durability of metals, considering experimental fatigue tests, mechanical properties, hardness, manufacturing technology (namely through intrinsic defects in the process), and empirical constants depending on the manufacturing processes and components' dimension. The presence of manufacturing defects in the materials leads to failures at much lower applied stresses. Therefore, it is of primary importance to consider such defect features as input parameters in fatigue limit assessment. This work aims to develop fatigue life prediction models for extruded 6060 aluminium. The methodology used in this study is based on experimental work and was divided into four phases: the manufacturing and preparation of the samples and specimens according to standard recommendations ASTM E3-11(2017) and ASTM E8/E8M-21, respectively; the manufacturing defects study; the Vickers hardness study following the ASTM standard E384-17, and the fatigue study. The materials used were obtained from three extruded pieces of 6060 aluminium with different geometries (a rectangular section with smooth faces and recessed faces and a solid rectangular section) and different heat treatments (T1 andT4). The manufacturing defects of the stress concentrations zones were studied. The algorithm to predict durability is based on the experimental results obtained. All the samples were observed under an optical microscope to analyze the size and distribution of the defects found. A total of 2330 images were analyzed. In the distribution defect study were considerate 14 classes. This study concluded that, for all pieces, the [0, 10[ $\mu m^2$ area class presented the highest number of defects. A sinusoidal wave was used on the fatigue tests with a constant amplitude and stress ratio of R=0.05. It was also applied at a frequency of $f$= 10 Hz during each test and a room temperature of 25ºC. For the Vicker hardness tests, a load of 0.1 kgf was applied for 10 seconds, and the distance between indentations was 0.5 mm, ensuring a minimum distance of 2.5 times greater than the Vickers diagonal. In each sample, five indentations were made. In conclusion, new models to predict the fatigue limit were developed for the 6060 aluminium extruded, considering different geometries and heat treatment.

# #537 Design methodology of vessel produced by L-PBF stainless steel using representative specimens

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*[2] Mondragon University (Spain)*

*Additive manufacturing* *Steel 316L* *Fracture Mechanics*

**Abstract** This work presents the preliminary results of an ongoing project with a double objective: on the one hand, the characterisation of the mechanical properties against fatigue damage of an additively manufactured 316 stainless steel produced by laser powder bed-based (L-PBF) technology; on the other hand, the implementation of numerical simulation techniques able to predict the mechanical behaviour of the material in order to optimise and reduce the design costs of vessels used in the chemical sector. The current state of the work developed in this research framework allows showing the first batch of experimental results of crack propagation rate (FCGR) and high cycle fatigue (HCF) tests. The geometry of the vessels studied presents three clearly differentiated regions, either in terms of thickness (11-15 mm) or concerning the inclination of the walls to the direction of manufacturing (0º - 45º). The experimental campaign carried out so far allows identifying the differences in behaviour when comparing different extraction locations around the vessel. This is due to the variations in thermal cycles that the deposited material undergoes during the manufacturing process. Therefore, this causes variations in the microstructure which lead to changes in the response of the material. In this work, these differences are analysed qualitatively and quantitatively from the results of FCGR and HCF, thus allowing to locate the regions with the highest risk in terms of structural integrity against fatigue. This preliminary phase together with the numerical simulation of the additive manufacturing process are key to achieving a reliable description and modelling of the material. The latter will make it possible to address the priority aim of this project, involving the manufacture of independent samples whose properties are representative of the original material extracted from the reference vessels. It is, therefore, a comprehensive methodology for the design of additively manufactured components based on the localised fatigue mechanical properties of representative specimens.

# #538 AISI P20 steel under VHCF testing conditions

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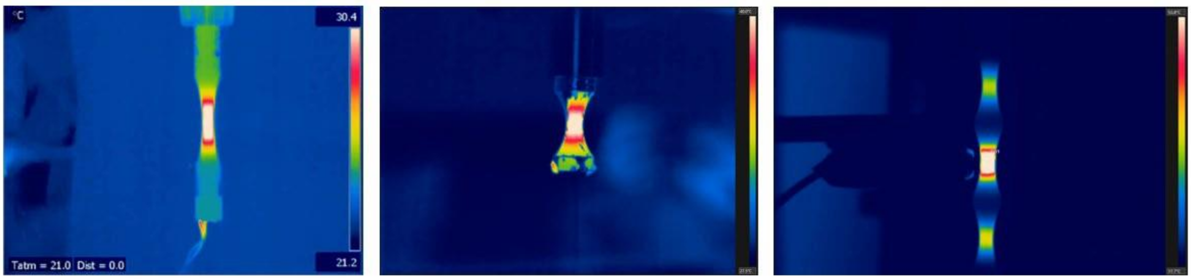
*Ultrasonic fatigue Testing* *Multiaxial fatigue* *Very High Cycle Fatigue*

**Abstract** As more complex materials, structures and machines are created and applied in the modern world, the importance and complexity of fatigue testing methods become more indispensable for any mechanical project. This study focuses on an AISI P20 Steel Very High Cycle Fatigue (VHCF) regime, between $10^6$ to $10^9$ cycles, under different loading conditions: Tension-compression, pure torsion, and multiaxial tension/torsion. To reach such a considerable high number of cycles, no conventional fatigue testing method is energy and time reliable. Therefore, the present study conducted ultrasonic fatigue testing methods under 20kHz. Each stress type fatigue method was reached from its respective and different ultrasonic fatigue setup. The study research team built all three machines at Instituto Superior Técnico. Significant testing associated conditions and methodology, such as temperature, frequency and displacement, were carefully controlled, recorded, and made similar for all three methods. Stress-life results, material behaviour throughout fatigue testing and fracture surfaces for each stress type were compared for behaviour and damage correlation between pure torsion, tension- compression and the multiaxial combination of the two, tension-torsion. After all conducted fatigue tests, the obtained fatigue crack surfaces were analyzed by scanning electron microscope (SEM) and compared between methods. Each tested method presented fatigue fracture surfaces with associated fracture morphologies similar to conventional fatigue methods. The novel tension-torsion ultrasonic fatigue fractures showed both axial and torsion fatigue fracture dependencies and complexities, proving the induced stress field of interest.



A B C

***Figure 1** – Thermographic image during ultrasonic fatigue testing in: (A) tension-compression; (B) pure torsion; (C) multiaxial Tension/Torsion*

# #539 Multiscale Optical Methods to Measure the Fatigue Crack Closure

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*Fatigue Crack* *Crack Closure* *Optical Methods*

**Abstract** In this work, two different high-resolution optical tools with different resolution are used to measure in-plane displacements on the crack flanks, close to the crack tip, which can then be used to determine the presence of crack closure in propagating fatigue cracks. Middle tension (MT) specimens, made of different aluminum alloys, are fabricated with an initial notch and then submitted to a cyclic fatigue-loading condition to open the crack with a pre-determined length. Then, the cracked specimens are monotonically loaded, with defined load increments, to reach the maximum load. Digital image correlation (DIC) and electronic speckle pattern interferometry (ESPI) are employed to collect the experimental data at different resolution, calculating the displacement and deformation fields while the specimen is statically loaded. The force-displacement variation on the vertical virtual gauges defined on the crack flanks close to the crack tip is also closely monitored. Results from both techniques are compared, and a complementary multiscale methodology is proposed for the crack closure phenomenon.

# #540 Fatigue Behavior of Ti6al4v Alloy Coated With Sic Layer and Cr Interlayer Deposited by Magnetron Sputtering with Hipims And Dc Sources

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*Fatigue* *Titanium* *Thin Films*

**Abstract** In this work the effects of a thin film of Silicon Carbide (SiC) and Chromium interlayer on the fatigue behavior of Ti-6Al-4V alloy were investigated. Films of 400 nm and 200 nm were deposited by the Magnetron Sputtering technique using two sources: HiPIMPS and DC. The characterization of the layer was performed by optical microscopy, AFM, XRD techniques and qualitative and quantitative adhesion tests (scratch test). Uniaxial fatigue tests were carried out under load control, determining the S-N curve for each condition and verifying through fractography studies how the coatings interfere in the nucleation and propagation of fatigue cracks.

# #541 Construction and demolition waste, a new life in mortar composites

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*CDW* *Sustainability* *Mechanical properties*

**Abstract** Raw materials are becoming limited in the building industry and their extraction and processing have a significant environmental impact. Therefore, in recent years the European Union (EU) has been supporting recovery strategies focused on the reuse of Construction and Demolition Waste (CDW), which is one of the heaviest and most voluminous waste streams generated in the EU (it accounts for approximately 25% - 30% of all waste generated in the EU), causing environmental problems due to its uncontrolled disposal. Nowadays, some reuse techniques, such as concrete and brick wastes as filling for road pavements, have been extensively researched but only allow for a limited disposal volume. This work aims to study the use of recycled CDW in building applications, allowing for the disposal of a substantially higher amount of waste created each year.

For this purpose, several specimens were performed to evaluate the mechanical properties of mortar specimens with different standard sand substitution percentages in weight of aggregate with CDW (25%, 50%, 75% and 100%). The test results of this study indicate a promising future for the use of construction and demolition waste aggregates at high substitution rates in the construction sector.

# #542 Asymmetric cyclic loading behavior of welded Inconel 740H nickel-based superalloy at 760°C

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*Ratcheting fatigue* *Plastic strain accumulation* *Mean stress*

**Abstract** Inconel 740H is one of the promising alloy having applications for manufacturing the components of advanced ultra-supercritical (A-USC) power plants. The present study is to understand the ratcheting fatigue behavior of the Inconel 740H weld joint fabricated with Nimonic 263 as the filler metal. Fusion welding is an essential route for the fabrication of structural components used in power plants. Weld metal and heat-affected zone (HAZ) developed during welding are generally considered being the weakest link in any welded construction, and the structural inhomogeneity developed during welding is the main cause for premature failure. The proposed research emphasizes fatigue and fracture issues, which often occur in the structural components due to welding inhomogeneity and variable pressure. This study would enable for better understanding of the fracture/microstructural behavior of the weld joints under asymmetric cyclic loading at relevant service temperature in the range of 700-760°C. The testing is carried out with variable mean stress, stress amplitude, and stress rate at 760°C. The experimental outcomes show that with increase in mean stress and stress amplitude, the ratcheting strain accumulation increases with reduction in fatigue life. However, increase in stress rate leads to improvement in fatigue life of the material due to lesser ratcheting strain accumulation.

# #546 Investigation Of The Effect Of Dwell Period In Load Controlled Fatigue Tests Of Inconel 718 Superalloy

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*Rotating Bending Fatigue* *Inconel 718* *Dwell Fatigue*

**Abstract** The use of nickel alloys has become widespread in many industries during the last century. Inconel 718 is a niobium-modified nickel-based superalloy as a member of this family, and mostly used in the hot sections of a turbine engine. It works under both static and dynamic loadings during service conditions in aero-engine applications. In this study, the effect of dwell period on high cycle fatigue behavior of Inconel 718 was investigated.The main objective of this work is to determine the material's fatigue behavior under rotating bending fatigue conditions in the presence of sequential interruptions and thermal effects. In this context, the fatigue tests were conducted at room temperature and at 450°C with dwell times simulating the material's operating condition in the engine applications. In addition to the fatigue tests, hardness measurements and nanoindentation were also performed at room temperature. Fracture surface and microstructure of the samples after the fatigue tests were examined by an optical microscope and a scanning electron microscope (SEM).The results revealed that dwell sensitivity of Inconel718 depends on the temperature and the applied stress amplitude.

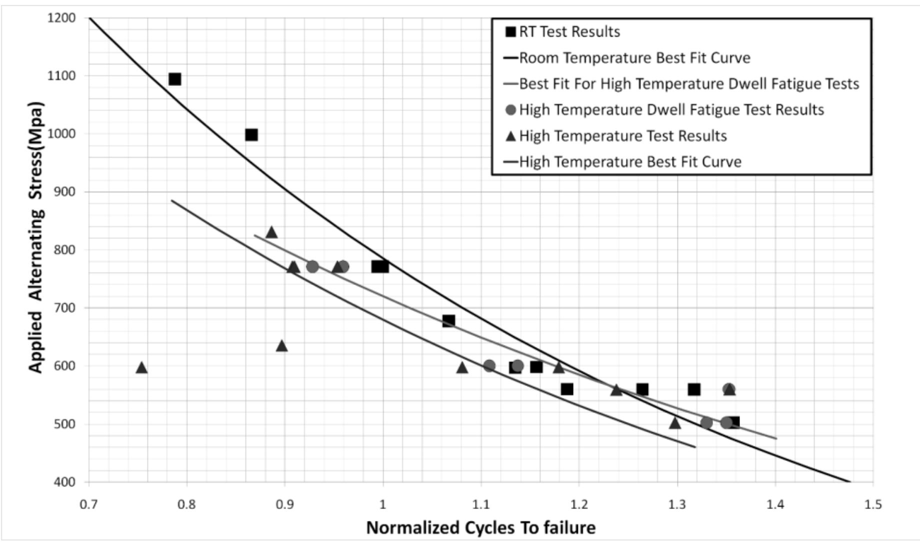


***Figure 1*** *–S-N curve of Inconel 718 after Rotating Bending fatigue tests*

# #547 Processing of top creep and oxidation resistant Fe-Al based ODS alloys

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*ODS alloy* *nanooxides* *creep*

**Abstract** The Fe-Al based oxide dispersion strengthened (ODS) alloys are investigated since the 1970's. The alloys are produced by mechanical alloying of metal powders and $Y_2O_3$ followed by hot consolidation such as extrusion, rolling or rotary swaging. The oxides are dissolved during mechanical alloying in the powder matrix and they subsequently precipitate during the hot consolidation and thermal treatment. The processing involves several parameters which need to be carefully optimized and controlled to produce a successful alloy with excellent creep properties. The presented systematic testing and microstructure studies are necessary to identify the values of the most important parameters. The coarse-grained ferritic Fe-10Al-4Cr-4$Y_2O_3$ oxide dispersion strengthened alloy exhibits top creep and oxidation resistance. Compared to commercial INCOLOY MA956 it involves twice more Al, ten times more $Y_2O_3$ precipitates and exhibits twice higher creep strength at 1100-1300 °C. Moreover, the creep rate is practically immeasurable and the time to fracture reaches several thousands of hours at applied stresses of 60-70 % of the ultimate strength in the order of 120 MPa for 1100°C and 60 MPa for 1300°C. The paper describes decisive processing steps and characterizes the most important microstructural and mechanical properties.

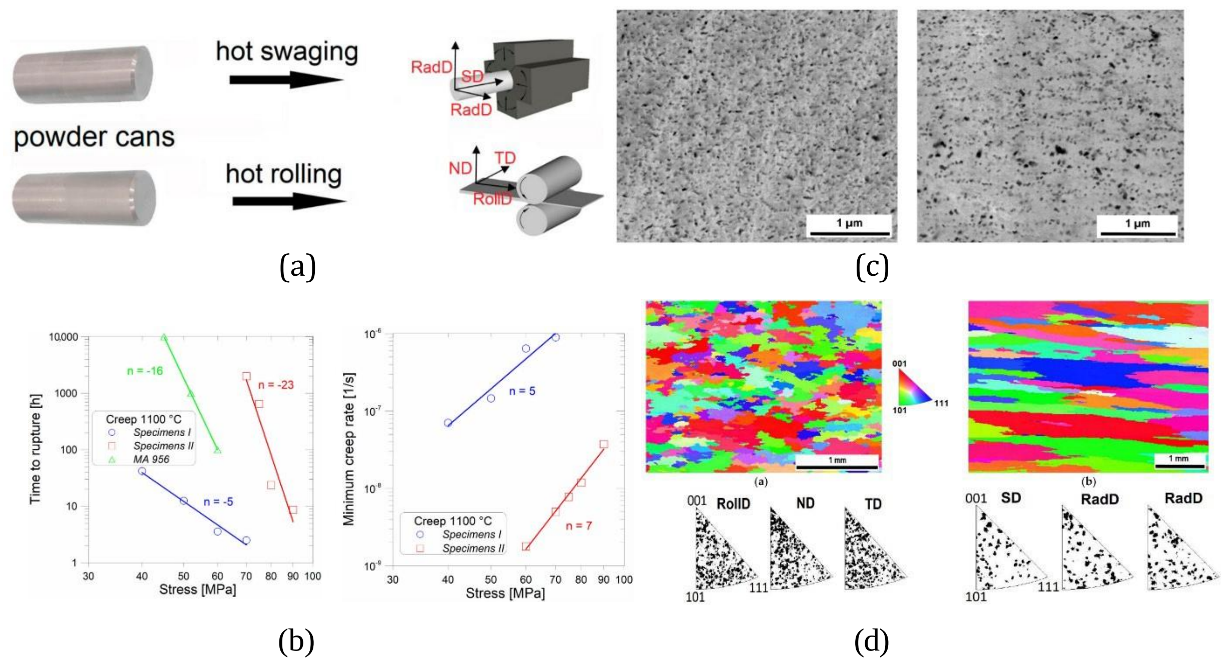


***Figure 1 – (a)** scheme of the processing, **(b)** creep characteristics, **(c)** illustration of precipitates and **(d)** microstructure*

# #549 Influence of flexoelectricity on an interface crack between two dissimilar dielectric materials

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**Abstract** Layered composite structures are frequently utilized in microelectronics. Usually a severe thermal load of electronic parts requires to apply a thin film technology with a strong thermal resistant material properties in protection layer. Due to a poor adhesion of protection layer and basic material, the interface crack can be created there and for the prediction of failure of these structures it becomes essential to investigate distribution of the interfacial stress and strain fields.
Flexoelectricity is a size dependent electro-mechanical coupling phenomenon, where the electric polarization is induced by a strain gradient in dielectrics. The strain gradients may potentially break the inversion symmetry in centrosymmetric crystals and polarization is observed even in all dielectric materials [1]. The polarization is proportional to the strain gradients in the direct flexoelectricity

$$P_i \approx f_{ijkl} \varepsilon_{jk,l} \, ,$$

where $f_{ijkl}$ are the components of the so-called flexoelectric tensor.

The flexoelectricity can play an important role in the crack tip vicinity, where there are large strain gradients. The large strain gradients are localized on a small region which size is comparable with the microstructural length scale. The scale independent classical continuum mechanics isn't applicable to description of size-dependent phenomena. On the other hand, the higher-grade continuum theory has appeared to be suitable for study of coupled electro-elastic fields at the crack-tip vicinity. In literature one can find some studies of cracks in homogeneous materials analyzed by the gradient theory [2-4]. However, studies devoted to interface cracks between two dissimilar materials analyzed by the gradient theory are very rare [5,6].
In the present paper, the interface crack between two dissimilar dielectric materials under a mechanical load is investigated with including flexoelectricity effects. According to the best author knowledge this subject has never been reported in literature. The gradient theory is applied to both homogeneous regions. Governing equations in the gradient theory contain higher-order derivatives than in the standard continuum mechanics. Therefore, a reliable computational tool is required to solve these boundary-value problems. The mixed finite element method (FEM) is developed, where the standard $C^0$ continuous finite elements are utilized for independent approximations of displacements and strains. The constraints between the strain gradients and displacements are satisfied by collocation at Gaussian integration points inside elements [7].

In numerical examples, a parametric study is performed with respect to flexoelectric and elastic coefficients for both material regions. The influence of these parameters on the crack opening displacement is discussed.

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# #550 Ranges of Influence of the Stress Invariants and Hardening: Monotonic and Cyclic Applications

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*Stress Invariants* *Ductile Fracture* *Fatigue*

**Abstract** The objective the present work is to evaluate the effects of the stress invariants $I_1$ and $J_3$ on the mechanical behavior of metallic materials. In this regard, the Ductile Fracture (monotonic), Ultra-Low (ULCF) and Low Cycle (LCF) fatigue behavior of SAE 1045 steel was analyzed supported by the experimental information furnished by Bai (Bai, 2007) and Leese & Socie (Leese & Socie, 1989). Furthermore, a Gao-based model (Gao, et al., 2011)with mixed (isotropic and kinematic) hardening was proposed to capture $I_1$ and $J_3$ influences. The numerical simulations conducted assuming von Mises behavior did not describe properly the mechanical response from Ductile Fracture, ULCF, and LCF data, which demonstrated the SAE 1045 steel dependence on $I_1$ and $J_3$. After the calibration of Gao's $a$ and $b$ parameters, the numeric responses provided better agreement with respect to experiments. Interestingly, $a$ and $b$ were affected by the hardening type considered. Significant differences between Mises and Gao based constitutive modeling arose in monotonic and ULCF conditions, while the discrepancies in LCF were less pronounced in terms of stress amplitudes. Nevertheless, the evolution of the accumulated plastic strain expected by Mises and Gao approaches deviated considerably, which suggests that stress invariants formulations may be an attractive option for incremental techniques for fatigue life assessments (Araujo, et al., 2020).

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# #551 In-situ micro-mechanical investigation of cut-edge failure: microstructure-driven crack toughening in laser-cut affected zones

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*Cut-edge failure* *Micromechanics* *In-situ testing*

**Abstract** Among the many cutting techniques, blanking and laser cutting are the most commonly used cutting techniques due to their high efficiency, sufficient accuracy and reasonable cost. Yet, a key concern for the industry is failure at the cutting surface during the subsequent forming, so-called 'cut-edge failure', especially for advanced high strength steels with complex phases used by the automotive industry. Yet, the number of well-defined micro-structural investigations of cut-edge failure in combination with the resulting micro-mechanical effects on formability is limited. Moreover, no direct comparison of the fundamental differences between two different cutting techniques, applied to the same sheet material, is available in the literature.

Therefore, in this work, the as-cut microstructure and resulting micro-mechanical deformation of blanking with 2.5% and 10% clearance and laser cutting was characterized in detail using in-situ biaxial Marciniak testing under optical and electron microscopy combined with digital-imaged-correlation-based strain mapping and nano-indentation. Dual phase (DP) steel is selected as a model material for this study because of (i) its relatively simple microstructure consisting only of ferrite and martensite, (ii) extensively researched microstructure and damage evolution, also in our lab, and (iii) high relevance for the automotive industry.

It was found that the strain-to-failure of laser cutting is almost twice that of blanking, even though micro-damage initiates already at 8% strain in the ~60µm-thick, brittle, fully-martensitic surface layer in the laser-cut affected zone. Detailed microstructural investigation, see e.g. Fig. 1, revealed that the ~145µm-thick tempered-martensite sub-surface layer provides the toughness to first delay micro-damage propagation and subsequently arrest the crack growth, see e.g. Fig. 2, which explains the high strain-to-failure of laser cutting. Based on this insight, guide-lines for an improved cutting process are provided.

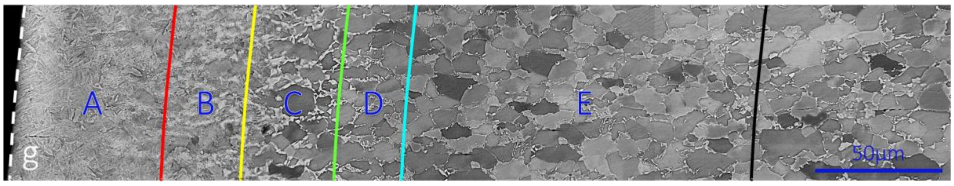


***Figure 1 -*** *Secondary electron (SE) image of the different microstructures in the heat-affected zone of a laser-cut specimen (the white dashed marks the cutting edge)*

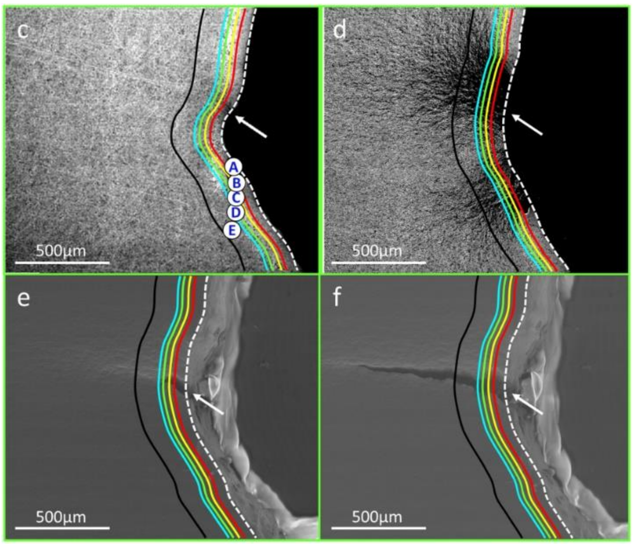


***Figure 2 -*** *(c–f) In-situ SEM images, captured in (c,d) BSE-mode for micro-damage visualization and (e,f) SE-mode for crack propagation visualization, at (c) first observation of micro-damage (indicated by the white arrow), (d) the last image before macro-crack observation, (e) arrested crack growth, and (f) final failure. The colored curves in (c–f) mark the location of heat-affected sub-zones,* ***A*** *–* ***E****, with the same color coding and distance to the (deformed) cut edge as the as-cut state in Fig. 1. The rolling direction is in vertical direction.*

**Conclusion** Blanking and laser cutting was studied in detail for dual phase steel, providing interesting new insight and understanding in cut-edge failure in general as well as specific guide-lines for an improved cutting process that can be readily adopted by the industry.

# #552 Full-field identification of mixed-mode adhesion properties in microelectronics from micrographs only

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*adhesion properties* *mixed-mode delamination* *in-situ testing*

*full-field identification* *integrated DIC* *microelectronics*

**Abstract** Mixed-mode loading conditions strongly affect interface failure mechanisms in microelectronic systems containing complex 3D material stacks. To measure adhesion properties under arbitrary mode-mixity, the integrated digital image correlation (IDIC) method [1,2] was extended to identify mixed-mode cohesive zone (CZ) model parameters from only the micrographs of a micro-mechanical experiment with restricted field of view and unknown far-field boundary conditions and forces [3,4]. Realistic virtual experiments showed that for optimized load cases, robust identification of the elusive interface parameters with errors below 1% is possible [4].

For proof of concept, the three mixed-mode CZ parameters of a flexible OLED were identified solely from in-situ optical micrographs of a single on-device mixed-mode delamination experiment, performed with a novel tri-axial micro-mechanical setup [5], with the imposed loading conditions outside view [6]. For optimized experimental load cases the IDIC optimization scheme robustly converged to a unique solution for the mixed-mode CZ parameters [6].

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# #553 Digital image correlation for accurate strain measurement in sharp notched specimens

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*Digital image correlation* *Notched specimen* *Welded specimen*

**Abstract** Notch stress concentration and the notch effects in general, play a significant role in the field of structural mechanics. Also, the strain measurement in notches is still a challenge. In cases, when the notch geometry is not exactly defined e.g., weld joints etc., the measurement of strains in notches becomes even more important. Therefore, the present work focuses on the problem of strain measurement on notched specimens, especially on sharp notches (notches with small minimum radius) by using the digital image correlation method. Initial measurements were carried out on the open-hole specimen and the results were compared with the analytical and numerical solution. Multiple camera positions with respect to the specimen are compared and discussed. Minimum number of pixels per notch radius for accurate measurement was determined based on the measured data. This limitation is influenced by several effects. The presented work focuses deeper on the influence of postprocessing filter method. Several possible solutions to overcome this limitation are presented. The obtained results and the knowledge gained by previous measurements were utilized by direct practical measurements e.g., brake component (Fig. 1) and weld notch stress concentration.

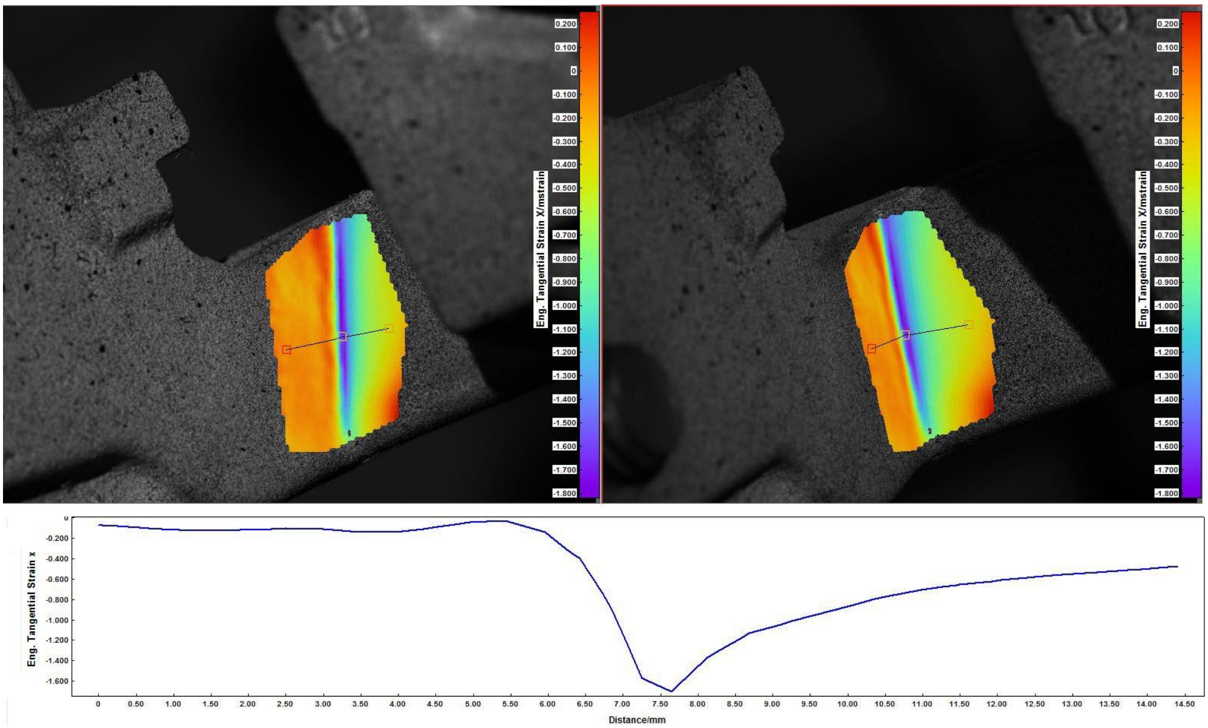


***Figure 1*** *Notched component X direction strain distribution*

# #554 Numerical simulation of pressurized disk tests for the study of hydrogen embrittlement

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*Hydrogen embrittlement* *Disk test* *FE simulation*

**Abstract** The susceptibility to hydrogen embrittlement of steels can be characterized using tests on pressurized disks (bulge test) following the ISO 11114-4 standard. However, failure often occurs in the clamping area. The analysis of results is then problematic. A new geometry was designed based on Finite Element (FE) simulations to overcome this difficulty. It consists of a 3mm thick disk thinned at its center so that its minimum thickness is 0.75mm, in agreement with the standard's requirements. A second geometry consists of a 2mm thick disk in which an axisymmetric notched is machined. Experiments were conducted on a line pipe steel under helium and hydrogen. The fracture always occurs outside of the clamping area for both designs.

Tests carried out under hydrogen were simulated based on the model by Sofronis and McMeeking [1] and corrected by Krom et al. [2]. Softening due to hydrogen was also accounted for [3]. Specific finite elements were developed to describe the strong coupling between mechanical loading and hydrogen diffusion. In addition to displacement, they use additional degrees of freedom representing pressure, volume change, and lattice hydrogen concentration. The use of a mixed pressure+volume change formulation presents two advantages: (i) volumic locking is avoided at high plastic strains [4], (ii) pressure is defined at nodes so that its gradient, which strongly influences hydrogen diffusion, can be straightforwardly computed. Simulation results are then used to interpret experiments qualitatively.

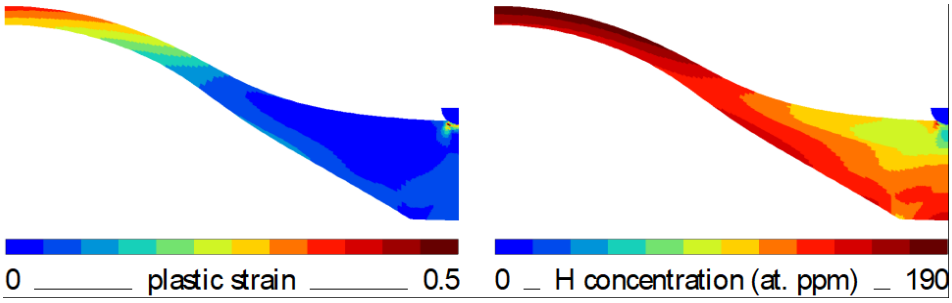


***Figure 1*** *– (a) Plastic strain, (b) Hydrogen concentration in the modified disk*

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# #555 Structural Optimization of a Passenger Train Seat using Finite Element Analysis

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*Finite Element Analysis* *Structural Optimization Process* *Railway Sector* *Train Seat*

**Abstract** Passenger train seats have strict requirements for durability, being subjected to daily use, multiple times, and to varying mechanical loading conditions. They should also be comfortable while considering the journey duration or the nature of the train – suburban trains do not need as much passenger comfort as regional trains, for instance. Reducing the overall weight of the seat has repercussions throughout the train leading to reduced energy consumption, along with less material used for the fabrication of said seat. Train seats are traditionally composed of a metallic structure that may or may not be visible, depending on whether it doubles as a cosmetic (non-structurally supporting) element as well, along with padded foam pillows lined with strong fabric to resist abrasion. The seat's structure configuration not only depends on the mechanical design aspect, which should follow certain standards along with the design's structural requirements, but also on the visual design and ergonomics of the seat which tend to impose constraints on the mechanical design aspect. These two may greatly influence the shape and construction of the structure of the seat and should be worked around to meet the necessary durability requirements. This paper analyses the proposed structure of a new train seat and attempts to maintain or increase the stiffness of the structure while lowering the overall weight. Topological optimization techniques are employed to achieve that goal while attempting to restrain production methods to those that would be traditionally employed in the manufacturing of a train seat (that is, metalworking techniques such as welding, riveting, bending, etc.), along with geometrical constraints imposed by the ergonomics and visual design of the seat in question. The seat structure is analysed by numerical modelling using finite- element analysis to gain insight into which parameters are passable of being altered using topological optimization algorithms.

# #556 Artificial Neural Networks for Nonlinear and Fracture Micromechanics

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*Damage* *Micromechanics* *ANN*

**Abstract** A new artificial neural network (ANN) based micromechanical models are proposed and generated for fiber-reinforced polymers (FRP) and metal-matrix composites (MMC). Pre-simulated mechanical stress-strain responses and behaviors are conducted to generate a training database for the ANN micromodels. The repeating unit-cell (RUC) micromechanical models include inelastic phasis with and without damage. The ANNs are trained with results from the simulation of the Parametric High Fidelity Generalized Method of Cells (PHFGMC) micromechanical model. The damage in the MMC-RUC is in the form of interface cracks between the fiber and matrix phases. The simulated training data is based on the RUC effective stress-strain responses with different applied multi-axial strain paths and damage parameters. Part of the pre-simulated data is not used for the training; instead, it is used to verify the prediction quality of the trained ANN. The ANN-micromodels show an excellent capability to capture the overall nonlinear constitutive behaviors of FRP and MMC with inelastic and interface cracks.

The trained ANN-micromodel can be used as a stand-alone or embedded as a surrogate proxy model within a multi-scale analysis of composite structures.

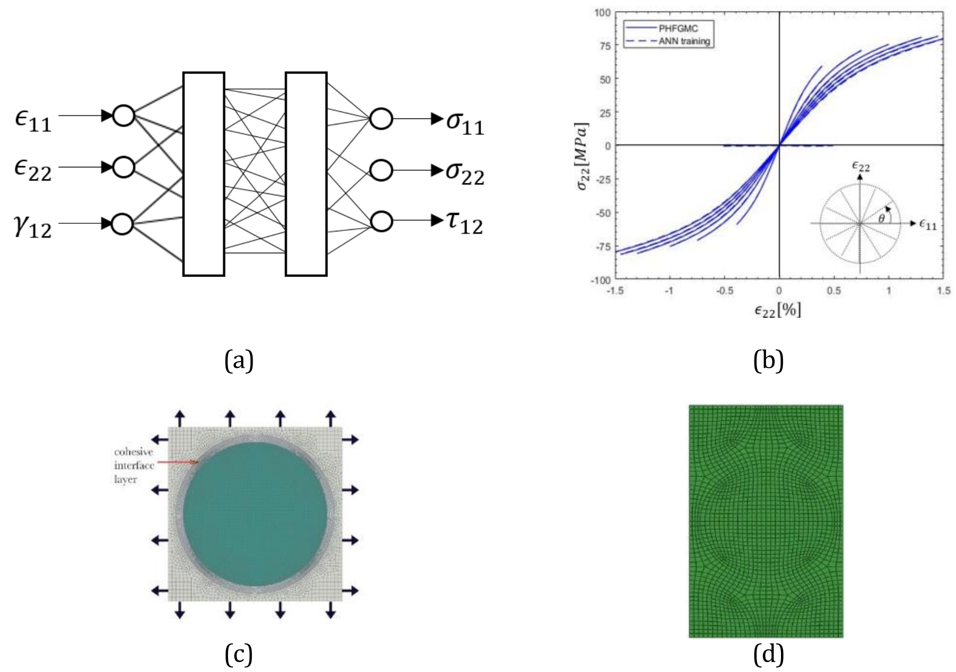


***Figure 1*** *– (a) Schematic representation of an ANN-micromodel where the ANN input and output include in-plane strain and stress components, respectively. (b) Prediction of a trained ANN-micromodel in the form of RUC average stress-strain responses for different strain paths. (c) A PHFGMC square RUC micromodel with interface cracks used for the ANN training data. (d) A PHFGMC hexagonal RUC micromodel with an inelastic matrix used for the ANN training data.*

# #557 The Fatigue Crack Initiation in Parabolic Leaf Springs: The FEM-MVM Approach for Random Loadings

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*Railway* *Parabolic Leaf Spring* *Maximum Variance*

**Abstract** Over the years, the rail sector has shown its potential to struggle against climate change. As a result of its huge potential, European countries had been investing as in the passenger sector as in the freight sector. With respect to the freight rail sector, the demand has risen in recent years, increasing its frequency of operationality. As expected, the greater usage of the freight wagons, the greater likelihood of emerging problems. Consequently, the availability of freight wagons decreases and economic compromises might be not reached. One cause of reduction of the availability is the fatigue phenomenon that occurs at leaf springs. Despite the previous knowledge about fatigue in leaf springs, the problem in the railway sector remains. Therefore, there is still a lack of knowledge about the leaf spring's health that requires to be investigated.

This research work intends to determine the critical spots and the corresponding fatigue crack initiation for parabolic leaf springs under real operating conditions. The loading conditions are predominantly under bending, however, non-vertical loadings exist during the suspension operationality. In spite of around 70% of the fatigue, failures have occurred in the middle of the master leaf, the rest of the percentage is respect to failures from notches. In order to achieve the objective, an analysis based on the critical plane approach is used. In this specific case, the critical plane is identified using the concept of the maximum variance. This approach is coupled with the finite element method. Once the direction of maximum variance is identified, the problem is no longer dependent on the length of the input loading history.

# #558 Strain rate sensitivity of AlSi10Mg components produced by SLM with and without post heat treatment

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*Selective Laser Melting* *High Strain Rate* *Mechanical Properties*

**Abstract** The strain rate sensitivity of selective laser melting (SLM) produced aluminum alloy (AlSi10Mg) components was investigated in this study. The effect of build direction on strain rate sensitivity was also studied by testing specimens built in three orthogonal directions. Another investigated aspect was the effect a post build process heat treatment had on the strain rate sensitivity. Varying strain rate tensile properties were assessed by quasi-static and high strain rate tensile testing, were the latter was achieved with the use of a Split Hopkinson Pressure Bar (SHPB) apparatus.

# #559 A Study of Different Considerations to Meet Gear Design Requirements

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*Gear design* *Design requirements* *microgeometry*

**Abstract** Gear designers make efforts to ensure the gear product will survive failure and fulfil the durability and other design requirements. The current article studies different gear design considerations, discusses how to select a microgeometry design accordingly, and investigates the effect of changing the design on the resulting fatigue life. The presented study provides engineers and researchers with a good understanding of the different practical design considerations and limitations. The considerations of dependency, tooth microgeometry asymmetry, peak-peak transmission error (PPTE), and misalignment variation are studied and discussed. PPTE is an important factor to study, which acts as an excitation source for Noise, Vibration, and Harshness (NVH). MASTA software tool is used for modelling the gear system and obtaining the misalignment values at different load levels. LDP software tool is used for performing the required gear design calculations and obtaining the generated stresses and PPTE. The macro- and microgeometry designs are discussed, calculations of different cases are performed, and comparisons are presented. The article concludes with a brief discussion that emphasizes the use of the studied considerations and explains under what circumstances should these considerations be adopted to meet the design requirements. The design requirements can conflict with each other, and then a compromised microgeometry design should be obtained. Changing the microgeometry design can significantly affect the predicted fatigue life and damage.

# #560 Stress intensity factors in the specimen with a surface semi-elliptical defect

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*Stress intensity factor* *Crack growth rate test* *Elevated temperature*

**Abstract** In this work, equations for stress intensity factors calculating in the specimen with a surface semi-elliptical defect in order to interpret experimental data of the surface crack growth rate tests at elevated temperatures were obtained. For the surface crack growth rate analysis at elevated temperatures a new specimen geometry was developed. The specimen has a number of advantages compared to analogues: smaller overall dimensions, the possibility of testing at elevated temperatures using the direct current potential drop method to control crack growth. In the commercial finite element code ANSYS 3D finite element models with surface flaws for the range of the relative crack depth b/t = 0.1…0.7 and the aspect ratio b/a = 0.3…1 were generated. For these ratios stress intensity factors were calculated based on the finite element method. For the same configurations of semi-elliptical crack fronts using Murakami stress intensity factors handbook stress intensity factors were calculated. It has been established that the results of numerical calculations and according to Murakami stress intensity factors handbook agree for the entire range of b/t and b/a ratios, except for the relative crack depth b/t = 0.4…0.7 and the aspect ratio b/a = 0.4…0.7. Therefore, for a given range of b/t and b/a ratios in the specimen geometry functions a correction function was added. The results allow to interpret the experimental data of the surface crack growth rate tests of the specimen at elevated temperatures.

Acknowledgements

The author gratefully acknowledges the financial support of the Russian Science Foundation under the Project 20-19-00158.

# #561 Fatigue Strength Properties of 18Ni Martensitic Steels as a Function of Microstructure Size

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*Fatigue* *Lath martensitic steel* *Microstructure size*

**Abstract** In recent years, the application of high-strength steel has been expanding due to the demand for lighter-weight transportation equipment to improve fuel efficiency. Lath martensitic steel has a fine microstructure and contains many dislocations, making it steel with excellent strength. In addition, lath martensitic steel has excellent toughness. Therefore it has been used as a basic microstructure of high-strength steels. However, lath martensitic steels have lower fatigue limits than predicted by empirical formulas that predict fatigue limits from tensile strength and hardness. The empirical formulas have been developed from experience with many kinds of steel. Furthermore, the scatter of the fatigue life is large compared with the other steels. Therefore, the authors want to clarify the fatigue strength properties of lath martensitic steels to reduce concerns about designing machines. In this study, the authors focused on the effect of the complex microstructure of the martensitic steels on the fatigue strength properties. Especially, the effect of the microstructure size of lath martensite on fatigue properties was discussed and clarified. For this purpose, the authors have selected 18Ni-Fe steel, suitable for martensitic transformation. The microstructure size was actively controlled, and fatigue tests were performed on this material.

# #562 Effect of Surface Microstructure on Fatigue Strength of Non-combustible Mg Products Fabricated by Selective Laser Melting

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*Fatigue limit* *Selective laser melting* *Mg alloy*

**Abstract** The additive manufacturing (AM), or so-called 3D printing, to manufacture products has been under development in recent years. The AM is spreading rapidly due to its advantages of high flexibility in shape, time, and cost reduction. In addition, the use of magnesium alloys is expanding to reduce the weight of products. Recently, the authors have shown that the as-built products fabricated by selective laser melting (SLM) of non-combustible Mg alloy are composites. Products fabricated by SLM have different cooling rates for just below the side face of the products that are in direct contact with air and the center of the product. Therefore, the interior just below the surface of the product side face has an irregular coarse-grained microstructure, and the internal microstructure becomes dominant toward the center of the product. Furthermore, the authors considered that the coarse-grained microstructure just below the side face affects the fatigue behavior of the products because the hardness of the coarse-grained microstructure is softer than that of the internal microstructure. Furthermore, when loading is applied, cracks will be initiated in the coarse-grained microstructure from defects on the product surface. Therefore, the authors assume that the coarse-grained microstructure can be treated as a pre-crack for fatigue loading and consider the fatigue life and fatigue limit. Two kinds of specimens were prepared, one is a specimen with a small artificial defect that can be treated as a crack equivalent to the size of the coarse grains, and the other is a plain specimen. Then fatigue tests were conducted to clarify the influence of the coarse-grained microstructure just below the side face on the fatigue strength.

# #563 Fracture Toughness Measurement of Non-Combustible Mg Products Fabricated by Selective Laser Melting in As-Built Conditions

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*Selected Laser Melting* *As-built condition* *Fracture toughness*

**Abstract** The ASTM standards can be used to determine the fracture toughness of metallic materials. Several studies measuring fracture toughness of components fabricated by Selected Laser Melting (SLM) have been performed by making an oversized component and subsequently mechanically shaping the component to the recommended geometry indicated in the ASTM standards. The component's microstructure in as-built conditions differs between the inner and outer surfaces due to differences in cooling rates. However, the influence of the inherent different microstructure distribution between SLM products' inner and outer surfaces cannot be analyzed due to the machining process. For this purpose, several non-combustible Mg alloy CT specimens were fabricated and followed by machining without mechanically removing the microstructure duality. Subsequently, the specimens were tested according to the ASTM E1820 standard procedure to determine fracture toughness. Before the test, the CT specimens fractured when the pre-crack was introduced during the procedure. Furthermore, fractography results show a transition from stable crack growth to unstable fracture during pre-crack formation by fatigue loading, where the outer microstructure transitions into the inner microstructure. Additionally, since the pre-crack length required by ASTM exceeds the range of the outer microstructure, it is difficult to measure the fracture toughness considering the outer microstructure with a specimen with pre-crack. Therefore, this study discusses the introduction of pre-crack by fatigue loading and proposes the alternative of pre-crack for determining fracture toughness in the characteristic microstructure of SLM products under as-built conditions.

# #564 The role of cavitation in stress relaxation creep using a novel cantilever test

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*Creep cavitation* *Cantilever beam test* *Cavity growth/closure*
*OFHC copper* *Stress relaxation*

**Abstract** Many metallic engineering components operate at temperatures and stresses where they are in the creep regime, which can result in reduced operational life. Components, such as those used for electrical power generation, are typically fabricated from ferritic and austenitic steels, and the designs are developed using uniaxial, constant load creep data accelerated either in stress or temperature. In service they are frequently subject to a range of complex stresses that can vary with service history or, in the case of reheat or stress relief cracking, residual stresses that progressively relax. These changes can modify the overall creep behaviour and safe operating life. Creep life, in general, is limited by a combination of creep deformation and failure processes. In this study, we use a novel small-scale constant displacement cantilever beam bend specimen designed to simulate stress relaxation and explore cavity nucleation and early-stage growth/closure in polycrystalline oxygen-free high thermal conductivity (OFHC) copper with a range of grain sizes. Analytical and computational modelling have been adopted to predict the stress distribution in the specimen, and the rates of stress relaxation and deformation during a test. The models introduced grain size as a variable parameter in both the theoretical and finite element analyses. The beam shape changes due to plastic deformation and/or creep deformation during tests are calculated. The models have been validated by comparison of these predicted displacements with the final creep deformation measured on the test specimens; there is good agreement.

Stress relaxation creep tests have been conducted on OFHC copper cantilever geometry specimens, with a size of 25mm x 6mm x1mm, and grain sizes in the range 43 µm to 2350 µm at a temperature of 250 °C for 2000hrs. Each test was conducted in a vacuum of $10^{-8}$ MPa. On completion of the tests, both creep deformation and creep cavitation were measured. For the latter a range of higher spatial resolution techniques were adopted, including scanning electron microscopy, electron backscattered diffraction and focused gallium ion beam milling serial sectioning. Creep cavity number and size measurements were made with respect to position within the test specimens using advanced image analysis procedures. The results are discussed with respect to the comparison between modelling predictions and experimental measurements for creep cavity size and distribution, and subsequent shrinkage under the conditions of stress relaxation.

# #565 Effects of Temperature on the Mechanical Properties of X60 Elbow Pipe Steel Under Bending Moment Using X-FEM Numerical Method.

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*API 5L X60 thermo-mechanical behavior Brittle-ductile transition.*

**Abstract** During service, the pipes are subjected to internal pressure, temperature, soil pressure and other accumulated loads. The bending moment of API 5L X60 steel elbows under thermo-mechanical behavior and in the presence of pressure and different temperatures wasinvestigated in this study. Finite element analysis is utilized to apply the XFEM method. Our goal is to assess the reaction and resistance capabilities of the steel elbow based on its location in the tube-elbow-tube system under mixed pressure and temperatures loading in all situations. The temperatures used in this study is extracted from the brittle ductile curve of steel API 5L X60, one in the brittle level and in the ductile level and two in the transition level. Moment-rotation curves are used to display numerical damage data with different temperature. They depict the diversity in damage as a consequence of various impacts, which occur concurrently.

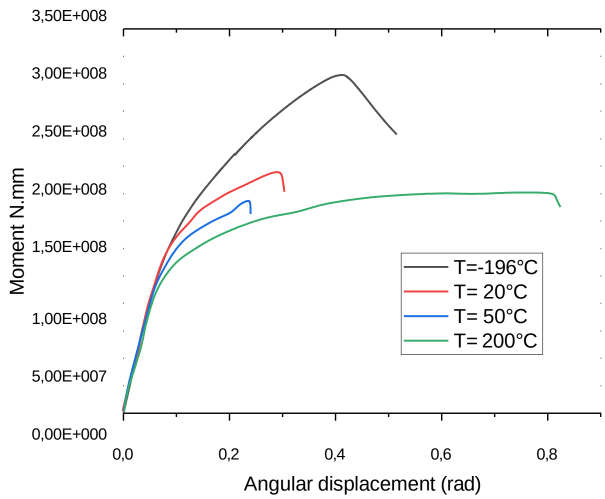


***Figure1-*** *End rotation vs. Moment for different temperatures degrees*

# #566 Report of Cracked Expansion Joint Heat Exchanger Assessment Using Finite Element Analysis: Inspection and Proposal of Work Solutions

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*Crack*  *Finite Element Analysis*  *composite materials*

**Abstract** A heat exchanger is a heat transfer device that exchanges heat between two or more process fluids. Heat exchangers have widespread industrial and energy applications. The actual design of heat exchangers is a complicated problem. The cost of fabrication and installation, weight, and size play important roles in the selection of the final design from a total cost of ownership point of view. We have presented in this work a modern technique to repair the structural defect of extension joint steel. This technique is called a composite material. Using a database which obtained from the service location, we perform a numerical analysis to estimate the hoop stress distribution which is responsible for failure. According to the obtained results, the composite material considers the suitable method for repairing the circumferential crack of steel. In fact, the superior fatigue performance of composite materials enables them to be used to repair metallic materials with fatigue damage. Finally, this work confirms that the composite sleeve considers a suitable technique to repair expansion joint cracks under high temperature.

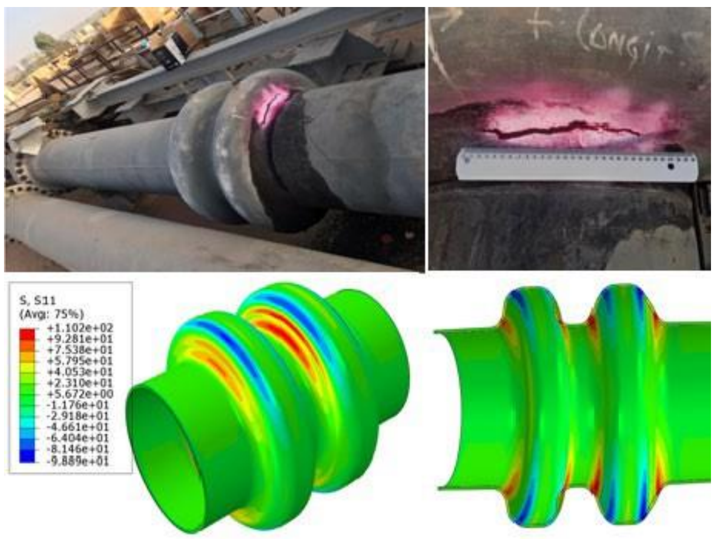


***Figure 1*** *-The location of circumferential crack in the expansion joint of heat exchanger.*

# #568 Residual stress measurements and weld characterization in wind turbine support structures

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*Residual stress* *Submerged-arc welding* *Wind turbines*

**Abstract** Tensile residual stresses are a byproduct of welding processes. They have a negative impact on the fatigue life and structural integrity of large, welded structures because they will be superimposed on the service and structural loads. Due to the high manufacturing costs involved and the harsh environments in which they tend to operate it is highly desirable to have an overview of the residual stresses present in the structure. To gain further insight on the magnitude and nature of welding residual stresses introduced to tubular steel for Eolic towers, two specimens that were circumferentially welded were obtained from an on-shore and off-shore tubular steel tower, respectively. The specimens were extracted from door cut-outs that permit access inside the towers. The Contour method was employed for measuring the locked-in residual stress. To characterize the welds a microstructural analysis was performed, and the impact toughness and Vickers hardness were measured. This work describes a strategy for evaluating the final characteristics, residual stresses and deformations, of a steel tubular section used in the construction of steel wind towers and obtained by submerged arc welding.

***Figure 1** – Tubular steel towers sections. Courtesy of Tegopi.*

# #569 An Industrial Approach to High Strain Rate Testing

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*Dynamic loading* *Fracture toughness* *Plasticity*

**Abstract** Some industrial applications require dynamic fracture toughness of materials to be determined to evaluate components' safety in the event of an impact. Understanding the behavior of materials subjected to extreme dynamic loading will aid in enhancing their design. This work is based on developing methods to appraise high loading rate measurements. Different approaches to quantify material properties such as finite element method (FEM), instrumented Charpy testing, and impact testing using servo-hydraulic testing machines are considered. Testing is performed at various loading rates, extending existing quasi-static fracture toughness determination to higher loading rates, and accounting for strain-rate dependent properties. The high loading rate servo-hydraulic test machine located at TWI, Cambridge has the capacity to test up to a displacement rate of 20 m/s. The force, displacement, and time parameters are captured by Digital Image Correlation (DIC), which improves the accuracy of the result obtained from the experiment. Moreover, the undelaying plasticity theory to capture the influence of the strain rate is presented, along with damage constants for FEM calculations adopting the Johnson-Cook model. It is found using single-edged notch three-point bend specimen that yield strength of the material increases with loading rate, leading to a ductile to the brittle transition of metals. These strategies are used to establish a revised approach for testing and determining dynamic fracture toughness. In addition to the Johnson-Cook approach to defining plastic deformation, analytical solutions using dislocation evolution theory were applied which features the effect of phonon drag and dynamic recovery coefficient in body-centered cubic materials of which X65 grade steel was applied. Also, a deep learning framework was built to predict the tensile curves when given specific test conditions and sample specifications.

# #570 Effect of process parameters on ductile failure behavior of flow forming process

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*flow forming* *plastic deformation* *ductile fracture*

**Abstract** Flow forming is a cold metal forming technique used to manufacture hollow cylindrical tubes with favorable mechanical properties and high surface finish quality. It is a widely used process in the aerospace and defense industries. The thickness of the workpiece is gradually reduced with the axial and radial movement of the rollers and consequently the workpiece is exposed to complex forces during the process. Thus, it is challenging to predict the ductile failure during such a process. The studies in the literature focusses mostly the simulation of the process itself and the number of works addressing the ductile failure is quite restricted (see e.g.

[1] and [2]). In a previous work of the authors, the process is simulated using finite element method and failure was predicted using modified Mohr-Coulomb damage model with a rate-independent von Mises plasticity material model [3]. The effect of thickness reduction ratio and the roller arrangements on damage accumulation was examined. The current study is concerned with the effect of the materials and process parameters such as feed rate, revolution speed and roller geometry on the damage evolution. The constitutive framework is extended to include strain rate and temperature dependencies. Simulations are conducted with the explicit finite element solver of Abaqus with user defined material subroutine to implement damage models. In addition, the formability limits are compared with the full-scale workpieces formed with REPKON 3 roller flow forming machine. It has been observed that the damage evolution is highly sensitive to feed rate and thickness reduction ratio. The optimum process parameters are susceptible to type of material as well.

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# #571 Crack initiation and propagation in dual-phase steels through crystal plasticity and cohesive zone frameworks

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*Dual-Phase Steels* *Crystal Plasticity* *Cohesive Zone Elements*

**Abstract** Ferrite-martensite dual-phase (DP) steels have become quite popular in weight-reduced automotive components due to their straightforward thermomechanical processing and excellent mechanical properties. Even though it has been a popular and productive area of research there are still many open questions related to their interesting microstructure and its relation to macroscopic mechanical response. Being composed of brittle martensitic clusters dispersed in a ductile ferrite matrix, DP steels benefit from the properties of both phases, which induce interesting failure mechanisms at the same time. The microstructural parameters such as martensite volume fraction, grain size, and carbon content, martensite/ferrite morphology, ferrite grain size, and texture, as well as micro- and mesoscale segregation make them difficult to analyze, which have to be studied to link the underlying microstructural influence to macroscopic behavior (see. e.g. [1] for an overview on the topic). In this context, the modeling techniques at the microstructure scale should be utilized for physical understanding. In this work, we employ initially a local rate dependent crystal plasticity framework for the modeling of ductile ferrite phase while the isotropic J2 plasticity model is used to simulate the hard martensite phase at RVE scale (see e.g. [2] for a similar plasticity modeling approach). Moreover, the influence of intergranular interactions is considered by the incorporation of a cohesive zone model at the grain boundaries for the prediction of crack initiation and propagation. Naturally the traction-separation relations for different phase interactions would be different and a macroscopic analysis is conducted to obtain them. The effect of microstructural parameters on both plastic and fracture behavior is analyzed in detail for different loading cases employing the developed framework. Furthermore, the plasticity models are extended to lower order strain gradient frameworks in order to capture the size effect intrinsically in both phases. The detailed analysis from the local models and the preliminary results from the nonlocal models are discussed in detail in the context of micro scale plastic and fracture behavior of DP steels.

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# #572 PTFE-Functionalized $WS_2$ Nanotubes for Friction Applications

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*Surface functionalization* *$WS_2$ nanotubes* *Friction and wear*

**Abstract** Inorganic nanotubes and fullerene-like nanoparticles of $WS_2$/$MoS_2$ penetrate and exfoliate at the contact interface and facilitate tribofilm formation. While the tribological and mechanical properties are greatly improved by exfoliated nanoparticles that shed easily, they may be diminished by agglomeration in oil. Therefore, surface functionalization is employed to improve dispersion in oil-based suspensions. In this work $WS_2$ nanotubes were functionalized by polytetrafluoroethylene (PTFE) in a simple and cost-effective bath sonication method. $WS_2$ nanotubes with two concentrations of added PTFE were characterized by scanning and transmission electron microscopy, micro-Raman spectroscopy, and thermogravimetric analysis. Superior distribution of $WS_2$ was observed before and during friction experiments. Chemical analysis showed a significantly greater number of PTFE-coated nanotubes on rubbed surfaces, in accordance with the improved friction and wear properties.

Two composites were prepared by adding PTFE preparation: 1.4 and 5.6× the weight of the $WS_2$ nanotubes. The addition of the first of the composites (1.4×) to PAO4 oil provided the best friction and mechanical wear properties of the studied contact pairs. The deterioration and fracture of so produced composite nanoparticles facilitates their penetration to the contact interface. Similar coating of inorganic fullerene-like nanotubes may produce cost-effective lubricants with excellent tribological properties.

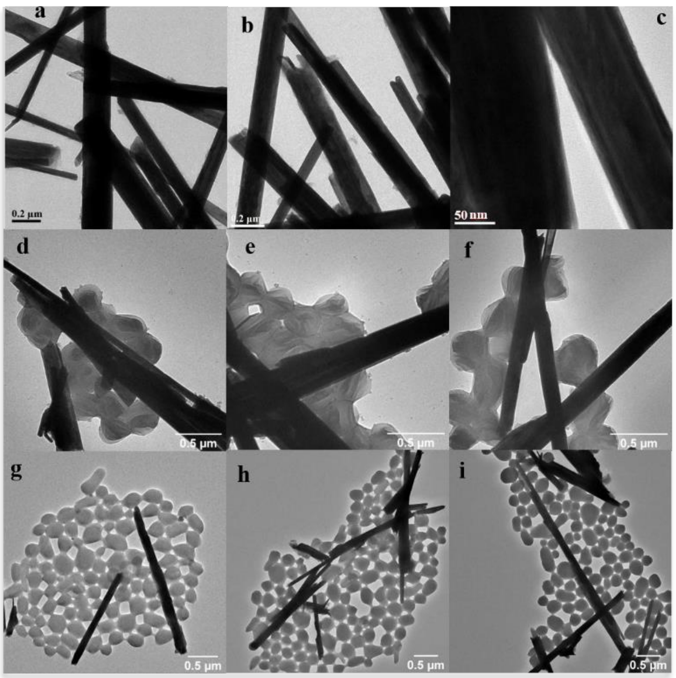


***Figure 1 -*** *TEM images of (a–c) as prepared $WS_2$ nanotubes; (d–f) $WS_2$ nanotubes- 1.4×PTFE; (g–i) $WS_2$ nanotubes-5.6×PTFE.*

# #574 Can Simple Estimates from Neat Polymers Provide Safe Fatigue Fracture Design Limits for Fiber-Reinforced Polymer Matrix Composites?

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**Retired Scientist*

*Fiber-Reinforced Polymer Matrix Composites* | *Quasi-Static and Fatigue Fracture* | *Test Methodology and Design Limits*

**Abstract** There have been extensive efforts aiming at standardization of fatigue fracture test methods for fiber-reinforced polymer-matrix composites. However, these efforts have not yielded validated standard procedures yet and several aspects are still debated, e.g., the effects of fiber bridging [1] and issues related to two-dimensional delamination propagation in planar structural components [2]. Selected literature data [3-5] seems to indicate that quasi-static or fatigue fracture tests on neat matrix polymers might yield reasonably safe estimates for fatigue fracture design limits for the respective fiber-reinforced polymer matrix composites (Figure 1). The feasibility and the limitations of this approach will be discussed in detail.

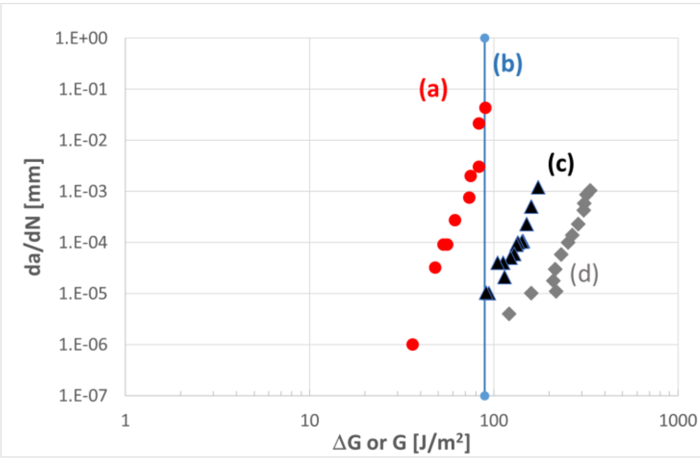


***Figure 1*** *–selected toughness data from literature (a) mode I fatigue fracture of neat RTM6 [3], ΔK converted to ΔG via an average modulus of 3000 MPa, (b) quasi-static mode I toughness of neat RTM6 [4], (c)and (d) two sets of mode I fatigue fracture of a carbon-fiber 5HS weave/RTM6 composite indicating scatter band for material and testing [5]*

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# #576 Failure analysis of the half-shafts of a three-wheeled electric vehicle

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*Half-shafts* *Electric vehicle* *Fatigue failure*

**Abstract** In vehicles, the half-shafts are used to provide a connection between the driven wheels and the differential, which are positioned in its ends and are in charge of power transmission and rotational motion.

This paper studies and assesses the issues that keep arising in the half-shafts of the rear transmission of a three-wheeled electric vehicle. The main objective of this work is to investigate the root causes that leads to failure of the aforementioned components.

To investigate the failure mode of the half-shafts, a visual inspection and fractographic analysis, was carried out using the optical and scanning electron microscope. Fracture surface analysis was performed, and samples were taken from both half-shafts for metallographic analysis, chemical composition analysis, tensile and hardness tests. Visual inspection of the fracture surface of the half-shaft to the left of the differential (rear view) revealed that it resulted from reversed bending fatigue combined with torsion loading. Analysis of the fracture surface of the half-shaft to the right of the differential (rear view) revealed that it resulted mainly from bending fatigue loading.

Moreover, regarding the mechanical design safety of the half-shafts, calculations were made taking into account different trajectories, limit speeds and different design criteria. Finally, concerning the aforementioned issue some recommendations are drawn in order to improve the design safety of this mechanical component.

# #577 Modeling the behavior of CFRP-strengthened RC slabs under fire exposure

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*Fire* *Strengthening* *CFRP*

**Abstract** This paper presents a numerical investigation of the performance of reinforced concrete (RC) slabs strengthened with carbon fiber reinforced polymer (CFRP) strips applied in two different techniques, externally bonded (EB) and near-surface mounted (NSM), under fire exposure. A three-dimensional (3D) nonlinear finite element (FE) model is developed to predict the thermal and structural behavior of strengthened RC slabs subjected to fire. The model incorporates temperature-dependent thermal and mechanical properties of concrete, steel reinforcement, and CFRP, as well as mechanical interaction between CFRP and concrete. The predicted temperature profiles, ultimate loads, and midspan deflections are compared with previous published experimental data. Results from the proposed model show good correlation with the experimental data throughout the exposure duration. The validated model can be adapted to conduct parametric studies intended to inspect the effect of important factors that influence the behavior of strengthened RC slabs under fire.

# #578 Very high cycle fatigue behaviour of S690 structural steel

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*Very high cycle fatigue* *Structural steel* *Ultrasonic testing*

**Abstract** During the last century, the main focus of fatigue research were low cycle (between $10^4$ and $10^5$ cycles) and high cycle (between $10^5$ and $10^7$ cycles) fatigue regions, while the conventional fatigue limit has been settled around $10^7$ cycles. This limit was strongly influenced by cost and time limitations, since testing beyond $10^7$ cycles in a conventional machine, which usually works in a maximum frequency around 50Hz, would be extremely time consuming [1]. However, several engineering components and structures can experience a number of cycles larger than this conventional fatigue limit during their service life. For that reason, the region beyond $10^7$ cycles, usually named as very high cycle fatigue (VHCF), and the concept of fatigue limit has been matter of study and interest in the last decades. In order to overcome the time effort required, the ultrasonic fatigue testing machine has been developed and widely used, since this technology is capable of performing fatigue tests in higher frequencies such as 20kHz.

Nevertheless, ultrasonic testing introduces new challenges and topics of research, such as the effect of frequency, the overheating due to high testing frequencies, new mechanisms of failure (internal crack initiation and fish-eye are observed such as portrayed in Fig.1 (right)),… In these fatigue tests, the specimens geometry is also a critical point, since they must be designed to vibrate at the operating frequency of the ultrasonic testing machine (Fig.1) (left).

Thus, the main goal of this research work is to characterize the fatigue behaviour of S690 structural steel in the very high cycle fatigue region. Therefore, an experimental campaign of twenty-one specimens was performed in an ultrasonic testing machine at a frequency of 20kHz. A large scatter was present in the results as well as levels of stress higher than expected, which could be explained by a frequency effect. Furthermore, both surface and internal crack initiation mechanisms were observed. As future work, notched specimens will be designed and tested to evaluate the notch effect in the very high cycle fatigue region.

***Figure 1*** *– VHCF smooth specimens (right) and fracture surface of a specimen (left)*

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# #579 Understanding the effect of surface and sub-surface parameters including roughness and porosity on fatigue life of laser powder bed fusion (L-PBF) aluminium (AlSi10Mg) alloy

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*Fatigue* *Additive manufacturing* *Surface roughness*

**Abstract** The fatigue life of components manufactured by laser powder bed fusion (L-PBF) process is highly dominated by the presence of defects, such as surface roughness and internal porosity. However, surface roughness has always been considered as the crucial reason for fatigue failure of additively manufactured (AM) produced parts. The present study focuses on the relative effect of surface roughness and porosity in determining the fatigue life of AlSi10Mg alloy produced by L-PBF. For this instance, the pore size and location was measured through X-ray tomography, and the surface roughness was measured using a profilometer. The fracture surfaces of the test samples were characterised to follow the crack initiating pore and subsequent crack growth under fatigue loading. The fatigue property of L-PBF produced AlSi10Mg samples built in the Z direction is investigated in this study for both as-built (AB) and machined (M) conditions, as shown in Figure 1. As-built L-PBF samples possess higher surface roughness compared to the machined ones. Hence, for similar loading conditions, the machined samples survive higher fatigue cycles than that of the as-built samples due to their improved surface quality. The presence of internal porosity seems to have no significant effect on the fatigue life of as-built samples. However, for machined samples with relatively low surface roughness, the subsurface porosity becomes the most dominant factor for fatigue failure rather than the overall surface roughness. The pore size and location effects are analysed using the linear elastic fracture mechanics theory. Based on the results of fracture surface characterisation, the critical stress intensity factors for L-PBF AlSi10Mg alloy samples are estimated. This work will provide valuable inputs for the structural integrity assessment of engineering components made of AlSi10Mg or similar alloy type manufactured by laser powder bed fusion.

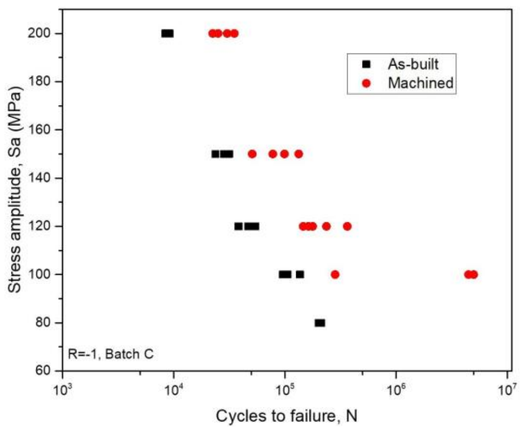


***Figure 1-*** *S-N curve showing comparison between as-built and machined samples*

# #580 Hydrogen embrittlement resistance of Al-$Al_2O_3$ coatings deposited by cold gas dynamic spray on pipeline steel

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Cold spray hydrogen embrittlement mechanical properties

**Abstract** Hydrogen produced from water, biomass or fossil fuel is the promising green energy vector and an important alternative to fossil energy [1, 2]. One of the main objectives of the energy sector is to transport and distribute hydrogen fuel using existing pipeline networks, made of steels suspected to be subject to hydrogen embrittlement [3]. It is therefore important to find a solution to protect pipeline materials from this effect.

In the present study, a method of pipeline protection against hydrogen embrittlement is proposed by applying an Al-$Al_2O_3$ cold spray coating. The hydrogen test protocol include electrochemical hydrogen pre-charging [4], slow strain rate test and characterization by scanning electron microscopy. The effect of Al-$Al_2O_3$ cold sprayed coating on pipeline material (low carbon ferrite-pearlite steel) was investigated by the hydrogen test protocol. Composite Al-$Al_2O_3$ coatings were deposited by low pressure cold spraying on steel tensile test specimens and were expected to act as physical barriers to $H_2$ permeation.

Smooth tensile specimens, without Al-$Al_2O_3$ coatings, showed a significant degradation of relative elongation to failure and reduction in area, with increasing $H_2$ charging time. In addition, the fracture surfaces showed a gradual change from ductile dimples to brittle fracture when increasing $H_2$ charging time. The Al-$Al_2O_3$ cold spray coatings exhibited a dense microstructure with good adhesion to the low carbon steel substrate. Coated samples were subjected to the hydrogen testing protocol and showed a significantly enhanced resistance against hydrogen embrittlement.

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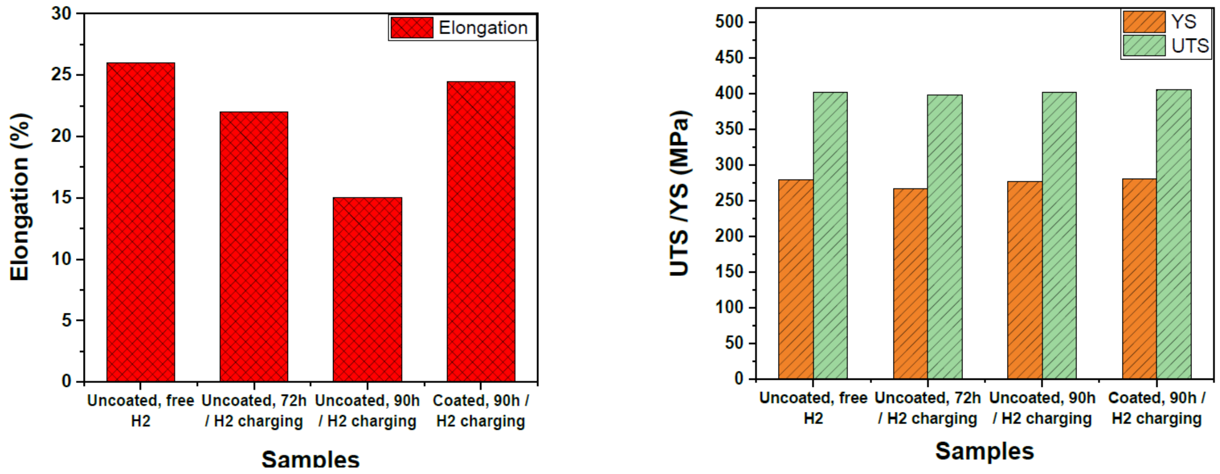


***Figure 1:*** *Tensile properties of uncoated specimens tested at different pre-charging time and coated specimen pre-charged at 90 hours.*

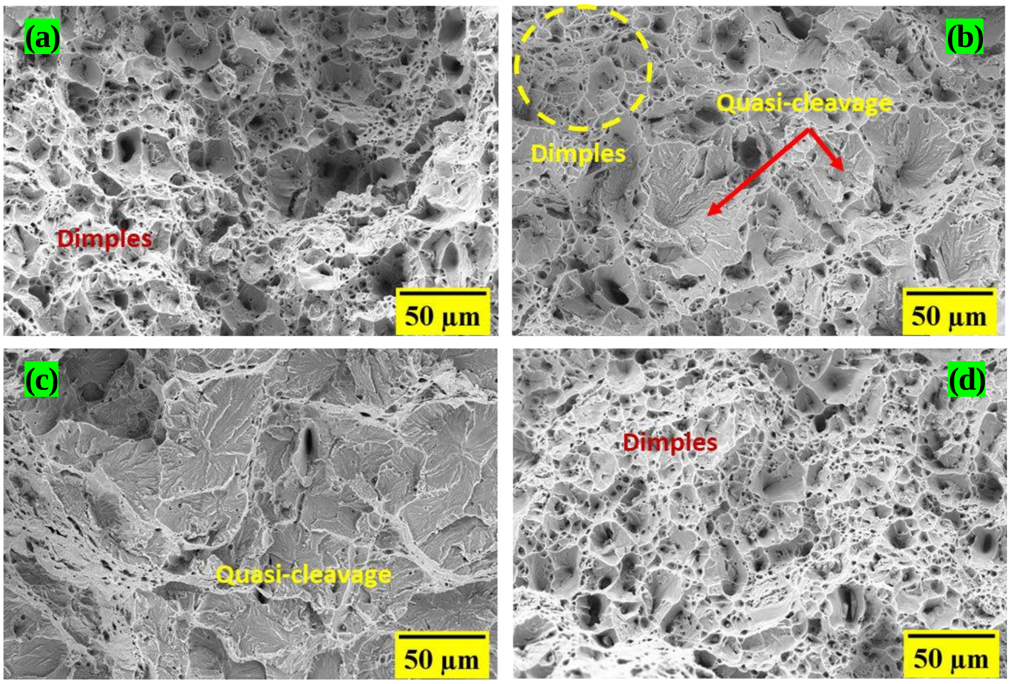


***Figure 2 :*** *SEM images showing the fracture surfaces of (a) uncoated and uncharged (free H2), (b) uncoated and hydrogen charged for 72 hours, (c) uncoated and hydrogen charged for 90 hours, (d) coated and hydrogen charged for 90 hours.*

# #582 Stress field around cylindrical pore by various surface elasticity models

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*Stress field* *Nanopore* *Surface elasticity*

**Abstract** Typical representatives of inhomogeneous materials are whole classes of fibrous composites with metal, polymer and ceramic matrices. In these materials fibers of different scale levels, ranging in diameter from hundreds of microns to several nanometers, are distributed in different ways. The strength and physicochemical properties of materials largely depend on the features of the stress strain state of near-surface and near-boundary layers in inhomogeneous systems. The development of plastic deformation and fracture processes in these areas determines the mechanical behavior of the material as a whole and is therefore of great interest [1]. It is important to note that the traditional consideration of micro- and nanoscale heterogeneities in the framework of the classical theory of elasticity may lead to inaccuracies in determining the levels of real deformations and stresses [2].

In this work, we present a brief review of the works using various surface elasticity models. Within the present research, we are going to analyze the solution of the two-dimensional problem on a circular cylindrical pore in an infinite body incorporating surface elasticity and residual surface stress by all this models. Based on various models of surface elasticity, the proper boundary conditions at a cylindrical surface are derived according to the corresponding generalized Laplace – Young law in terms of complex variables for the case of plane strain. With the help of Goursat – Kolosov complex potentials and Muskhelishvili representations [3], the solution of the problem is reduced to the singular integro-differential equation in an unknown complex displacement. The algorithm of solving the integral equation is constructed in the form of a power series as in [4]. Based on the explicit forms of the analytical solution for all surface elasticity models, we present the numerical results for the stress field near the boundary of the nanopore and discuss the difference between them and the results obtained with the original Gurtin – Murdoch model.

## Acknowledgements

The research was supported by the Russian Science Foundation (project no. 22-11-00087).

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# #584 The role of microstructural features on the strengthening effect of biomedical ultrafine-grained titanium by low temperature annealing

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*Ultrafine-grained titanium* *Mechanical properties* *Low temperature annealing*

**Abstract** Commercially pure Ti (Grade 2) is widely used in the biomedical fields such as oral implantology due to its relatively low elastic modulus and density, excellent corrosion resistance and biocompatibility. However, its mechanical strength turns out to be too low for load-bearing applications such as modern narrow dental implants. Grain size refinement to the ultrafine-grained scale (< 1 μm) and dislocation strengthening by large plastic deformation make it possible to significantly improve mechanical properties of pure Ti. The mechanical performance can be further enhanced by a low temperature annealing due to the rearrangement of crystal lattice defects (grain boundaries, dislocations) or crystallographic texture changes. The aim of this work was to analyze the role of different microstructural features (grain size, dislocation density, crystallographic texture) on the strengthening effect of ultrafine-grained titanium by annealing at 250°C. Firstly, the ultrafine-grained titanium was achieved by cold rolling to a total thickness reduction of 90%. It exhibited a significantly enhanced mechanical properties (hardness of 259 HV0.2, YS = 600 MPa, UTS = 798 MPa) as compared to its microcrystalline counterpart. Its short-time annealing (250°C/15 minutes) caused a further increase of hardness and strength by ~ 4 and ~ 6%, respectively. In the next stage, the ultrafine-grained titanium has been deformed more severely to 95% and 97% by cold rolling as well as rolling at 400°C to obtain four different types of microstructures varying by grain and dislocation structure as well as crystallographic texture. The detailed analysis of microstructural features has been performed based on transmission electron microscopic observations, dislocation density and texture measurements by X-ray diffraction whereas the mechanical properties of the analyzed ultrafine-grained Ti sheets were assessed in microhardness measurements and uniaxial tensile tests of miniaturized samples. The preliminary electrochemical tests were also conducted to characterize their corrosion resistance. It has been shown that the analyzed microstructural features and texture strongly affected the occurrence and intensity of the strengthening effect of ultrafine-grained Ti by low temperature annealing. Moreover, the rearrangement of microstructure defects during short-time heating influenced electrochemical response of the investigated material what improved its performance and potential for biomedical applications.

# #585 Damage evolution in pultruded composite bars using acoustic emission

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*Composite materials* *rebars* *Acoustic emission*

**Abstract** Composite materials are getting more attention in industrial applications due to their excellent properties such as high relative stiffness, endurance or chemical resistance. One of the uses in civil engineering is concrete reinforcement by composite pultruded bars. They are mainly used for application in harsh environment like sea water, sewage treatment plants or in special objects like military outposts, research laboratories, energy facilities. Use of steel material in them provide to faster loss of strength of the entire structure or interference with electronic devices working inside.

Inhomogeneity of the structure results in various failure mechanisms that causes the loss of integrity of pultruded composite bars. Otherwise, to commonly known engineering materials (homogeneous) those materials failure in rather local fashion than in general manner. One of the major weaknesses of the structures made from composite materials is delamination phenomenon. To enhance the design and development of composite structures, the knowledge of material's resistance to interlaminar fracture may be useful.

In this paper, the interlaminar fracture toughness under mode I loading conditions of pultruded bars is investigated. Smooth, circular bars reinforced with unidirectional fibers manufactured by pultrusion system were an object of interest for determining the strain energy release rate. An initial delamination was provided in each bar by automatic diamond wire saw. Double cantilever beam test was performed with in-situ monitoring by means of acoustic emission (AE). Since the bars had a circular cross-section, it was necessary to use metal waveguides. The results of AE signals were evaluated in terms of maximum frequency, amplitude and number of counts. Additionally, an attempt to localize AE event was performed by using two acoustic sensors. Although the damage mechanism in composite materials is complex, it was possible to distinguish AE signals referring to delamination mode.

**Acknowledgements**

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# #586 Fatigue characterization of polyurethane elastomers

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*Polyurethane elastomers* *fatigue* *Fracture surface*

**Abstract** Polyurethane materials are an excellent example of materials that can successfully replace rubber in automotive components. In this paper, two material configurations of so-called polyurethane rubbers - elastomers with different hardnesses - are presented for testing. The effect of hardness on fatigue properties and crack growth rate was studied. Fatigue tests were conducted on an MTS Bionix testing machine using specially designed Diabolo type specimens. A significant effect of hardness on the fatigue curves (Fig. 1) was shown for the displacement-control mode tests. After fatigue test, detailed analysis of fatigue fracture surfaces were examined for different load levels.

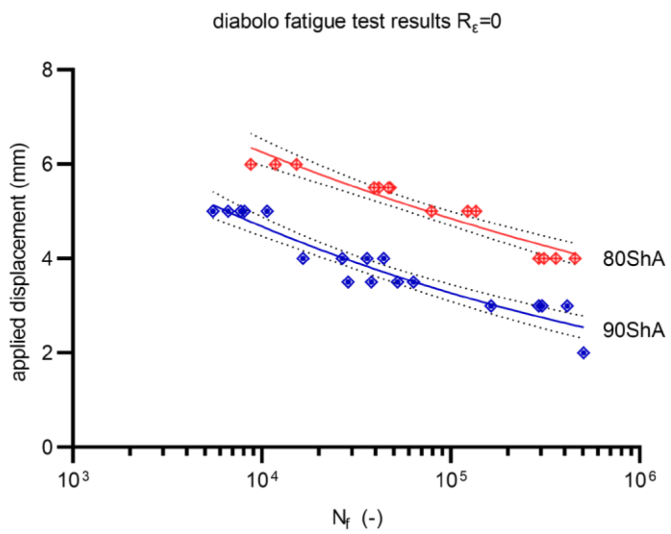


***Figure 1*** *– Fatigue curves for PUR elastomers (80 ShA, 90ShA) tested under displacement control mode, R=0*

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# #587 Extending reliability of FEM simulations, based on optically assisted tensile tests – a digital twin

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*FE simulation* *Optically assisted tensile test* *Digital twin*

**Abstract** *FE* simulations are widely used in industry to predict the future behavior of components at different confidence levels. One of the most challenging tasks of such simulations is to predict the structural integrity limits of components and systems. Damage mechanics is a promising approach for ductile materials, but the potentially existing predictive capabilities of these methods are very difficult to achieve. A major problem in real industrial applications is that the plastic flow curves produced from the results of measurements are generally not reliable enough. This is particularly true for very large deformations where damage effects are intensified.

Standard tensile tests were performed on specimens with square cross-section. A combination of contact strain gauges and an optical system were used in the tests. The optical system consists of two cameras placed perpendicular to each other and to the specimen. Square grids were printed on the surfaces of the specimens facing the cameras. Evaluation of the series of images provided the possibility to track the contours of specimens as well as to predict the deformations on the faces of the specimens by reconstructing the real dimensions.

Using the contours determined from the pictures, the nominal stresses could be determined for the minimal cross-section of the specimen. By determining necking radiuses and using analytical formulae, further corrections could be made on the flow-curve. The corrected flow-curve was used in *FE* analyses for the “digital twins”. The deformations calculated at the surface of the *FE*-model were compared with the deformations measured at the surface of the specimens. The process is presented in Figure 1.

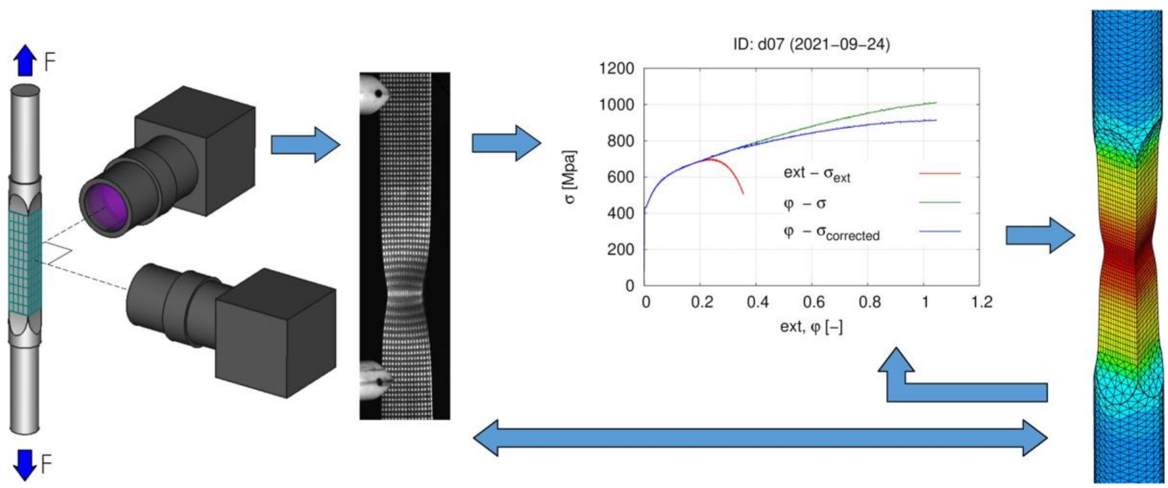


***Figure 1** – The process of obtaining the flow-curves.*

# #588 Phase field modeling of fatigue crack growth at constant and variable amplitude loading

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*Phase Field* *Fatigue Crack* *Mixed-Mode Cracking*

**Abstract** Fatigue failure is one of the most prevalent forms of mechanical failure in engineering applications. While the bulk of models developed to predict fatigue failure have remained empirical, computational solutions to this problem are being developed to be able to predict fatigue crack growth under complex cyclic loading. One of the recently popular modeling techniques is the phase field approach which provide diffuse boundary solutions to otherwise complex numerical problems with evolving boundary conditions through the introduction of a phase field variable. The method has been adapted to fracture problems with no remeshing required and can predict complex phenomenon such as crack branching without the need for any further ad hoc criteria. Beyond the case of simple brittle failure, different numerical features and additions have been explored in the literature to draw closer to empirical data on the material behavior. Through the introduction of a fatigue damage variable, phase field modeling has been adapted to fatigue crack growth problems as well (see e.g. [1,2]).

In this work, a phase field modeling framework is developed in ABAQUS to study fatigue crack growth in metallic materials. A coupled temperature-displacement model is used, with temperature serving the role of the phase field variable [3]. The results are compared to experimental data from the literature as well as to the results produced by the XFEM, with agreement in crack paths achieved. The scalability of the fatigue results is also examined to evaluate the suitability of the phase field method in studying high cycle failure. Furthermore, the influence of the overload effects is included in the framework to accurately capture variable amplitude loading fatigue effects and the preliminary results are discussed again in comparison to XFEM. This study hopes to highlight the utility of the phase field method in the study of complex fatigue fracture phenomenon as well as the challenges involved.

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# #589 An overview of FASTCOLD project results on cold-formed details fatigue categorization

A.M.P. de Jesus[1,2], C.D.S. Souto[1,2], V.M.G. Gomes[1,2], J.A.F.O. Correia[1,2], A.A. Fernandes[1,2], G. Lesiuk[3], Alessandro Menghini[4], Carlo Castiglioni[4]

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*Cold-formed details* *Fatigue Categories* *Eurocode 3*

**Abstract** Thin-walled cold-formed steel sections are widely used in various applications, including as load-bearing members in rack structures that are subjected to fatigue phenomena caused by cyclic loading-unloading of heavy palleted products. However, European Standards (e.g., Eurocode 3) do not have considerations for the fatigue design of these sections, as they are primarily concerned with hot-rolled sections. FASTCOLD EU project addressed the fatigue performance of typical rack structures components looking to provide S-N design curves to be possibly incorporated in future revisions of the Eurocodes. The work will present an overview of important results of FASTCOLD project, in particular the results about bolted joints on thin plates, covering different values of bolt preloads (e.g. snug tight joints). In addition, thin-walled profiles under local wall bending are considered by this work, as they are representative of many critical locations of rack structures as for example the rails where the shuttles travel generating local bending between the flange (rail path) and the web. Innovative full-scale tests were performed on the rack structural components. Numerical finite element models of the tests were developed in order to allow the definition of a convenient stress categorization compatible with a detail fatigue categorization compatible with existing Eurocodes. Also, the possibility of using local fatigue approaches were investigated, which included the residual stress effects obtained from cold-roll forming simulation and experimental validation.

# #590 Corrosion inhibition of carbon steel with synthesized surfacts in acidic medium

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**Abstract** The effects of newly synthesized anionic surfactants of two Algerian petroleum fractions: GOS and KES on the corrosion of carbon steel in 1.0 M HCl were investigated using potentiodynamic polarization, electrochemical impedance spectroscopy and scanning electron microscopy (SEM). All measurements showed that the inhibition efficiency increased with increase in the concentration of inhibitor and the effectiveness of these inhibitors was in the order of: GOS > KES. Polarization curves revealed that the studied inhibitors were mixed type inhibitors. Electrochemical impedance spectroscopy technique exhibit one capacitive loop indicating that, the corrosion reaction is controlled by charge transfer process.

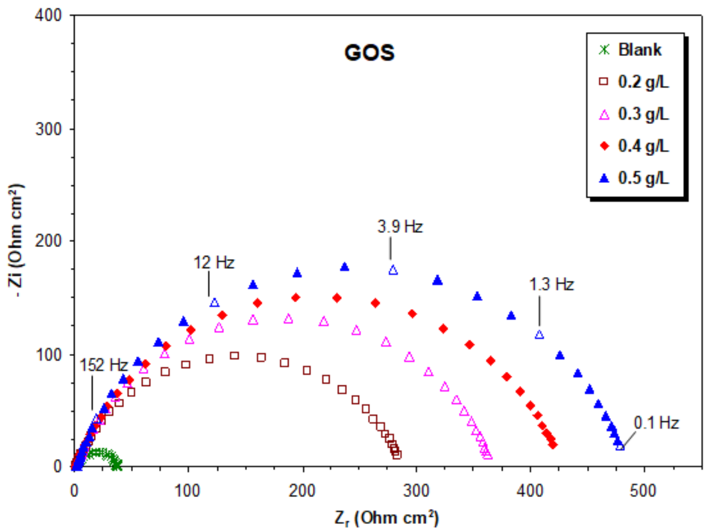


Figure 1. Nyquist plots of the corrosion of carbon steel with different concentrations of GOS at 298 K.

# #591 Fatigue crack growth characterization of additively manufactured IN625 and IN718 alloys

Felipe Fiorentin[1], Grzegorz Lesiuk[2], Paweł Zielonka[2], Szymon Duda[2], Konrad Gruber[2], Szymon Dziuba[2], Patrycja Szymczyk-Ziółkowska[2], Jose A.F.O. Correia[4], Abílio M.P. De Jesus[4]

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*Additive manufacturing* *Fatigue fracture* *Inconel alloys*

**Abstract** In this study the fatigue crack growth of two Inconel alloys produced by distinct additive manufacturing processes are compared. While the Inconel 718 was produced by Laser Powder Bed Fusion (L-PBF), the Inconel 625 was produced by Directed Energy Deposition (DED). The effect of heat treatment on the fatigue crack growth characterization of additively manufactured Inconel 718 was investigated. Inconel 718 specimens were manufactured by L-PBF and heat treated in two variants according to ASTM F3055-14a standard. Inconel 625 was produced through DED and tested in as-built condition for two crack propagation systems. All tests were carried out using ASTM E647 standard in order to characterize the sensitivity of materials for mean stress effect. Exemplary kinetic fatigue fracture diagram is shown in Fig. 1. In the paper, the main features of FCGR description for Inconel alloys were discussed and compared for IN625 and 718 data generated in this research and compared with the literature.

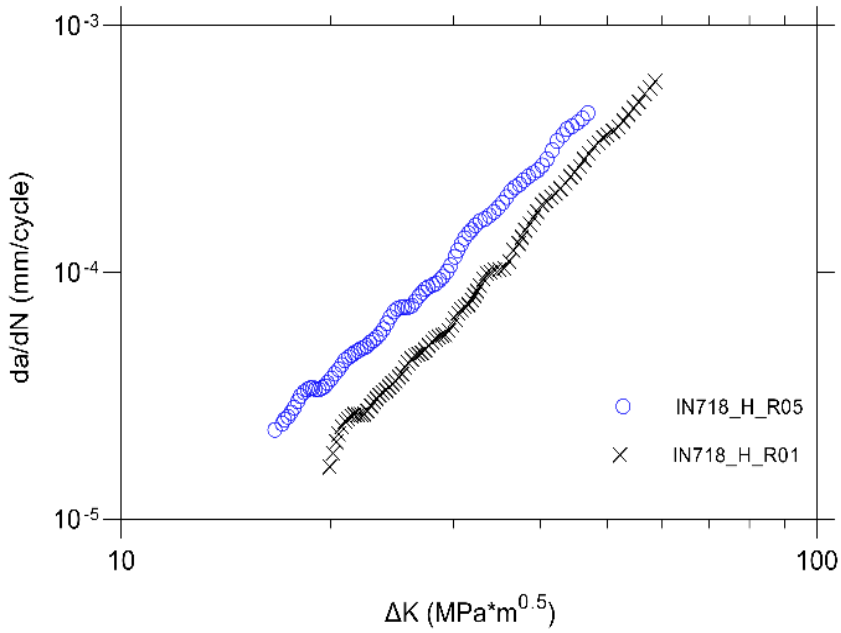


***Figure 1*** *– Fatigue crack growth rate for IN718 after HIP for R-0.1 and R-0.5*

# #592 Evaluation of fracture toughness in graphene-based cementitious nanocomposites via electrical impedance

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*Fracture toughness* *Cementitious nanocomposites* *Electrical impedance*

**Abstract** Cementitious composites have been used in a wide variety of applications, despite demonstrating low tensile strength and fracture toughness, attributed to their brittle nature. Essential research has been performed to alleviate the brittleness of cementitious composites by introducing various natural and synthetic reinforcing materials. Among them, the exploitation of carbon-based nanomaterials, which exhibit exceptional mechanical and electrical properties, meets the demand of creating multi-functional smart cementitious composites with improved crack-bridging and self-sensing properties. In this study, a widely used carbon-based material, i.e., exfoliated graphene nanoplatelets (xGnPs), is exploited as reinforcing nanofiller for improving the mechanical response, along with providing conductive properties in the cementitious matrix.

The current work investigates the effect of different concentrations of xGnPs on the fracture toughness ($K_{Ic}$) via three-point bending tests on prismatic specimens of the hardened, nano reinforced cementitious matrix. Additionally, the electrical properties of the cementitious matrix were investigated via electrical impedance spectroscopy (EIS), towards establishing a correlation between the electrical response of the nanocomposites under alternate current and the exhibited fracture toughness values.

The flexural test results show that the incorporation of the xGnPs in the matrix increase the average $K_{Ic}$ value compared with the reference matrix. The matrices with lower xGnP contents demonstrate an increase of their $K_{Ic}$ up to 29 % compared to the reference mixture. Then, as the xGnP content increases, the average $K_{Ic}$ value tends to decrease, while it continues to remain higher than the reference value. The observed mechanical response was attributed to the density enhancement, accompanied by inhibition of crack propagation caused by the incorporation of the xGNPs in the cement paste. Moreover, from the comparison of the resistivity-values ($\rho$) obtained by EIS measurements and the $K_{Ic}$ values as a function of the xGnP concentration, a reverse relation between the two parameters ($K_{Ic}$ and $1/\rho$) was observed. The functional correlation between these parameters was also confirmed by linear regression analysis, resulting from the experimental data fitting, providing evidence that EIS can be used as a non-destructive tool to assess the fracture toughness of cementitious (nano)composites.

# #593 The effect of solution aggressiveness on the corrosion-induced mechanical properties degradation of aeronautical aluminum alloy 2198

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*Corrosion* *Aluminum alloy* *Mechanical properties*

**Abstract** The increasing demand for improvement in energy efficiency and mechanical performance in aviation industry led to the development of new, lighter metallic structures with improved mechanical properties. The low manufacturing costs and the previous extensive use of aluminum alloys led to the development of a third generation of wrought Al-Cu-Li alloys which developed to replace the conventional aluminum alloys, since they can offer approximately 5 % weight reduction of the structure as well as enhanced property balance and corrosion resistance. The addition of Li to Al has the advantage of reducing the structural weight of aluminum alloys, since for each 1 wt. % Li added to Al the density is reduced by 3 % while the modulus of elasticity is increased by almost 6 %. Their improved mechanical properties are often attributed to their complex precipitation hardening system including δ ($Al_3Li$), $\theta$ ($Al_2Cu$), $T_1$ ($Al_2CuLi$) and $S$ ($Al_2CuMg$) phases. Nevertheless, these precipitates may influence the electrochemical behavior of the alloys due to the different microstructural characteristics of the matrix and therefore increase their corrosion susceptibility.

The material used in this study was a wrought aluminum alloy 2198-T8 which was received in sheet form of 3.2 mm nominal thickness. Exposure of the specimens to three different corrosive environments, e.g., exfoliation corrosion (EXCO), 3.5% wt. NaCl as well as Harrison's solution were used according to specifications ASTM G34, ASTM G44 and ASTM D5894 respectively, to investigate the effect of solution aggressiveness on the corrosion-induced degradation mechanism. The corroded specimens were examined with light optical microscopy to investigate the corrosion attack mechanism. Finally, tensile specimens with prior corrosion exposure were tested to quantify the degradation on the mechanical properties. It was found that the EXCO solution leads to higher degradation of the conventional yield stress $R_{p0.2\%}$ and ultimate tensile strength $R_m$ of AA2198-T8, when compared against the other two solutions studied, especially for short exposure times. Diluted version of Harrison's solution and 3.5% wt. NaCl solution seems to affect the mechanical strength properties ($R_{p0.2\%}$ and $R_m$) of AA2198-T8 in a similar manner by means of the remaining percentage of properties after the same corrosion exposure times. However, significant differences were found regarding the surface corrosion attack mechanism. The elongation at fracture $A_f$ decreases in higher rates when exposed to Harrison's solution as well as EXCO solution than to 3.5% wt. NaCl, with the difference to be more intense in short exposure times where the pitting corrosion is the dominant degradation mechanism.

# #594 VHCF under tension/torsion loading of medium carbon steel


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*Ultrasonic fatigue Testing* *Biaxial fatigue* *VHCF*



**Abstract** Ultrasonic fatigue testing is a recent fatigue methodology that applies resonant principles for the induction of cyclic stresses in a specific designed specimen applying fatigue damage at high frequencies. The main purpose is the study of fatigue life in the Very High Cycle Fatigue regime between 10E07 and 10E09 cycles with a higher performance of time and energy wise in comparison to conventional servo-hydraulic machines. In this study an ultrasonic fatigue testing machine was used in order carry out tension/torsion fatigue tests at a frequency of 20 kHz. The objective is to reach a reliable multiaxial fatigue testing method, by modifying only the specimen, with the ability to choose the shear-axial stress ratio. The improved design of the testing method was focused in innovative design specimen by conducting both numerical and experimental analysis. Thermographic imaging, laser displacement measurements, and the application of rosette strain gauges to the main stress region of the specimen were carried out in order to validate the new design concept and compared with the ones obtained by finite element and a good agreement was achieved. A series of fatigue tests were carried out in tension/torsion fatigue, either at ultrasonic frequencies or in servo-hydraulic machines and the results are compared and discussed in order to understand the feasibility of multiaxial fatigue tests at ultrasonic frequencies.


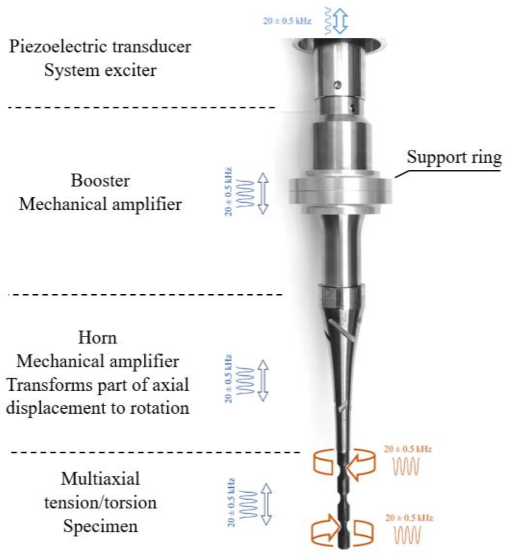


***Figure 1** – VHCF setup*

# #595 Damage of the concrete gravity dam under the effect of hydrodynamic loads

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*Crack* *Dam* *Hydrodynamic*

**Abstract** For the proper design of vital structures as a dam, in order to avoid considerable damage in downstream of the structure, a deepen study must be established. The hydrodynamic behavior is very important for the determination of the damages through the body of the dam, which have effects on the failures and consequences on the internal resistance and the stability of the structure. This article attempts to elucidate the effect of seismic loading and inertia through the variation of Peak Ground Acceleration (PGA), the time of seismic recording and the type of foundation. A damage model based on a continuous approach and taking into account the tensile strength of the concrete and the elastic deformations is applied. The Koyna dam situated in India with a height of 103 m, which experienced in 1967 a considerable earthquake causing the rupture of the structure is taken as an example of application for our study.

# #596 Physical and Mechanical properties of Optical Components produced by Additive Manufacturing

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*additive manufacturing* *optical components* *physical and mechanical properties*

**Abstract** Additive Manufacturing (AM) plays an unquestionably important role in the world today. The Wohler's Report 2022 [1] states that in 2021, the AM industry, consisting of all AM products and services worldwide, grew 19.5% to approximately $15 billion. Besides the importance already achieved by AM at the present time, it is expected that its significance will increase in the future [2]. AM contributions extent to several fields such as aerospace, automotive, construction, electronics, energy, healthcare, and optics [3,4]. In the last years, many works have been published describing the applications of AM in optics, [4]. In the scope of optical technologies, AM processes (combining high design freedom, speed, simplicity, and reduced costs) can be particularly valuable for the fabrication of optical components (OC) as one potential alternative to the expensive CNC based machining or moulding processes, that are employed. The integration of OC produced by AM in optical systems of various fields, such as aerospace, automotive, illumination and biomedical engineering, implies that these OC must meet restrict physical and mechanical requirements. In this context, this work, intent to be a contribution for describe the state of the art of the geometric and mechanical properties of 3D printed OC. The 3D printed OC include lens, prisms, mirrors, or freeform optics. The main physical properties of these OC such as: dimensional/geometric tolerances and surface finish, will be evaluated, as well as the mechanical properties (hardness, tensile and flexural) of the employed resins. The obtained results will provide guidelines for the design of 3D printed OC produced by AM, aiming at its potential application in the above-mentioned technological fields.

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# #597 Model for Determination of Equivalent Stress During Combined Fatigue Loading of Pre-Deformed Metastable Austenitic Steel

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*Metastable Austenite* *Fatigue* *Equivalent stress*

**Abstract** The domed end manufacturing process creates a complex deformation-stress state, which is not easily replicated in laboratory testing conditions. In this work we show that with prior bending and then tensile loading we create a composite stress state, which can only be analysed in a single critical point on the inner surface of the bent specimen. With numerical modelling of the stress state, we approached the experimentally determined conditions during fatigue under constant loading of the pre-deformed specimens. Based on the numerical analyses, supported by experimental testing, we obtain values of the dynamic strength in agreement with Wohler's S-N curve, both for bending with three different levels of pre-deformation as well as for cyclic tensile-bending loading with different force amplitudes, considering changes in the amplitude and the stress relation. Paper presented procedure and model for determining the stress state of pre-deformed bent specimens. It is shown that the residual stresses in metastable austenite AISI 316L, a consequence of deformation and phase transformation into a martensitic microstructure, influence initiation and growth of fatigue cracks, and the resulting stress state in the material is different from the force state of fatigue due to the residual stresses where residual stress vary fatigue loading ratio. Experimentally obtained values on Wohler's S-N curve of a semi-circular notch specimens and fatigue behavior of pre-strain billet specimens shows good agreement respect to number of cycles and equivalent stress level.

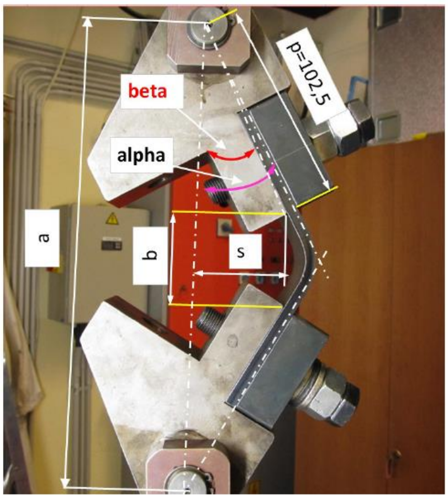


*Figure 1 - Apparatus for loading of bended billet*

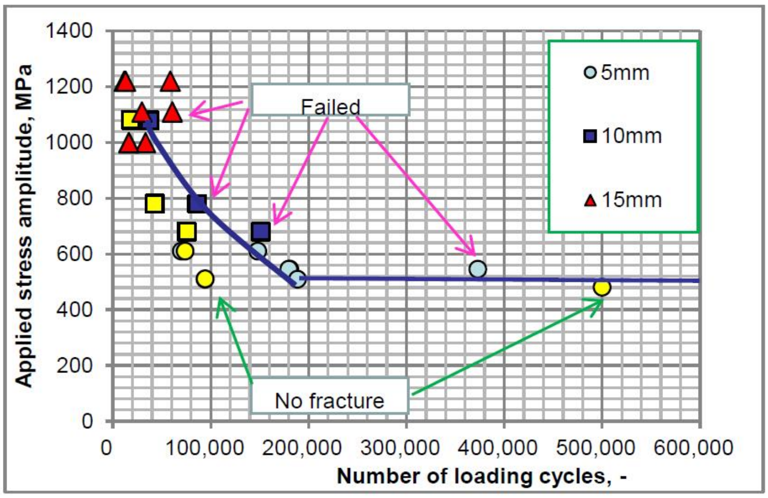


*Figure 2 – Results of combined fatigue loading*

# #598 Validation of the Phase-Field Model for Brittle Fracture

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Phase-field approach; Brittle fracture; Staggered algorithm; Polymethylmethacrylate (PMMA);

**Abstract** The phase-field approach to fracture modelling has gained much attention in the field of computational fracture mechanics in the past decade. The phase-field approach eliminates the need for the numerical tracking of the sharp crack discontinuities by the smooth transition of a scalar damage field whose value differentiates between the broken and intact material states. Its variational based approach has been proven to be thermodynamically consistent and able to solve complex fracture processes. Consequently, many different phase-field fracture models have emerged. In this contribution, a few well-known phase-field models for brittle fracture modelling have been implemented within the staggered algorithm with stopping criterion based on the control of the residual norm, recently developed by the authors. The implementation has been conducted within the commercial finite element software Abaqus and expanded to the three-dimensional settings. The experimental validation of the numerical models is then conducted on the tensile, compact tension (CT) and single edge notched bend (SENB) specimens made of the thermoplastic polymer, polymethylmethacrylate (PMMA). It has been demonstrated that with a suitable choice of the length scale parameter, the developed staggered phase-field fracture models can provide valid prediction of the brittle crack initiation and propagation under quasi-static loading conditions.

# #599 Effect of strain rate on additive manufacturing (SLM and LMD) steel tensile properties

Daniel F.O. Braga[1], Lucas Azevedo[2], Miguel Onofre[1], Gonçalo P. Cipriano[1], Carlos Furtado[2], Pedro M.G.P. Moreira[1]

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*Additive Manufacturing* *High strain-rate* *Tensile Testing*

**Abstract** The strain rate sensitivity of metal powder based additive manufacturing steels was investigated. The effect of build direction in both selective laser melting (SLM) and laser metal deposition (LMD) in high strain-rate tensile properties were assessed for both C300 maraging steel and 316L stainless steel. A special accelerated tensile testing device was developed and used in conjunction with high speed cameras and digital image correlation.

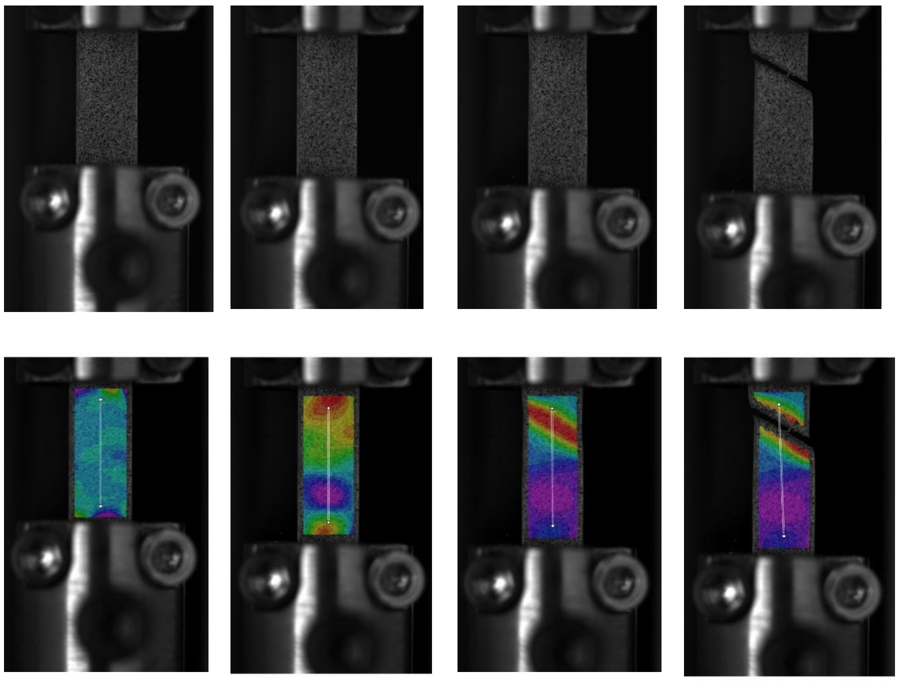

***Figure 1*** *– Digital Image Correlation strain measurements in high strain-rate tensile testing of a metal additive manufacturing specimen*

# #600 Experimental structural assessment of conductors in power transformer windings

Daniel F.O. Braga[1], Emanuel E. Almeida[2], Gonçalo P. Cipriano[1], Ricardo Lopes[2], Pedro M.G.P. Moreira[1]

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*Power transformers* *Buckling* *Adhesive Joints*

**Abstract** The stability of continuously transposed cables (CTC) used in power transformers was assessed. Instability of the CTC due to the electrodynamic forces generated by short-circuit currents is one of the main causes of failure in power transformers, due to radial buckling. Mechanical tests were performed to evaluate the strength of the connection between individual strands of material as well as the corresponding multi-strand cables. The influence of curing conditions (temperature and time) on commercially available CTCs was evaluated through shear testing of bonded copper strands. The buckling of the corresponding CTCs was investigated under room and high temperatures.

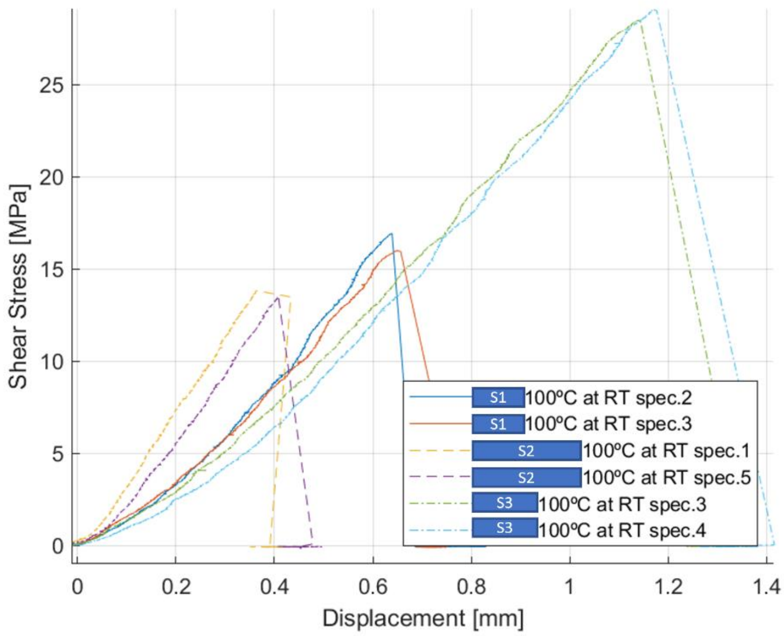


***Figure 1 –** Shear stress vs. displacement of 3 CTC copper joints cured at 100ºC for 80h*

# #601 The effect of build direction and additive manufacturing process on the tensile properties of C300 and 316L steel

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*Additive Manufacturing* *Quasi-static* *Tensile Testing*

**Abstract** Build direction of metal powder based additive manufacturing processes effect on tensile properties were experimentally studied. Quasi-static tensile testing of selective laser melting (SLM) and laser metal deposition (LMD), C300 maraging steel and 316L stainless steel was done along with conventional manufacturing for benchmarking purposes. Oposite trends for strength and ductility were found for the two different materials regarding manufacturing processes and was correlated with failure mode, with C300 being more fragile and 316L more ductile

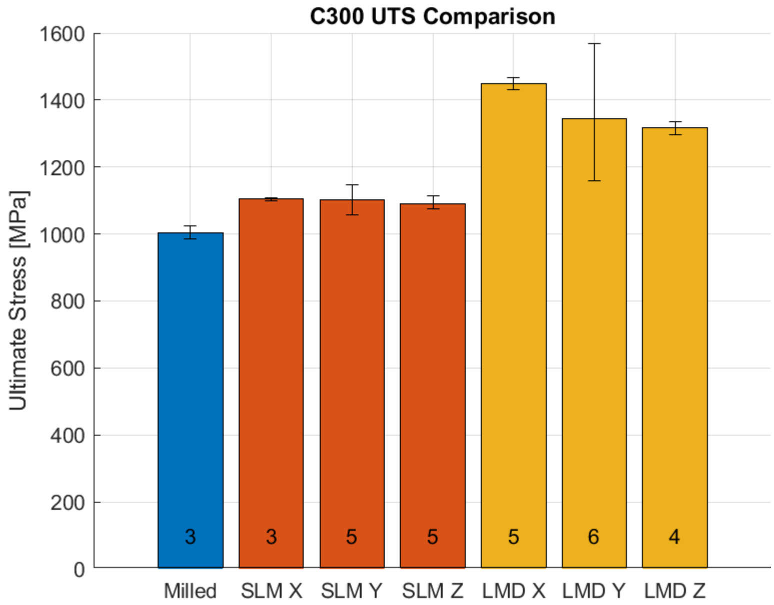


***Figure 1** – UTS comparison of C300 process and build direction*

# #603 Digital Image Correlation on a rotating airfoil with independent moving cameras

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*Digital Image Correlation (DIC)* *Structure from Motion (SFM)* *Unmanned Aerial Vehicle (UAV)*

**Abstract** Wind turbines are a sustainable energy source with high power generation capability, however high maintenance costs are a significant limitation of this technology. The present project aims to reduce this effect and to develop methods to assess failure, malfunction or loss of efficiency in power generation. One possible solution focuses on the development of non-destructive methods, namely with 3D Digital Image Correlation (3D-DIC) with independent cameras on Unmanned Aerial Vehicles (UAV), using Structure from Motion (SfM) and GPS-based synchronization. SfM is an image processing technique which determines the spatial position of the camera at each image acquisition, as well as the camera's intrinsic parameters, through feature matching operations.

Laboratory tests have been conducted on a recreational model aircraft, and time synchronization between the cameras was obtained with a u-blox ZED-F9T high-precision GPS synchronization module for each camera. The method extracts the blade displacements of rotational turbines during their operation and compares them with the material's expected behavior, to monitor possible failures. This approach aims to reduce the maintenance costs in wind turbines and consequently improve the appeal of this sustainable energy source. Furthermore, this method can be adapted to perform DIC in structures which are out of reach.

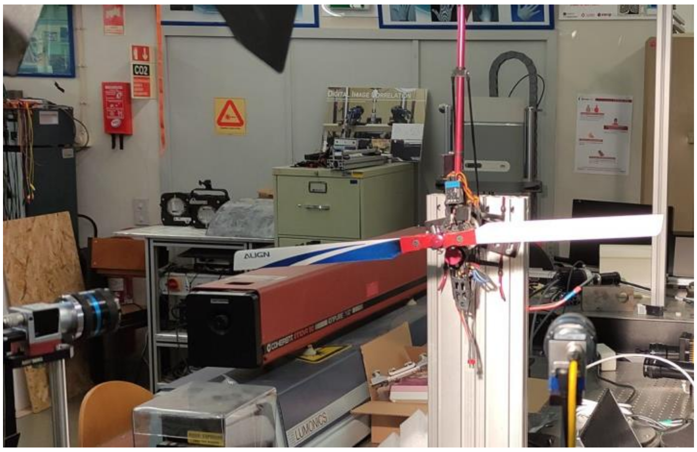

*Figure 1 – Setup for the laboratorial tests*

# #604 Advanced fibre optic sensing structural health monitoring system

Tiago Domingues[1], Pedro J. Sousa[1], Pedro M. G. P. Moreira[1]

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Fiber optic sensing *Structural health monitoring* *Wind turbine blade*

**Abstract** Fibre optic sensing technologies, such as FBG (Fibre Bragg Grating) and DFO (Distributed fibre Optic), are emerging tools for the development of SHM (Structural Health Monitoring) systems, particularly for systems embedded in wind turbine blades. Fibre Bragg grating sensors are UV laser inscribed microstructures that reflect narrow bandwidths of light, which allow the measurement of parameters such as strain and temperature through the evaluation of reflected light. Similarly, DFO sensing solutions allow the evaluation of strain and temperatures through microstructures inscribed in an optical fibre. The ultimate feature of DFO sensing technology is the ability to have a high density of sensors along a long fibre, allowing nearly continuous evaluation along a line.

The scope of this work was the development of a laboratory setup for the development and validation of a SHM system for a wind turbine blade using FBG and DFO sensing solutions. All access variables have been defined in accordance with the "IEC 61400-13 - Wind turbines

- Measurement of mechanical loads" standard, and the positions and technologies of the sensors have been chosen for each variable. A material compatibility test setup was developed to evaluate fibre sensor application techniques on wind turbine materials. Afterwards, a representative scale model of the SHM system was executed, where all the sensors, both FBG and DFO, to be applied on a real case scenario were applied to a scale version of a wind turbine blade produced by additive manufacturing. Both configurations were tested using a two-point bend test methodology to validate sensor application techniques and proper operation of the developed SHM system.

# #605 Tensile and fatigue behaviour of FFF 3D printed PEI

Tiago Domingues[1], Pedro J. Sousa[1], Daniel F. O. Braga[1], Pedro M. G. P. Moreira[1]

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*Fused filament Fabrication*  *High-performance plastics*  *Fatigue Testing*

**Abstract** Fused Filament Fabrication (FFF) is an addictive manufacturing process based on the extrusion of a continuous filament of thermoplastic material. High-performance plastics, such as Ultem® 1010 (PEI - Polyether Imide), can produce components with greater strength and toughness than commonly used printing thermoplastics, as well as higher service temperature. These materials are particularly relevant as they may constitute structural parts operating in more demanding environments at elevated temperatures and in more complex and higher loading scenarios.

The scope of this work was the quasi-static tensile and fatigue strength assessment of Ultem® 1010 parts produced in a custom system adapted from a commercially available 3D printer for high temperature operation. A parametric study of the effect of printing temperature on mechanical performance was conducted. Tensile testing was carried out according to D 638 – 02a on four different temperatures in order to find the printing temperature which produces specimens with the highest ultimate tensile strength. Using this printing condition, the determination of uniaxial fatigue properties was performed according to D7791-12 standard, using a stress ratio of 0.1 and a frequency of 10 Hz.

No significant effect of the printing temperature within the tested range on ultimate tensile strength was found in this study. A SN curve of Ultem® 1010 printed with the parameter set resulting in the highest tensile strength was obtained.

# #606 Transient Response of Collinear Griffith Cracks in a Functionally Graded Strip Bonded between Dissimilar Elastic Strips under Shear Impact Loading

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*Collinear cracks* *Crack arrest* *Functionally graded material* *Stress magnification factor* *Transient response*

**Abstract** This article analyses the interaction between a central and two symmetrically placed collinear Griffith cracks subject to transient response under anti-plane shear impact loading. The cracks are situated in a strip constituted by functionally graded material (FGM) bonded between two dissimilar elastic strips of equal thickness. The material properties of FGM are assumed to vary exponentially as a function of thickness. Applying integral transforms, the boundary value problem reduces to a system of singular integral equations in the Laplace transformed domain. These equations are solved numerically using the Lobatto- Chebyshev collocation quadrature approach. The inverse Laplace transform is used to find the approximate expressions of dynamic stress intensity factors (DSIFs). The striking feature of the article is the study of phenomenal changes of shielding and amplification through dynamic stress magnification factor (DSMFs) at the tips of the cracks under the sudden impact loading applied at the upper material surface. The effects of impact load applied at different surfaces, positions of cracks' axis and the thickness of the strips of the composite material on the possibilities of cracks' arrest are depicted graphically for different particular cases.

# #607 The Rise of Passive Safety Technological Solutions for M3 Class II/III Buses

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*Finite Element Method* *ECE R66* *Rollover Test*

## Abstract

**Abstract** The pursuit of vehicle safety is a key driver in the emergence of a new stage of transportation systems, involving new technologies and business opportunities. Buses are commonly used as more stable and safer public transportation in comparison with other vehicles. This study is considering accidents may occur on the roads and the manufactures and operators intend to establish new responses to minimize the consequences of eventual accidents to the passengers, by collapsing the body frame structure. The idea is to apply new engineering concepts through numerical modelling on the bus superstructure based on the nonlinear Finite Element Method, FEM, formulation in the field of passive safety satisfying the United Nations Economic Commission for Europe (UNECE) Regulation No. 66. It conforms to the sphere of solutions that act not to prevent an accident, but after it occurs to reduce its severity. This regulation is mandatory for M3 Class III and/or M3 Class II; long distances (coaches) or intercity, independently of the power train (combustion/Hybrid/Electric).

This work aims at the development of new safety solutions for the M3 Class II/III buses, supported by geometrical optimization of superstructure profiles and introduction of metallic hybrid zones with high-energy absorption rates. It focuses on the creation of a new generation of buses with innovative solutions that contribute to ensuring the safety of the driver and passengers in the event of a rollover. In addition, a real experimental test on the bus superstructure will be performed to corroborate the numerical results and to evaluate the regulation R66 requirements.

# #608 Oxidation-Induced Damage Modeling in Micro Gas-Turbines Combustion Chambers

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*Oxidation* *Damage* *MGT*

**Abstract** The combustion chambers of micro gas-turbines are generally operated under very lean global air-fuel ratios for two main reasons: to contain the production of pollutants (NOx), and to cool-down the metal walls with cooling air. The abundancy of oxygen contained in the air flowing over the metal surfaces, together with the high temperatures due to combustion, constitute an oxidizing environment. The thin oxide layer can crack due to alternating system operative conditions, potentially initiating a crack detrimental to the combustion chamber's life. An oxidation damage term should be computed in order to provide information of the component's life. In this paper, an oxidation-induced damage model for superalloy INCONEL 718 is applied to the MTT Enertwin micro gas-turbine combustion chamber. Oxidation growth and material parameters are obtained from experimental data. The phasing of thermal loads with mechanical strains is also considered. The results show a distribution of the oxidation-induced damage on the combustion chamber walls which depend on temperature and mechanical strain rate, suggesting that this damage mechanism is relevant under these operative conditions. Therefore, it should be included in a broader life-assessment methodology, which includes oxidation, mechanical fatigue and creep.

# #609 Darkfield lighting system for cylindrical specimen crack growth monitoring

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*Illumination System* *Optical Metrology* *Crack-Tip Growth UHCF*

**Abstract** This letter reports on the development of a dedicated illumination system for fatigue crack growth measurement system in cylindrical UHCF specimens (Figure 1). The system uses darkfield lighting with a circular led system and a circular reflector for Central Crack Test (CCT) specimen illumination. Numerical ray-tracing optimization was employed for the specific specimen limitations, such as size and reflectivity properties as well as the requirement for uniform field illumination around the central area of specimen.

Traditional illumination systems for fatigue crack growth testing shows a severe limitation in contrast and a rather low detection capability for narrow crack opening. Furthermore, the lack of discernment between the crack opening and superficial artifacts that result from scratches, dust or other surface perturbations, prevents the correct identification of the crack-tip position and total length. Although these are not severe problems for the traditional crack-tip position measurement with a travelling microscope, they become very significant when trying to use image methods as an alternative. An important image processing rule is to start with the best possible image, or otherwise, statistical and morphological data processing will hardly be able to remove all unnecessary clutter.

Developing an illumination system involves a correct specification of the test specimen geometry and physical properties as well as the envisaged feature characteristics. For the UHCF test specimens and crack detection this implies a diffuse tangential illumination to increase the contrast of the crack relatively to the surface. It also requires a suitable wavelength for the specific detection sensor. In this project, a circular cold LED lighting (green parts in Figure 2) was used with an appropriate wavelength distribution and a special geometry for darkfield illumination was designed and optimized trough numerical ray-tracing.

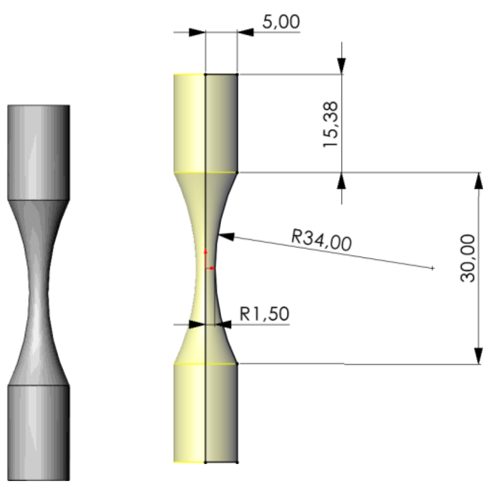


***Figure*** 1 – UHCF Specimen

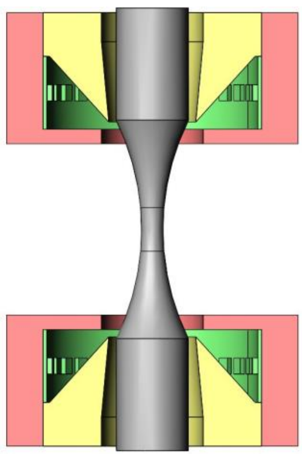

***Figure*** 2 – UHCF Illumination system

# #610 Numerical analysis of ballistic impact through FE and SPH methods

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*Ballistic impact* *Ductile damage* *Numerical simulation*

**Abstract** In defense and aerospace industries, structures are designed to be resistant to ballistic impact loads. Experimental analysis of ballistic impact has been conducted successfully for many years, and alternatively numerical techniques have been employed due to the complexity of the tests. In this study the ballistic impact of metallic materials is addressed with both finite element (FE) and smoothed particle hydrodynamics (SPH) methods. A single-shot ballistic impact model consisting of a deformable plate and a rigid projectile is developed in Abaqus/Explicit solver where user material subroutines (VUMAT) are implemented using FE and SPH methods. These two methods are compared considering Johnson-Cook (JC) and Modified Mohr–Coulomb (MMC) damage frameworks. The strain rate and temperature dependent JC fracture model can effectively express the sudden strain changes that occur in high velocity ballistic impact. Due to shear dominant nature of the loading MMC performs well which depends both on the Lode parameter and triaxiality. Various numerical setups consisting of different parameter sets are generated such as target thickness, impact velocity, projectile nose shape, and angle of attack of the projectile. The damage response, axial and shear stress, strain rate and temperature changes of plate target are discussed in detail and the results are compared with the experimental ones from the literature.

# #612 Computational investigation of the Várzeas bridge steel under monotonic tensile by means of CPFE modelling

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*Crystal Plasticity Finite Element* *Bridge steel material* *Monotonic response*

**Abstract** It is possible to trace back the evolution of current structural steels to the early 18th century with the discovery of iron smelting with coke by Darby resulting in further improvements into the latter half of the 18th century when workable wrought iron was developed and rolling iron into standard shapes was made available, resulting in a wide range of structural applications such as railway bridges. Even though wrought iron as a primary construction material continued predominantly until the end of the 19th century, a gradual evolution of steel was made with the addition of chemical elements during the manufacturing process, whose refinement led to the creation of the standards such as the EN10025 for modern structural steels. Despite the controlled conditions involved in the manufacturing in ferrite-pearlite steels, or modern structural steels as they are commonly referred to, a certain level of randomness is to be expected, hence, resultant scatter in the final material mechanical, chemical and morphologic properties can be found. In the present work, a computational framework is presented with aims to include the effect of grain size distribution and morphology in the numerical crystal plasticity finite element (CPFE) by means of polycrystal modelling with aims to describe the monotonic material parameters and a comparison between experimental and numerical stress-strain curve for the transition mild structural steel from the Várzeas railway bridge is presented.

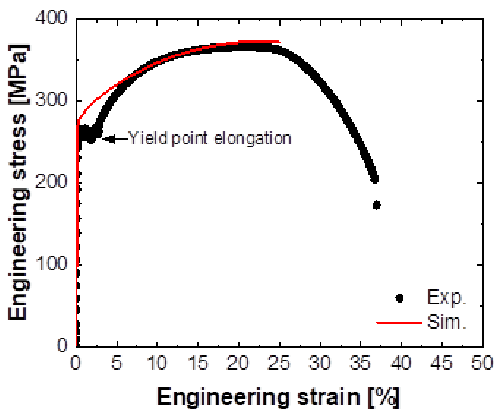


***Figure 1*** *– Comparison between experimental and computational results.*

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# #613 Probabilistic Fatigue Strength Modelling Based on Various Statistical Approaches for a Double-Side Welded Connection

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*S355 steel S-N curve Bayesian inference Hot-spot stress Nominal stress*

**Abstract** S355 steel is currently used in fabrication of most wind turbine monopile support structures and offshore structures. In this type of structures, most fatigue failures occur in the welded connections where cyclic loading is the main responsible for this phenomenon. Similar to high cycle fatigue analysis, the stress life method utilizing stress-cycle curves (S-N curves) can be used to determine the strength of a welded joint under fatigue loading. In this research, the evaluation of design S-N curves for a double side welded connection made of S355 steel is proposed. This study concludes with a comparison between the experimental fatigue curves obtained and the design S-N curves proposed in design codes for offshore structures and general steel structures. For the specimens under investigation, the hot spot and nominal stress approaches are taken into consideration. The characteristic fatigue curve of the double side welded connection is obtained using statistical analyses based either presented in the ASTM E739 standard or ISO 12107 standard. The hot-spot and nominal stress approaches yield very similar S-N results considering the specimens under study. A comparison between these fatigue curves at 5% of probability of failure provided by standards and the probabilistic fatigue strength curves based on a Bayesian inference and a Weibull distribution is done.

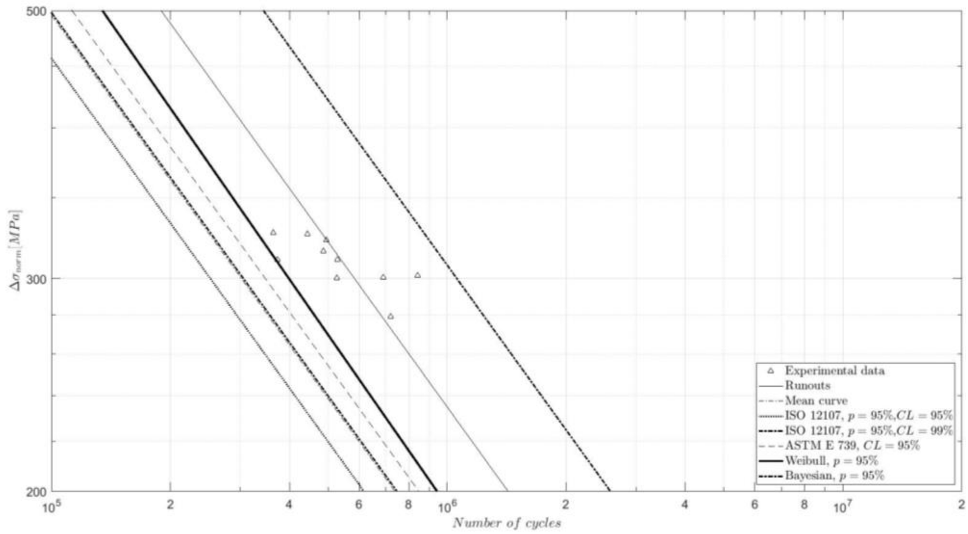


***Figure 1 -*** *Comparison of the $p_s$ = 5% P-S-N curves from different methodologies for the hot-spot stress case.*

**Acknowledgments**

This research work is supported by the following grants: project grant (UTA-EXPL/IET/0111/2019) SOS-WindEnergy - Sustainable Reuse of Decommissioned Offshore Jacket Platforms for Offshore Wind Energy by national funds (PIDDAC) through the Portuguese Science Foundation (FCT/MCTES); base funding - UIDB/04708/2020 and programmatic funding - UIDP/04708/2020 of the CONSTRUCT - Instituto de I&D em Estruturas e Construções - funded by national funds through the FCT/MCTES (PIDDAC); AARM4 - High Strength Steels in Metalmechanics 4.0 (POCI-01-0247-FEDER-068492) funded by national funds through the PT2020/COMPETE; and, individual project grant (2020.03856.CEECIND), awarded to José A.F.O. Correia, by national funds (PIDDAC) through the Portuguese Science Foundation (FCT/MCTES). Additionally, this work is financially supported by national funds through the FCT/MCTES (PIDDAC), under the MIT Portugal Program under the project MIT-EXPL/SOE/0054/2021.

# #614 Carbon based cementitious nanocomposites for de-icing applications

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*Cement mortar* *Carbon nanomaterials* *De-icing*

**Abstract** During the winter, roadways are subjected to a harsh environment. Frost developed on concrete roads/pavements creates problems for people and vehicles. To control snow and ice built up harmful deicing chemicals and salts are typically used, weathering and deteriorating the infrastructure.

This work focuses on implementing carbon nanomaterials, such as carbon nanotubes (CNTs) and graphene nanoplatelets (GNPs) to develop intelligent nano-reinforced de-icing mortars, which can be used to prevent and control ice and snow deposition on roadways, highways and pavements increasing their safety. The electrically conductive carbon nanomaterials develop several electrical current pathways inside the mortar matrix. As a result, when electric voltage passes through the mortar nanocomposite the temperature increases rapidly melting or preventing ice and snow build up. Different nanoreinforced mortars were produced having either CNTs or GNPs at concentrations of 0.05%, 0.1%, 0.2%, 0.4%, and 0.6% by weight of cement. Nanomaterials' dispersion was achieved into nanobubble water with or without the aid of a superplasticizer (SP).

Two experimental setups were used to study the effect of CNTs and GNPs on the temperature change of the nanocomposites: i) typical prismatic specimens having 4 electrodes at a vertical arrangement (4-wire method) covering the total cross section and sticking out and ii) specially designed mortar slabs having two embedded electrodes and two inserted thermometers. The electrodes were used to apply electrical voltage (AC). The nanocomposites were placed inside a fridge and a cooler to reach steady temperatures of below 5 ºC and -20 ºC. Following, electrical voltage was applied and their temperature change was measured using infrared thermometers, embedded thermometers and a thermal camera. The results were compared with the reference mortars without nanomaterials. It was found that the use of carbon nanomaterials strongly effects the temperature variation. The nanocomposites with SP and GNPs at a concentration of 0.2% by weight of cement demonstrated optimal results having 5 times higher temperature compared to the reference samples.

# #615 Application of crack growth similitude laws for evaluation of fatigue crack propagation in additively manufactured metal alloys

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*Fatigue crack growth* *Additive manufacturing* *Hartman-Schijve relation*

**Abstract** Additive Manufacturing (AM) has become a popular technology in the manufacturing of various engineering structures, with one primary application being the aerospace industry, both for new aircraft structural components and repair of existing parts. It has the potential to save almost 30% of the fuel costs compared to traditional fabrication techniques by introducing intricate lightweight design and reducing assembly and machining operation. Nevertheless, the applications of AM parts in manufacturing industries are in the early stages, as the reliability of mechanical properties is an indispensable pre-requisite for real-life applications. Damage tolerance design analysis is essential for aerospace industry to ensure requisite operational life. It is, therefore, important to determine the fatigue (*da/dN* versus *ΔK*) curves with a generic mathematical representation for AM alloys, which are likely to be used in load-carrying structural members. The present paper is aimed at developing generic forms of fatigue relationships for AM metal alloys by investigating similitude laws. The paper establishes that for several AM alloys, such as Ti-6Al-4V titanium alloy, 316L stainless steel, and AlSi10Mg titanium alloy, the *da/dN* versus Δ*K* curves have been represented by the Hartman and Schijve variant of the crack growth equation. Figure 3 shows the fatigue crack growth rate (FCGR) according to Hartman and Schijve's modified equation of Paris law for AM Ti-6Al-4V alloy. The original curves of *da/dN* versus *ΔK* were taken from test data of the Ti-6Al-4V alloy reported in the literature. Besides, a few other modified Paris law type equations have been applied to understand the effect of driving force parameters (threshold, load ratio, cyclic fracture toughness) on the AM fatigue crack growth (FCG) properties. The degree of correlation among different models is evaluated by plotting and analysing the existing literature fatigue data of different AM alloys. All the AM alloys considered here can be well represented by various modified FCG models. The coefficients of the fatigue crack growth relationships for AM alloys evaluated from the generic FCG equation show reasonable agreement with those produced by the traditional manufacturing methods. However, discrepancies are still found due to the scarcity of the FCG test data and the variation of AM processing and post-processing parameters.

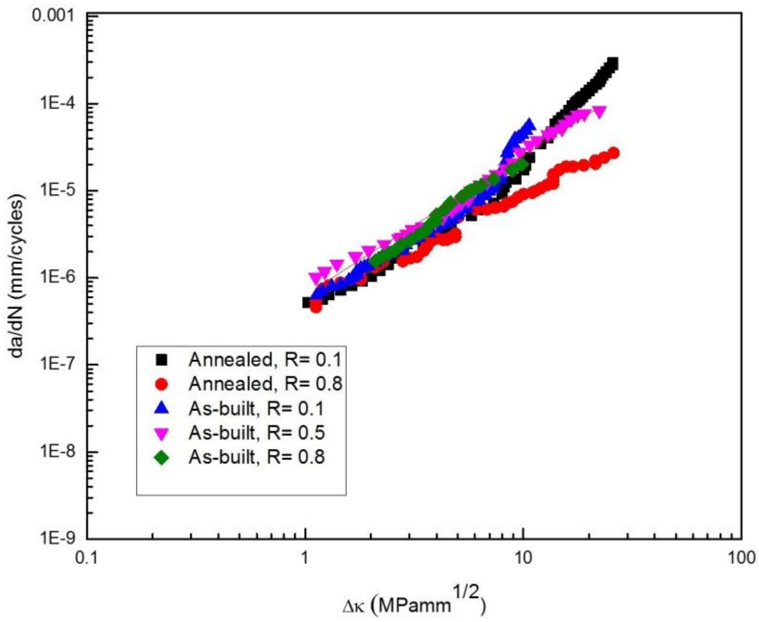


***Figure 3-*** *Hartman and Schijve representation of FCGR of Ti-6Al-4V tested at different R ratios [1]*

1. Galarraga, H., et al., Fatigue crack growth mechanisms at the microstructure scale in as-fabricated and heat treated Ti-6Al-4V ELI manufactured by electron beam melting (EBM). Engineering Fracture Mechanics, 2017. **176**: p. 263-280.

# #616 Patented Resonant Fatigue Testing Machine to perform HCF (High Cycle Fatigue) and VHCF (Very High Cycle Fatigue) Tests at 1000 Hz on test samples and small components

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**ABSTRACT**

There is no infinite fatigue life. In the recent decades we learned that fatigue testing with higher number of load cycles is required in some areas. The development of faster testing techniques e.g. Ultrasonic systems testing on 20kHz have allowed the conduction of many research activities in the giga cycle regime in the recent decades. In 2014 RUMUL presented the RUMUL GIGAFORTE, a new resonant fatigue testing machine, allowing a testing frequency of 1000Hz. The dynamic load up to 50 kN peak-peak is produced by an electromagnetic system. A static load of up to 50 kN is provided by two mechanical spindles. Any R-ratio is possible. Currently used flat and round specimen types used in fatigue testing can be tested. The specimen size/volume actually tested can be much larger than possible on ultrasonic systems. The RUMUL GIGAFORTE offers new possibilities for investigations of material properties in the very high cycle fatigue (VHCF) regime.

Since 2014 the RUMUL GIGAFORTE was intensively used in several laboratories in Germany as for example at the Fraunhofer institute/IWS Dresden in Germany. Some effects of the 1000Hz testing frequency on the fatigue behavior of the material have been observed. This paper provides a summary how the frequency of an alternating load affects the fatigue life of certain materials. Some examples of heating up of the specimen related to the 1000Hz testing frequency are shown. Normally continuous fatigue testing is possible, partially air cooling is required but sufficient to avoid the heating up of the test samples.

KEYWORDS *New Resonant Fatigue Testing Machine, VHCF_Very High Cycle Fatigue ,*

*Giga Cycle Fatigue, Frequency effects, Fatigue tests at low and high temperatures*