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ESIS Recommendations for Determining the Fracture Resistance of Ductile Materials

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SUMMARY

This document describes a European Structural Integrity Society Procedure for determining the crack growth fracture resistance behaviour of ductile materials. The fracture behaviour is characterised in terms of either the variation in fracture resistance J or crack tip opening displacement δ with crack growth.

Testing requirements and analysis procedures are given which enable J and δ to be calculated from both compact and single edge notch bend specimens. Fracture parameters are also defined for estimating J and δ close to the onset of crack initiation.

NOMENCLATURE

Dimensions

a	Crack length
a_i	Estimated initial crack length
a_o	Initial crack length, Figures 2 and 3
B	Specimen thickness
B_n	Net thickness of sidegrooved specimens
S	Span of single edge notch bend specimen, Figure 6
W	Specimen width
z	Either the distance of the knife edge from the load line, Figure 2, or the knife edge height defined in Figure 7

Material Properties

E	Young's modulus
ν	Poisson's ratio
$R_{p0.2}$	Yield strength equivalent to 0.2 percent proof stress
R_m	Ultimate tensile strength
R_f	Flow strength $(R_{p0.2} + R_m)/2$

Loads and Deformations

F	Load
F_y	Yield load, calculated using $R_{p0.2}$
F_L	Ultimate load, calculated using R_m
R	Ratio of lower to upper load during fatigue cracking
q	Load point displacement
V	Mouth opening displacement
V_p	Plastic component of the mouth opening displacement

Fracture Parameters and Related Quantities

Δ_a	Average crack growth
Δa_{szw}	Critical stretch zone width
Δa_{max}	Validity limit for J or δ-controlled crack growth

Δa_g	Limit of J or δ-controlled crack growth
Δa_ℓ	Reduced limit for J-controlled crack growth, Section 6.3.4
J_0	Fracture resistance not allowing for crack growth
J	Fracture resistance allowing for crack growth
J_i	Fracture resistance at crack initiation
$J_{0.2/BL}$	Fracture resistance at 0.2mm crack growth offset to the blunting line
$J_{0.2}$	Fracture resistance at 0.2mm crack growth including blunting
dJ/da	Slope of the J-Δa curve
J_g	Fracture resistance at upper limit of J-controlled crack growth
J_{max}	Validity limit for J
ω	A non-dimensional quantity for characterising J-controlled crack growth
η(a/W)	J-calibration function, Section 5.1.1
δ_o	Crack tip opening displacement (CTOD) not allowing for crack growth
δ	CTOD allowing for crack growth
δ_i	CTOD at crack initiation
$\delta_{0.2/BL}$	CTOD at 0.2mm crack growth offset to the blunting line
$\delta_{0.2}$	CTOD at 0.2mm crack growth including blunting
dδ/da	Slope of the δ-Δa curve
δ_g	CTOD at upper limit of δ-controlled crack growth
δ_{max}	Validity limit for CTOD
K	Stress intensity factor
ΔK	Range of stress intensity factor in fatigue
f(a/W)	Stress intensity function, Appendix 1

SI units should be used.

CONTENTS

1. INTRODUCTION

1.1 Objective, Scope and Significance

This document sets out a procedure for determining the fracture behaviour of ductile materials using laboratory test specimens. It incorporates European experience and includes many features of existing test Standards, see Bibliography. The intention of the document is to present the European Structural Integrity Society recommendations for ductile materials testing.

The fracture behaviour of ductile materials is characterised in the procedure in terms of either the variation in fracture resistance J or crack tip opening displacement δ with crack growth Δa. The document contains testing requirements and analysis procedures which enable J and δ to be calculated for both compact and single edge notch bend specimens.

The test method is based on the multiple specimen method which requires several nominally identical specimens to be loaded to different displacements. The extent of stable crack growth is marked and the specimens are then broken open to allow measurement of the crack growth. Single specimen methods based on, for example, the unloading compliance or potential drop techniques can be used to measure crack growth provided they meet accuracy requirements given in the procedure. The main body of the text is based on the requirements of the multiple specimen method which is considered the reference method. Due to the developing nature of the single specimen methods recommendations for these are described in the Appendices. With either approach the objective is to determine sufficient data points to adequately describe the J-Δa or δ-Δa behaviour of a material. The multiple specimen method measures average fracture properties whereas the single specimen method can provide additional information on material variability.

The scope of the procedure is summarised in the flowchart shown in Figure 1.

Three fracture parameters are defined in the procedure for estimating J and δ close to the onset of crack initiation:

(i) $J_{0.2/BL}$ and $\delta_{0.2/BL}$ which measure the material resistance at stable crack growth and provide an engineering definition of initiation. A value of 0.2mm was chosen as it was felt large enough to allow accurate experimental measurements of crack growth in the test specimens, yet small enough to give material resistance values close to crack initiation.

(ii) $J_{0.2}$ and $\delta_{0.2}$ which measure the material resistance at 0.2mm of total crack growth. These can be used as an engineering approximation to the initiation value. These parameters provide useful estimates of initiation which are generally lower bound estimates of $J_{0.2/BL}$ and $\delta_{0.2/BL}$.

(iii) J_i and δ_i which correspond to values of the fracture at crack initiation. The derivation of these parameters requires the use of a scanning electron microscope to measure the stretch zone width. It is considered to be the most accurate method for measuring J and δ close to the onset of crack initiation. Since there are practical difficulties in using this approach, which makes it unsuitable for routine materials testing, the method is described in an Appendix to this Procedure.

Additionally, parameters J_g and δ_g are defined which give the fracture resistance values that can be measured from a given test specimen. Also dJ/da and dδ/da, which are the slopes of the J-Δa and δ-Δa curves, respectively,are used to measure the material resistance to crack growth.

These parameters characterise the fracture behaviour of ductile materials. They can be used as an index for material selection and quality assurance purposes or to evaluate the effects of temperature, heat treatment, environment, welding and chemical composition on fracture properties. They also provide data which can be used to assess the structural integrity of components. Methods for assessing structural integrity are described in the European Guidelines for the Assessment of the Integrity of Structures Containing Crack-Like Defects.

This procedure does not apply to materials which fail by cleavage or brittle inter-granular mechanisms or exhibit pop-in behaviour.

2. SPECIMEN GEOMETRY, DIMENSIONS AND PREPARATION

2.1 Specimen Geometries

The procedure allows the use of either compact specimens or single edge notch bend specimens. A suggested compact specimen geometry is shown in Figure 2. Other loading hole separations, pin hole diameters and notch configurations can be used but care must be taken to avoid excessive plastic deformation at the pin holes.

The single edge notch bend specimen is shown in Figure 3.

2.2 Dimensions

2.2.1 Geometrical Considerations

The dimensions of the standard test specimens shown in Figures 2 and 3 are characterised by the specimen width W. The thickness B is 0.5W, although W can vary independently of B. Care should be taken to avoid those extreme thickness to width ratios which could cause buckling. It is recommended that the specimen thickness is the same as the component thickness or as large as practicable.

The specimen dimensions must satisfy the validity limits given in Sections 6.4.1 and 6.5.1. Since these limits depend on the measured properties, they can only be checked after the test has been completed. However, suitable specimen dimensions can be obtained before testing from an estimate of the maximum probable fracture resistance.

All test specimens must be machined to within the tolerances given in Figures 2 and 3.

2.3 Preparation

2.3.1 Fatigue Pre-cracking

2.3.1.1 A fatigue pre-crack must be produced in the test specimen from the end of the machined notch, shown in Figures 2 and 3, to give an initial crack length a_o in the range $0.5 \geq a_o/W \geq 0.65$. The test initial crack lengths which are in reasonably close agreement with each other. If the crack length range exceeds 0.05W, then report the discrepancy in Section 8.3.

It is recommended that for those materials in which the ultimate to yield strength ratio, $R_m/R_{p0.2}$, exceeds 2, the initial length should tend towards the upper limit of a_o/W to ensure that plastic deformation is limited to the uncracked ligament.

2.3.1.2 The fatigue pre-crack must exceed the larger of $0.05a_o$ or 1.5 mm. The notch geometry must be enclosed within a 30° included angle from the fatigue pre-crack tip, Figure 4.

2.3.1.3 The maximum fatigue load must not exceed the lower of $0.6P_y$ or the load corresponding to a stress intensity factor range to Young's modulus ratio ($\Delta K/E$) equal to or less than 1.5 x 10^{-4} $m^{1/2}$.

The load F_y, for a compact specimen, is given for the purposes of fatigue pre-cracking by

$$F_y = \frac{B(W-a)^2}{(2W+a)} R_{p0.2}$$

and, for the single edge notch bend specimen by

$$F_y = \frac{4B(W-a)^2}{3\ S} R_{p0.2}$$

where $R_{p0.2}$ is the yield strength. S is the span as shown in Figure 6. The stress intensity factor K at load F is calculated from

$$K = \frac{F}{B\sqrt{W}} f(a/W)$$

where the stress intensity function f(a/W) is defined in Appendix 1.

2.3.2 <u>Sidegrooving</u>

2.3.2.1 Sidegrooving promotes straight fronted ductile crack growth during a test. Specimens should be sidegrooved after fatigue pre-cracking. When the test specimen thickness is less than the component thickness, it is recommended that the specimens are sidegrooved.

2.3.2.2 The sidegrooves must be equal in depth and have an included angle of 30°-90° with a root radius of 0.4 ± 0.2 mm. A Charpy V-notch cutter provides a suitable profile. The depth of sidegrooving, $B-B_n$, must exceed 0.10B and must not exceed 0.25B where B_n is the net section thickness. For most materials, 20 percent total sidegrooving is recommended.

2.3.3 <u>Measurements</u>

Prior to testing, measure the thickness B, net section thickness B_n and width W, as shown in Figures 2 and 3, to an accuracy of 0.05 mm.

3. TEST REQUIREMENTS

3.1 Test Machine

The test machine must incorporate a rigid loading frame, and be capable of operating at constant displacement rate.

3.2 Test Fixtures

The test fixtures must be designed to be as rigid as practicable. Care must be taken to minimise indentation and frictional effects between the specimen and fixture.

Figure 5 shows a suitable clevis design for the compact specimen. Figure 6 shows a suitable loading frame for the single edge notch bend specimen. The lower support rollers must be free to move outwards.

3.3 Displacements

The fracture resistance J is evaluated from load-point displacement q, whereas the crack tip opening displacement, δ, is evaluated from mouth opening displacement V.

3.3.1 Load Point Displacement

When testing compact specimens, the load line displacement measured between knife edges placed between the pin holes, Figure 2, is usually taken as a measure of load-point displacement. For compact specimens which do not permit measurement of the load-line displacement, the relationship between the measured displacement and the load-line displacement must be established so that load-line values may be inferred.

When testing single edge notch bend specimens, it is important to exclude extraneous displacements arising from system compliance and load-point indentations. Suitable methods for measuring load-point displacements without extraneous displacements are referenced in Appendix 2. Other methods can be used provided the extraneous displacement arising from indentation effects and elastic deformation in the fixture are determined and subtracted from the measured displacement.

3.3.2 Mouth Opening Displacement

For the compact specimen shown in Figure 2, the mouth opening displacement corresponds to the load-point displacement. If the knife edges are not located at the load line, the mouth opening displacement is measured between knife edges at a distance z from the load line in the direction away from the crack tip.

In the case of the single edge notch bend specimen, the mouth opening displacement can be measured between knife edges at a distance z from the specimen surfaces, Figure 7.2

3.4 <u>Accuracy of Transducers</u>

The load and displacement transducer accuracy and reproducibility must be within ±1 percent of the measured value or 0.2 percent of the range encountered during the test, whichever is the greater. Linearity must be within ±0.5 percent of the transducer range encountered during the tests. Accuracy, reproducibility and linearity should be evaluated at the temperatures experienced by the transducers during the test.

3.5 <u>Test Temperature</u>

Measure the temperature on the surface of the specimen within 5 mm of the fatigue pre-crack. Prior to commencing a test, the recorded temperature must remain stable within a band of $T_{nominal} \pm 2.0$ °C for at least 21000/X minutes or $0.5B^2/X$ minutes, whichever is the greater. Typical values for X (mm^2/min) are

Aluminium alloys	4000
Ferritic steel	700
Austenitic steel	233

For specimens up to 200 mm thick, the stability times for an aluminium alloy, a ferritic and austenitic steel are 5, 30 and 100 minutes, respectively.

Throughout the test the temperature must also remain within this limit. Report the time at test temperature as required in Section 8.3.

3.6 <u>Specimen and Fixture Alignment</u>

For compact specimen testing, the centre-lines of the upper and lower clevises must be within the smaller of 0.03B or 1 mm of each other and within the smaller of 0.03B or 1 mm of both the specimen hole centre-line and the specimen mid-thickness centre-line.

For single edge notch bend specimen testing, the centre-line of the upper roller must be midway between the centre-lines of the lower rollers to within 0.5 percent of the distance between the lower rollers. The axes of the rollers must be parallel to within 1 degree of each other. The specimen must be aligned in the testing fixture so that the fatigue pre-crack is midway between the centre-lines of the lower rollers to within 1 percent of the distance between the lower rollers. In addition, the length of the specimen must be within 2 degrees of perpendicular to the axes of the rollers.

4. TEST METHODS

The load-displacement data are used to evaluate the fracture parameters J and δ. J and δ are used in conjunction with measurements of crack growth Δa to describe the ductile fracture resistance. The crack growth is measured using either the multiple specimen method or inferred from single specimen methods as described in Appendix 3.

4.1 Multiple Specimen Method

The multiple specimen method requires the testing of several nominally identical specimens to provide the data distribution specified in Section 6.2. Usually one specimen is required to give an indication of the displacement needed to obtain the maximum crack growth allowed by this procedure.

4.1.1 Measure and record the load-displacement behaviour of the test specimen at a loading rate which results in a load-point displacement rate less than 0.1W/minute using displacement control but sufficient to avoid time dependent effects. Each specimen must be loaded at the same rate. Report the rate as required in Section 8.3.

4.1.2 Load a specimen to a displacement just beyond the maximum load attainable, then reduce the load to zero allowing no further increase in displacement. It may not always be possible to use the result from this specimen in the data analysis.

4.1.3 Mark the extent of ductile crack growth by either heat tinting or fatigue cracking. The fatigue cracking should be performed at an R-ratio greater than 0.6 to avoid damage to the fracture surfaces from crack closure effects. The maximum fatigue load should not exceed three-quarters of the final load measured during the test.

4.1.4 Break open the specimen at or below room temperature to reveal the fracture surfaces. Measure the crack growth as described in Section 4.2 and evaluate J or δ using the procedures given in Sections 5.1 and 5.2, respectively.

4.1.5 Repeat the test procedure with further specimens terminating each test at the displacement judged to give crack growth satisfying the requirement given in Section 6.2.

4.1.6 Only data satisfying the crack growth criteria, Δa_{max}, can be used in subsequent analysis of the data.

4.2 Crack Length Measurements

The procedure is based on measurements of average crack length. Although the area-averaged method should provide the most reliable estimate, the 9-point average method produces acceptable results.

Difficulties may arise in measuring highly irregular crack fronts suchas spikes or regions of disconnected crack growth. For these situations, it may only be practicable to estimate the crack length by ignoring the spikes or subjectively averaging the crack growth regions. Care must be exercised when the results derived from highly irregular crack fronts are used to assess structural integrity. It is then recommended that such assessments should be based solely on crack initiation parameters and no advantage can be taken of the crack growth fracture resistance behaviour.

The method used to measure crack length and irregular crack fronts must be reported in Section 8.3.

4.2.1 In compact specimens, the initial crack length a_0 corresponds to the distance between the centre-line of the loading-pin holes and the end of the fatigue pre-cracked zone, Figure 8. In the single edge notch bend specimen, the initial crack length a_0 corresponds to the distance between the front surface and the end of the fatigue pre-cracked zone, Figure 9.

4.2.2 Initial crack length is measured to an accuracy of 0.25 percent or 0.05 mm, whichever is the greater between two reference lines defined at the minimum thickness positions as shown in Figures 8 and 9. The measurements are made at 9 equi-spaced points where the outer points are located at 0.01B from the reference lines. The value of a_0 is obtained by firstly averaging the two measurements at 0.01B from the surfaces and then averaging this value with the 7 inner measurement points. If the difference between a_0 and any of the individual measurement points contributing to a_0 exceeds $\pm$ 10 percent, then report non-uniform fatigue-crack growth as required in Section 8.3.

4.2.3 Measure the total crack growth Δa between the initial and final crack fronts to an accuracy of 0.05 mm using the averaging procedure described in Section 4.2.2.

4.2.4 Measure the maximum and minimum crack growth between measurement positions 1 to 9, Figures 8 and 9. If the difference is greater than 20 percent of the average crack growth Δa, or 0.15 mm, whichever is the greater, then report non-uniform crack growth as required in Section 8.3.

5. ANALYSIS PROCEDURES

The analysis procedures for determining either J or δ from multiple specimen data are given in this section.

5.1 Fracture Resistance J

There are several formulae available for determining the fracture resistance J. The formula given here is considered the most appropriate for multiple specimen testing. It has the advantage of avoiding the need to partition the area U under the load displacement record into elastic and plastic components. Furthermore, over the allowable a/W range the formula is virtually identical to those which partition U.

5.1.1 Calculate J_o for each sidegrooved specimen using the relationship

$$J_o = \frac{\eta U}{B_n(W-a_o)}$$

where η = 2 + 0.522 $(1-a_o/W)$ for compact specimens
= 2 for single edge notch bend specimens

and U is the area under the load versus load-point displacement record up to the line at constant displacement corresponding to the termination of the test, Figure 10a. For non-sidegrooved specimens replace B_n with B in the above formula.

5.1.2 Fracture Resistance J allowing for Crack Growth

The J-equation used in Section 5.1.1 does not allow for crack growth during a test. The errors in the J-values are usually negligible for crack growth less than $0.10(W-a_o)$. If the crack growth validity is extended beyond $0.10(W-a_o)$ then all data points should be corrected for crack growth. A suitable approximation is

$$J = J_o \{1 - \frac{(0.75\eta - 1)\ \Delta a}{(W - a_o)}\}$$

where η is defined in Section 5.1.1.

5.2 Crack Tip Opening Displacement δ

5.2.1 Calculate δ_o for each specimen using the relationship

$$\delta_o = \frac{K^2(1-\nu^2)}{2ER_{p0.2}} + \frac{0.4(W-a_o)}{(0.4W + 0.6a_o + z)} V_p$$

$$\text{where} \qquad K = \frac{F}{\sqrt{B\,B_n W}} f(a_o/W)$$

F is the load at termination of the test.

$f(a_o/W)$ is the stress intensity function defined in Appendix 1.

z is either the distance of the knife edge from the load line, Figure 2, or the knife edge height defined in Figure 7.

V_p is the plastic component of the mouth opening is placement at termination of the test as defined n Figure 10b.

For non-sidegrooved specimens replace B_n with B.

5.2.2 <u>Crack Tip Opening Displacement Allowing for Crack Growth</u>

The δ equation used in Section 5.2.1 does not allow for crack growth during a test. The errors in the δ-values are small for crack growth less than $0.25(W-a_o)$. If the crack growth validity limit is extended beyond $0.25(W-a_o)$ then all data points should be corrected for crack growth. A suitable approximation is

$$\delta = \frac{K^2(1-\nu^2)}{2ER_{p0.2}} + \frac{0.6\Delta a + 0.4(W-a_o)}{0.6(a_o + \Delta a) + 0.4W + z} V_p$$

where K is defined in Section 5.2.1.

5.2.3 In cases where the slope of the elastic loading line cannot be clearly defined an analytical method for determining V_p is given in Appendix 4.

6. CONSTRUCTION OF VALID CRACK GROWTH FRACTURE RESISTANCE CURVES

The data obtained in Sections 4 and 5 are used to construct a plot of fracture resistance against crack growth.

For structural integrity assessments, data are usually required which are independent of test specimen size. Validity limits are applied to the data in an attempt to ensure size independence so that J and δ characterise the fracture behaviour of ductile materials.

The validity limits are expressed in terms of the maximum J, δ and Δa values which can be measured for a given test specimen size. Limits have only been established for J, but experimental evidence suggests that the limits for δ are likely to be less restrictive than for J. The validity limits for J and suggested limits for δ are given in the following sections.

Only data satisfying the validity limits can be regarded as a material property independent of specimen size. Alternative validity limits to those recommended in this procedure can be used providing adequate evidence justifying their use is available. The use of alternative validity limits and their justification must be reported in Section 8.4.

6.1 Δa_{max} Crack Growth Limit

6.1.1 For each specimen, calculate Δa_{max} from either

$$\Delta a_{max} = 0.10(W-a_o) \quad \text{for } J$$

or

$$= 0.25(W-a_o) \quad \text{for } \delta.$$

6.1.2 Determine the slope of the blunting line as described in Appendix 5. Plot the blunting line on a graph containing the crack growth fracture resistance data.

6.1.3 Construct the crack growth limit exclusion line parallel to the blunting line at an offset corresponding to the minimum value of Δa_{max} calculated in Section 6.1.1, Figure 11.

6.1.4 Construct an exclusion line parallel to the blunting line at an offset of 0.10 mm, Figure 11.

6.2 Data Spacing Requirement

6.2.1 A minimum of four and preferably at least six data points must be used to describe the crack growth fracture resistance behaviour. Ideally the data points should be evenly spaced. At least one data point is required in each of the four equal crack growth regions shown in Figure 11.

6.3 Curve Fit

6.3.1 Determine the best fit curve through the data points which lie between the 0.1 mm and Δa_{max} exclusion lines, Figure 11, using the equation

$$J \text{ or } \delta = A\ (\Delta a + C)^D \qquad \text{where } C \geq 0$$

A method for evaluating the constants A, C and D is given in Appendix 6.

6.4 J Validity Limits

6.4.1 For each specimen, calculate J_{max} from the smaller of

$$J_{max} = (W - a_o)\ \frac{R_f}{20}$$

$$\text{and} \qquad J_{max} = B\ \frac{R_f}{20}$$

where R_f the flow strength is $(R_{p0.2} + R_m)/2$.

6.4.2 Construct an exclusion line to the J-Δa data at the minimum calculated J_{max} value, Figure 12.

6.4.3 The crack growth fracture resistance curve enclosed by the J_{max} and Δa_{max} exclusion lines may be regarded as a material property independent of specimen size.

6.4.4 The intersection of the best fit curve with either the J_{max} or Δa_{max} exclusion line defines a provisional value for J_g the upper limit to J-controlled crack growth behaviour.

6.4.5 Calculate ω from

$$\omega = \frac{(W - a_o)}{J_g}\ \frac{dJ}{d(\Delta a)}\Big|_{J_g}$$

where $\frac{dJ}{d(\Delta a)}$ is evaluated at J_g from the equation obtained in Section 6.3.1 and $(W - a_o)$ is the minimum value measured in the multiple specimen data. If $\omega \geq 10$, then the J-Δa curve enclosed by the J_{max} and Δa_{max} may be regarded as a material property independent of specimen size. J_g is the upper limit to J-controlled crack growth behaviour for the test specimen size.

6.4.6 If $\omega < 10$ at the upper limit J_g, calculate the reduced crack growth limit Δa_ℓ at $\omega = 10$ from

$$\Delta a_\ell = \frac{D(W-a_o)}{10} - C$$

for which the conditional relationship given in Section 6.4.5 is just satisfied. The constants C and D are defined in Section 6.3.1. Recalculate J_g at Δa_ℓ from the equation obtained in Section 6.3.1. The curve enclosed by J_g and Δa_ℓ, Figure 13, may then be regarded as a material property independent of specimen size.

6.5 <u>δ Validity Limits</u>

6.5.1 For each specimen calculate δ_{max} from the smaller of

$$\delta_{max} = \frac{(W - a_o)}{30}$$

$$\text{and} \qquad \delta_{max} = \frac{B}{30}$$

6.5.2 Construct an exclusion line to the δ-Δa data at the minimum calculated δ_{max} value, Figure 12.

6.5.3 The crack growth fracture resistance curve enclosed by the δ_{max} and Δa_{max} exclusion lines may be regarded as a material property independent of specimen size.

6.5.4 The intersection of the curve with either the δ_{max} or Δa_{max} exclusion lines defines δ_g, Figure 13. δ_g is the upper limit to δ-controlled crack growth behaviour for the test specimen size.

7. DERIVATION OF FRACTURE PARAMETERS

Two fracture parameters are described for estimating J and δ close to the onset of crack initiation from crack growth fracture resistance data.

These parameters are:

(1) $J_{0.2/BL}$ or $\delta_{0.2/BL}$ which measure the fracture resistance at 0.2 mm crack growth offset to the blunting line. They provide an engineering definition of initiation and avoid the use of a scanning electron microscope. These parameters attempt to rank materials covering a wide range of crack growth fracture resistance behaviour with respect to crack initiation.

(2) $J_{0.2}$ or $\delta_{0.2}$ which measure the fracture resistance at 0.2 mm of total crack growth including crack tip blunting. In many areas these parameters provide a useful engineering estimate of initiation which are generally lower bound values compared with $J_{0.2/BL}$ and $\delta_{0.2/BL}$. For high toughness materials, they may be ranked unduly low.

A more accurate estimate of the fracture resistance at crack initiation, J_i or δ_i, requiring the use of a scanning electron microscope is given in Appendix 7.

The choice and applicability of the fracture parameters for structural integrity assessments and materials characterisation is at the discretion of the user.

7.1 J Fracture Parameters

7.1.1 $J_{0.2/BL}$

7.1.1.1 Construct a plot of the blunting line, Section 6.1.2, and the best fit curve, Section 6.3.1 through the J-Δa data.

7.1.1.2 Construct a parallel line offset to the blunting line at 0.2 mm crack growth, Figure 14. The intersection of the best fit curve with the offset line defines $J_{0.2/BL}$. At least one J-Δa point should be within 0.1 mm of the offset line.

7.1.1.3 If $J_{0.2/BL}$ exceeds J_{max} determined in Section 6.4, then $J_{0.2/BL}$ is invalid according to this procedure.

7.1.1.4 Evaluate the slope of the J-Δa curve, $\left(\frac{dJ}{da}\right)_{0.2/BL}$ at the intersection point from the equation determined in Section 6.3.1. If the slope of the blunting line

$$\left(\frac{dJ}{da}\right)_{BL} < 2\left(\frac{dJ}{da}\right)_{0.2/BL}$$

then $J_{0.2/BL}$ is invalid according to this procedure.

7.1.2 $\underline{J_{0.2}}$

7.1.2.1 Construct a line corresponding to constant total crack growth of 0.2mm on a plot of the J-Δa data. The intersection of this line with the best fit curve through the data obtained in Section 6.3.1 defines $J_{0.2}$, Figure 15. At least one data point should be between 0.2 and 0.4 mm crack growth.

7.1.2.2 If $J_{0.2}$ exceeds J_{max} determined in Section 6.4, then $J_{0.2}$ is invalid according to this procedure.

7.2 <u>δ Fracture Parameters</u>

7.2.1 $\underline{\delta_{0.2/BL}}$

7.2.1.1 Construct a plot of the blunting line, Section 6.1.2, and the best fit curve, Section 6.3.1, through the δ-Δa data.

7.2.1.2 Construct a parallel line offset to the blunting line at 0.2mm crack growth, Figure 14. The intersection of the best fit curve with the offset line defines $\delta_{0.2/BL}$. At least one δ-Δa data point should be within 0.1 mm of the parallel offset line.

7.2.1.3 If $\delta_{0.2/BL}$ exceeds δ_{max} determined in Section 6.5, then $\delta_{0.2/BL}$ is invalid according to this procedure.

7.2.1.4 Evaluate the slope of the δ-Δa curve, $\left(\frac{d\delta}{da}\right)_{0.2/BL}$ at the intersection point from the equation determined in Section 6.3.1. If the slope of the blunting line

$$\left(\frac{d\delta}{da}\right)_{BL} < 2\left(\frac{d\delta}{da}\right)_{0.2/BL}$$

then $\delta_{0.2/BL}$ is invalid according to this procedure.

7.2.2 $\underline{\delta_{0.2}}$

7.2.2.1 Construct a line corresponding to constant total crack growth of 0.2 mm on a plot of the δ - Δa data. The intersection of this line with the best fit curve through the data given in Section6.3.1. defines $\delta_{0.2}$, Figure 15. At least one data point should be between 0.2 and 0.4 mm.

7.2.2.2 If $\delta_{0.2}$ exceeds δ_{max} determined in Section 6.5, then $\delta_{0.2}$ is invalid according to this procedure.

8. PRESENTATION OF RESULTS

When reporting the test results the following information should be presented:

8.1 MATERIAL - specification, yield strength, ultimate tensile strength and assumed value of Young's modulus at test temperature. These properties should be measured normal to the crack plane. If available, chemical composition and heat treatment.

8.2 SPECIMEN GEOMETRY - type, width, thickness, net thickness of side- grooved specimens and crack plane orientation from either a drawing or the notation given in Figures 16 to 18.

8.3 TEST DETAILS - maximum stress intensity factor and load during final stages of fatigue pre-cracking, temperature, single or multiple specimen method, load point displacement rate and machine control. Time at test temperature. Method of measuring initial crack length and crack growth. Measured initial crack length. If applicable, non-uniform and insufficient fatigue pre-crack growth. If non-uniform crack growth is exhibited the resulting data must be clearly identified in all subsequent use. Any unusual features on the fracture surfaces. If applicable, alternative method of defining a_i the estimated initial crack length.

8.4 RESULTS - record either the J-Δa or δ-Δa curve and all data points including details of the validity limits, exclusion lines, the constructional procedure and equations used to derive the fracture parameters $J_{0.2/BL}$, $J_{0.2}$, J_g, $\delta_{0.2/BL}$, $\delta_{0.2}$, δ_g and ω, whichever is applicable. If applicable, report and provide justification for the use of extended validity limits. If applicable, report the slope of the analytical blunting line.

8.5 Any departures from the recommendations of this procedure should be reported and justified. In such circumstances, the resulting data must be clearly identified in all subsequent use.

8.6 The results obtained from this procedure should be recorded on a report sheet and contain at least the information shown in Table 1.

9. BIBLIOGRAPHY

ASTM Standards, 1987, E1152-87, Standard Test Method for Determining J-R Curves, Annual Book of ASTM Standards, Section 3, Vol. 03 01, 1129-1145.

ASTM Standards, 1987, E813-87, "J_{IC}, a Measure of Fracture Toughness", Annual Book of ASTM Standards, Section 3, Vol. 03.01, 968-990.

British Standards, BS 5447, Methods of Test for Plane Strain Fracture Toughness (K_{IC}) of Metallic Materials.

British Standards, BS 5762, Methods of Test for Crack Opening Displacement (COD) Testing.

Gordon, J.R., 1985, WI Report 275/1985, The Welding Institute Procedure for the Determination of the Fracture Resistance of Fully Ductile Steels.

Hellmann, D. and Schwalbe, K.-H., 1986, On the Experimental Determination of CTOD Based R-curves, in The Crack Tip Opening Displacement in Elastic-Plastic Fracture Mechanics edited by K.-H. Schwalbe, Springer-Verlag, Berlin, Heidelberg.

Neale, B.K., Curry, D.A., Green, G., Haigh, J.R. and Akhurst, K.N., 1985, Int. J. of Pressure Vessels and Piping, A Procedure for the Determination of the Fracture Resistance of Ductile Steels, 20(3), 155-179.

TABLE 1

Data Report Sheet

Material	Condition
Specimen identification	Specimen type
Test method	Test temperature °C
Specimen width, W mm	Specimen thickness, B mm
Initial crack length, a_o mm	Crack growth, Δa mm
Fracture resistance, J MPam	CTOD, δ mm

NB If a single specimen method has been used, tabulate all the intermediate values of J, δ and Δa.

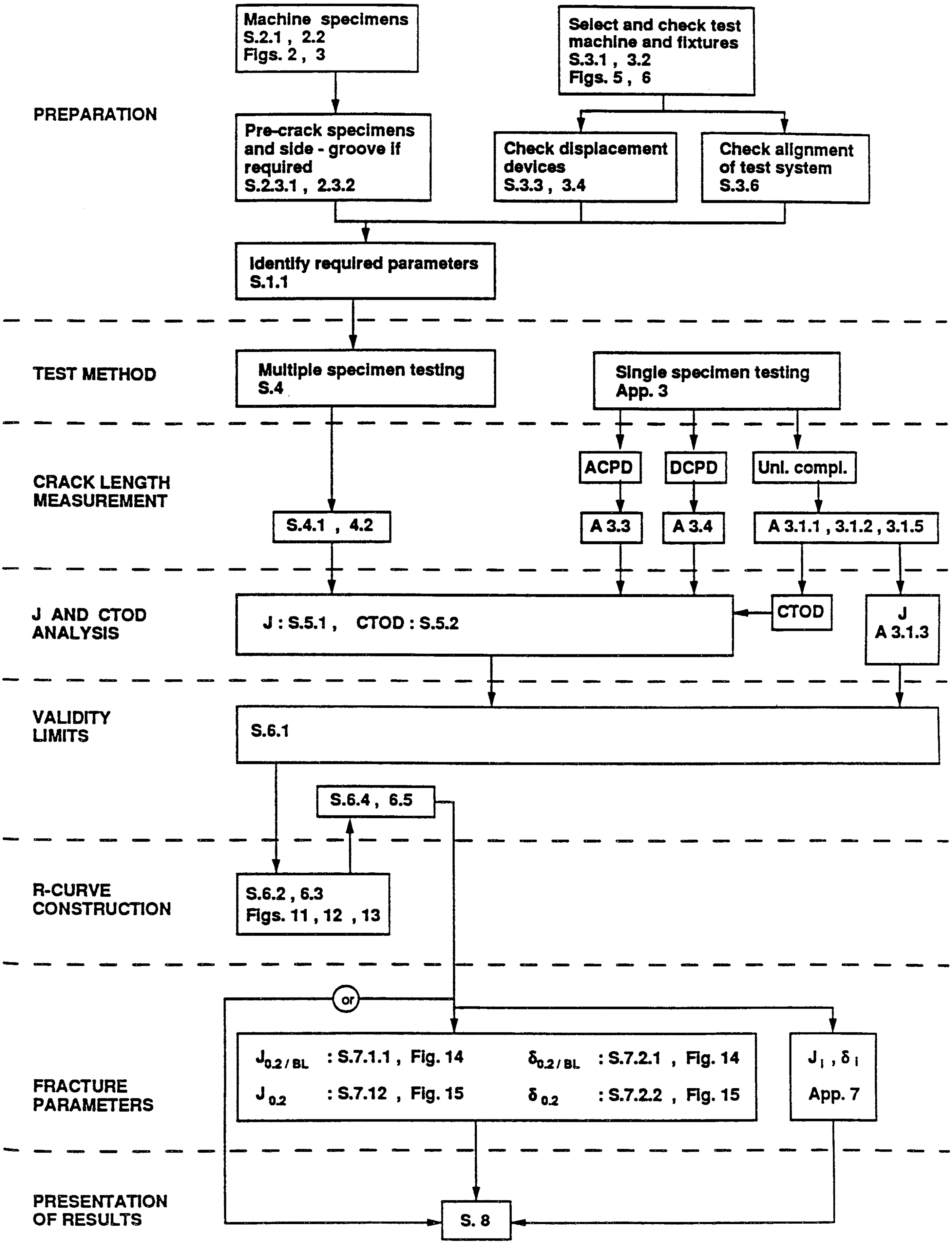
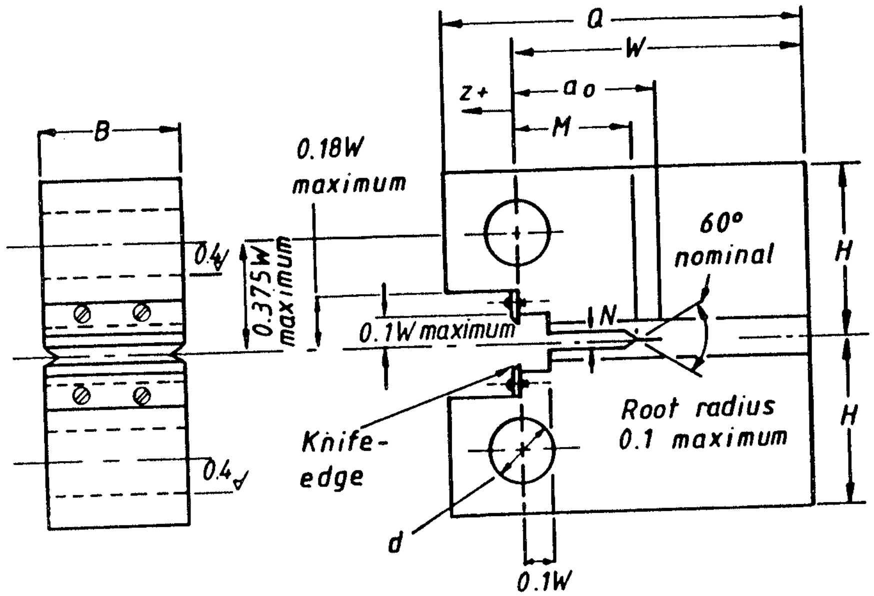


Fig.1 ESIS Procedure flow chart

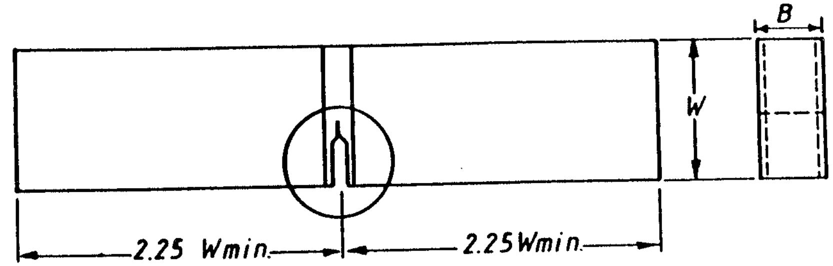


x√ is the surface finish to xμm

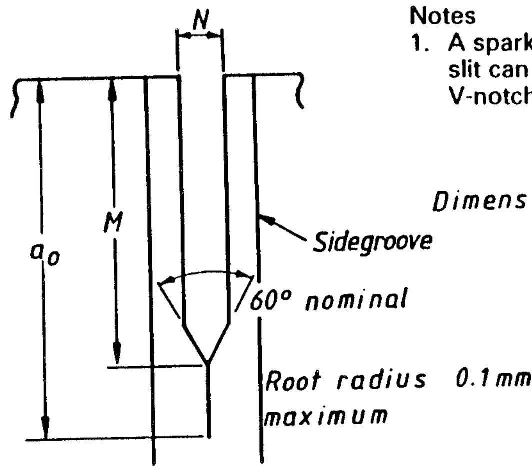
Net width W = 2B
Total width Q = 1.25W ± 0.01W
Thickness B
Half height H = 0.6W ± 0.005W
Hole diameter d = $0.25W \begin{smallmatrix} +0.004W \\ -0 \end{smallmatrix}$
Notch width N = 0.06W max. or 1.5mm max. if W ⩽ 25mm
Effective notch length M = 0.4W min.
Effective crack length a_0 = 0.5W to 0.65W

Notes 1. A spark eroded or machined slit can be used instead of the V-notch profile.
2. Spacing between knife-edges depends on type of clip gauge to be used.
Squareness and parallelism to be within 0.002W.
Holes to be square with faces and parallel.

Fig.2 Suggested compact specimen.



Notes
1. A spark eroded or machined slit can be used instead of V-notch profile.

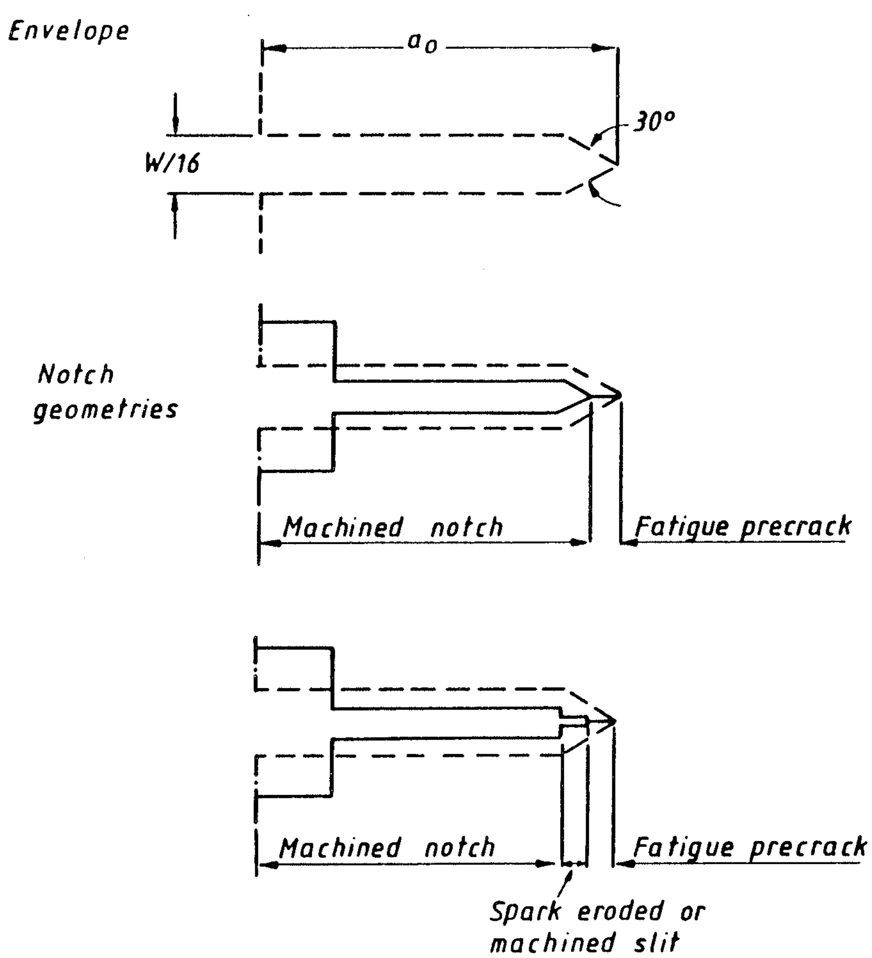


Dimensions in mm

Width = W = 2B
Thickness = B

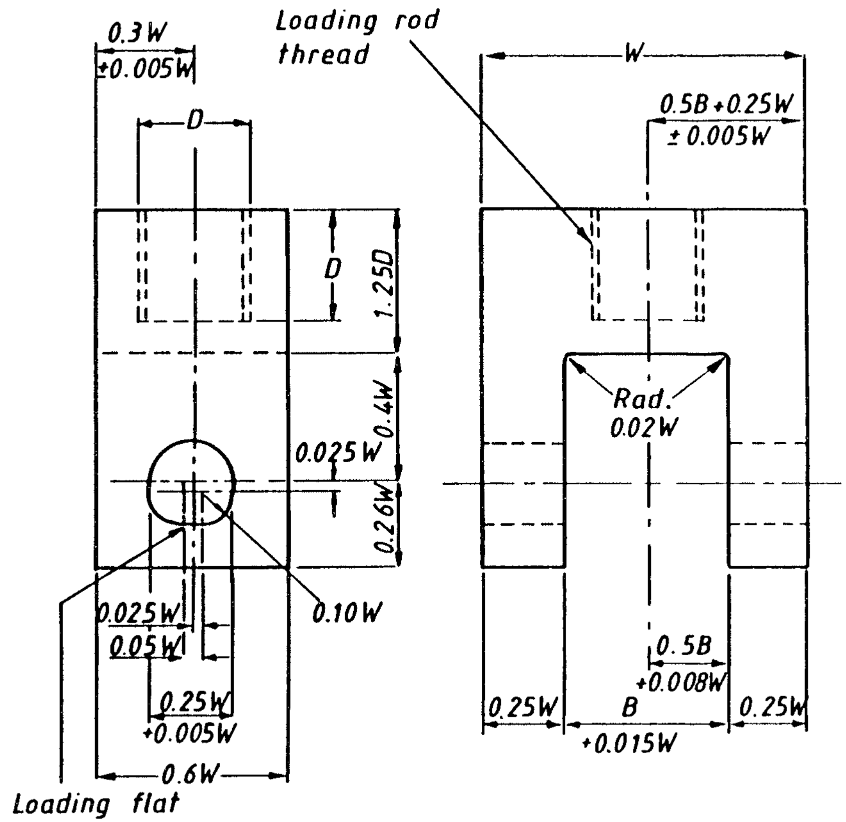
Notch width N = 0.06W max. or 1.5mm max. if W ⩽ 25mm
Effective notch length M = 0.4W min.
Effective crack length a_0 = 0.5W to 0.65W
Squareness and parallelism to be within 0.002W
Notch to be square with specimen faces and notch faces to be parallel

Fig.3 Single edge notch bend specimen.



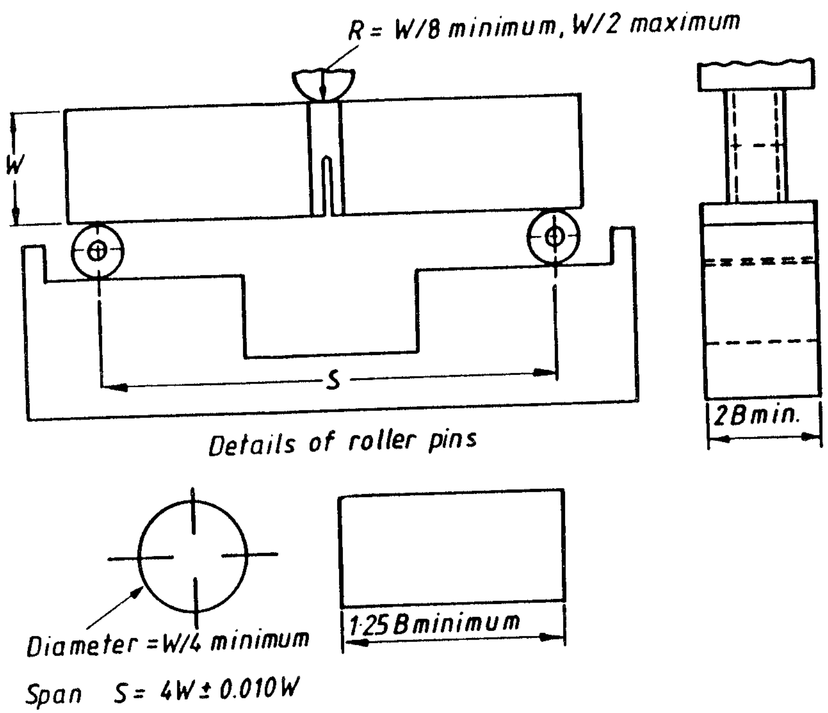
Notes
1. Machined notch width must not exceed 0.06W or 1.5mm if W ≤ 25mm.
2. The intersection of the notch surfaces with the two specimen sides shall be equidistant from the top and bottom of the specimen to within 0.005W.

Fig.4 Acceptable machined notch geometries.



Notes
1. Thickness B usually 0.5W, see Section 2.2.1.
2. Loading pin diameter — 0.24W (+0, −0.005W)
3. Surfaces must be flat, in-line and perpendicular as applicable, to within 0.002W.
4. Hardened steel or ceramic inserts in the clevis at the loading flats can be used to reduce indentation.
5. Fabricate pins and clevises from a high strength steel sufficient to resist plastic deformations in general use.
6. The loading pinhole diameter and the width of the loading flat may need increasing for austenitic steels.

Fig.5 Clevis for compact tension specimen testing.



Notes
1. Roller pins and specimen contact surface of loading ram must be parallel to within 1 degree.
2. Rollers must be free to move outwards.
3. Fabricate fixture from a high strength material sufficient to resist plastic deformations in general use.

Fig.6 Fixture for single edge notch bend specimen testing.

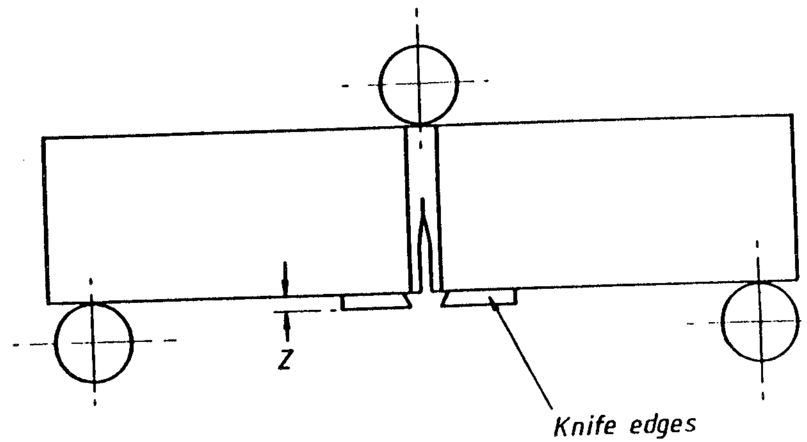


Fig.7 Position of knife edges for measuring mouth opening displacement in the bend specimen.

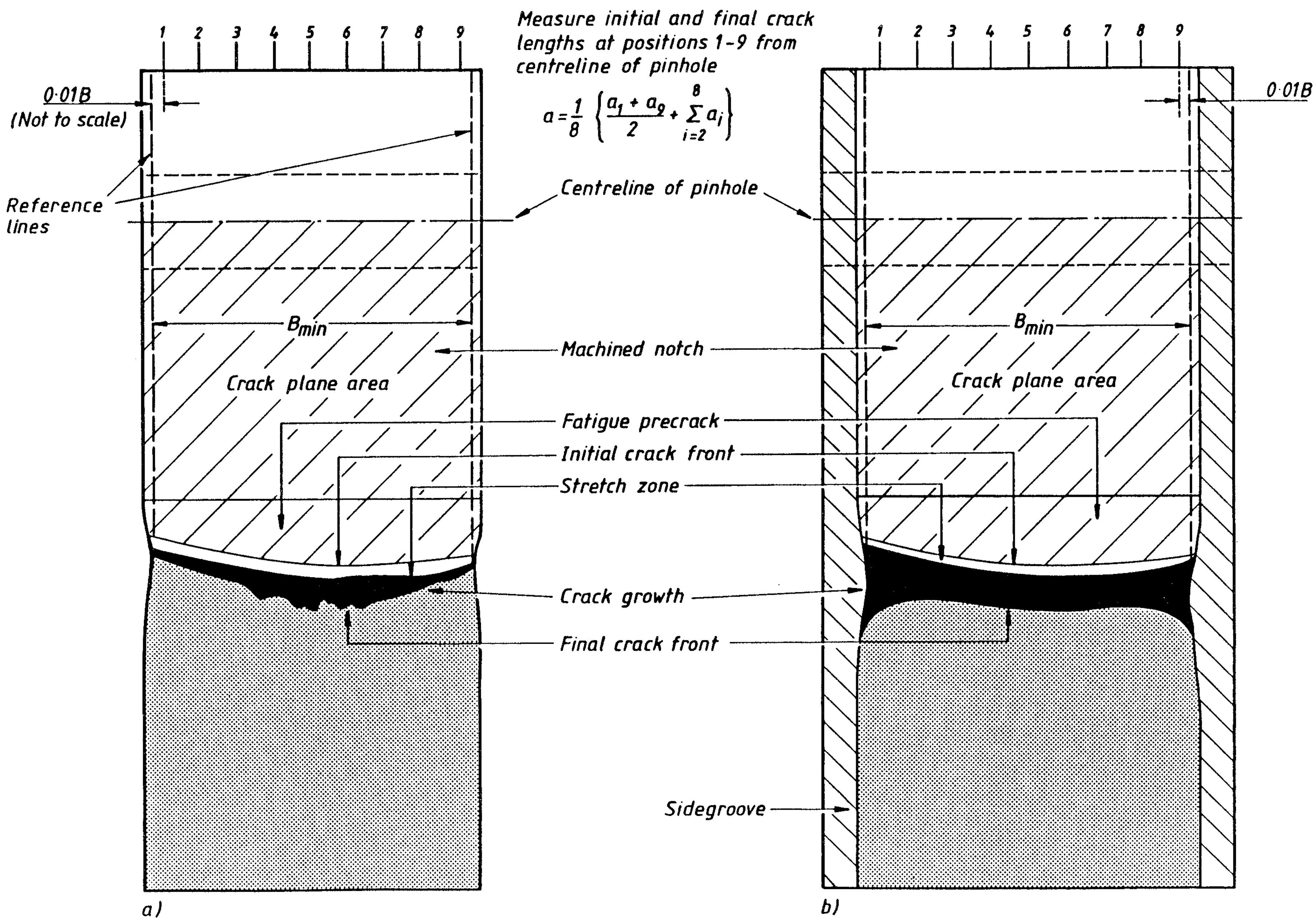


Fig.8 Measurement of crack lengths on compact specimens:

a) Plain sided specimens; b) Sidegrooved specimens.

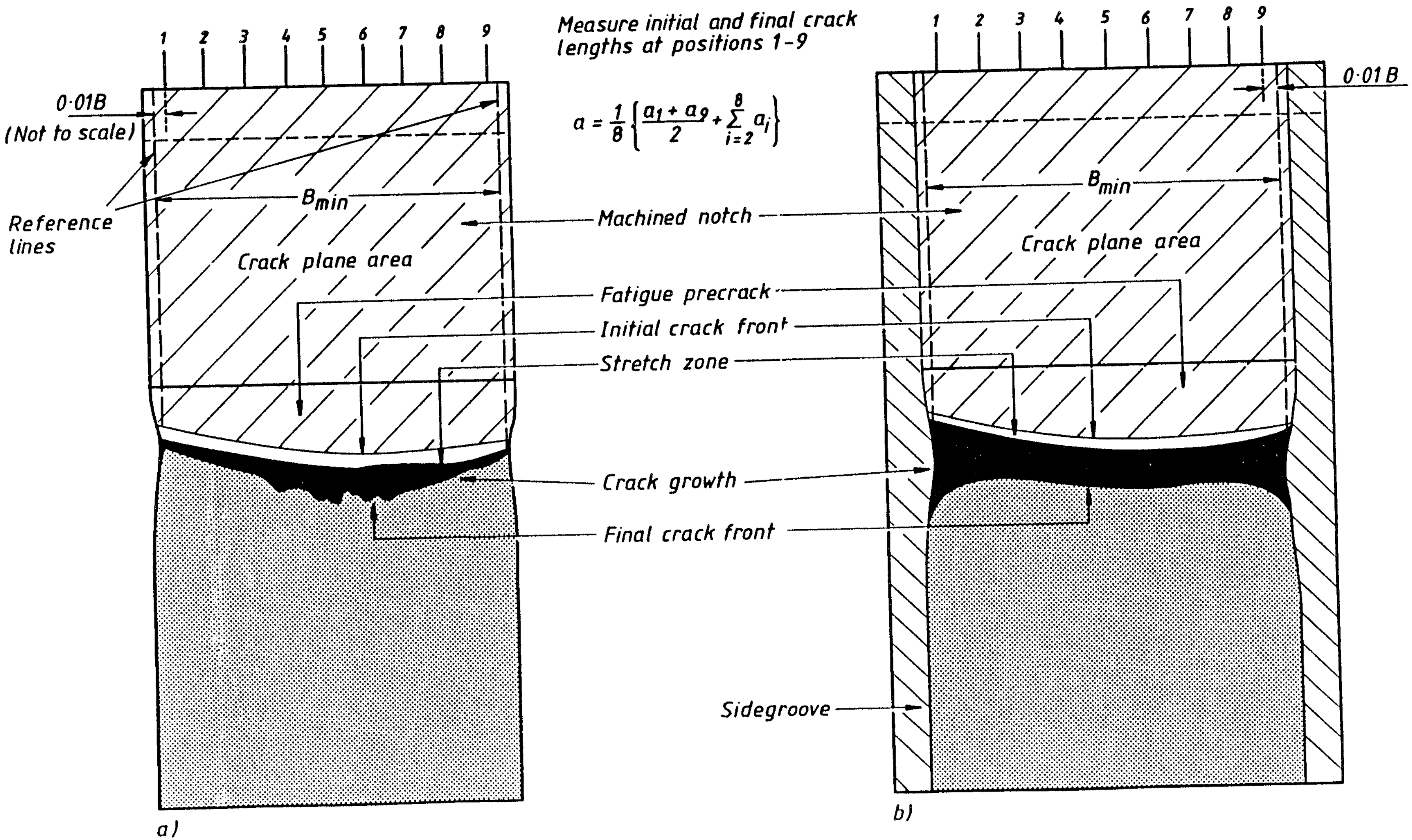


Fig.9 Measurement of crack lengths on single edge notch bend specimens:

a) *Plain sided specimens;* b) *Sidegrooved specimens.*

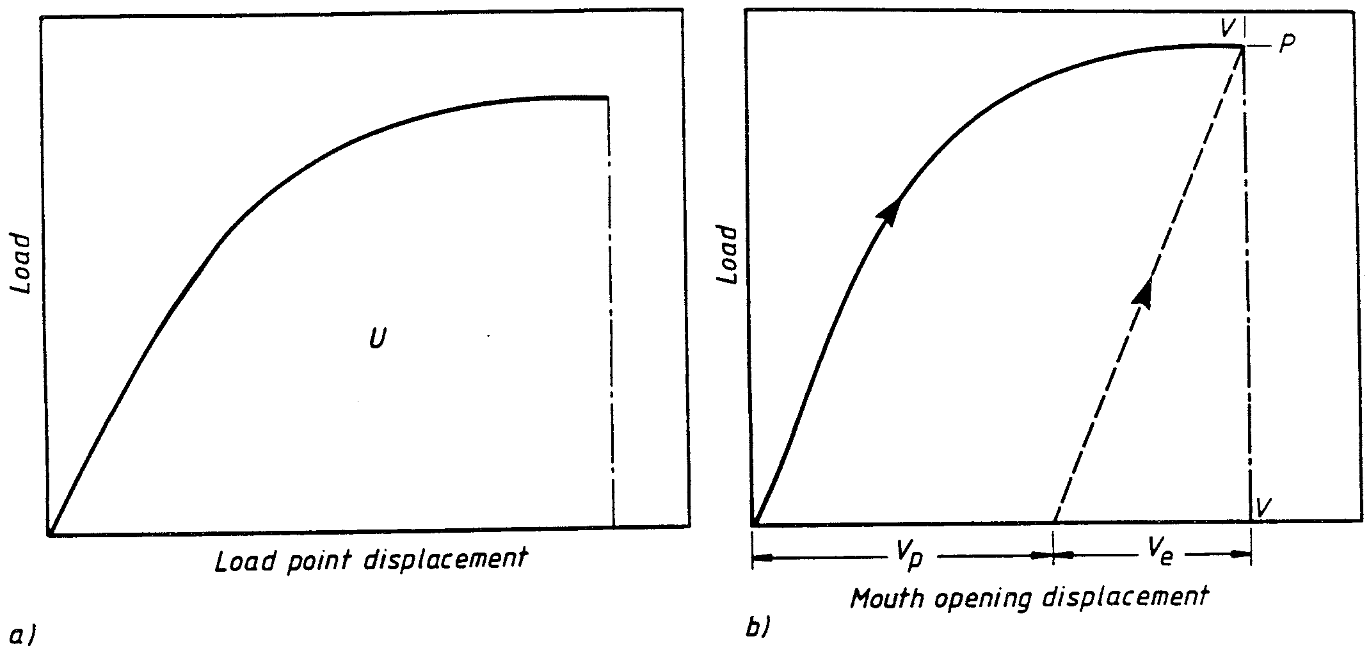


Fig.10

a) *Definition of absorbed energy U;* b) *Graphical determination of* V_p.

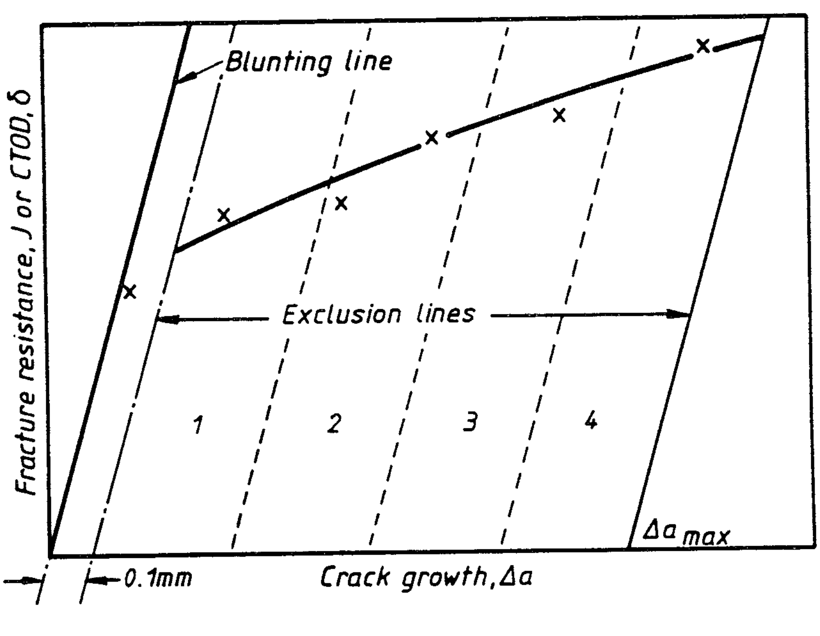


Fig.11 Data spacing and curve fit.

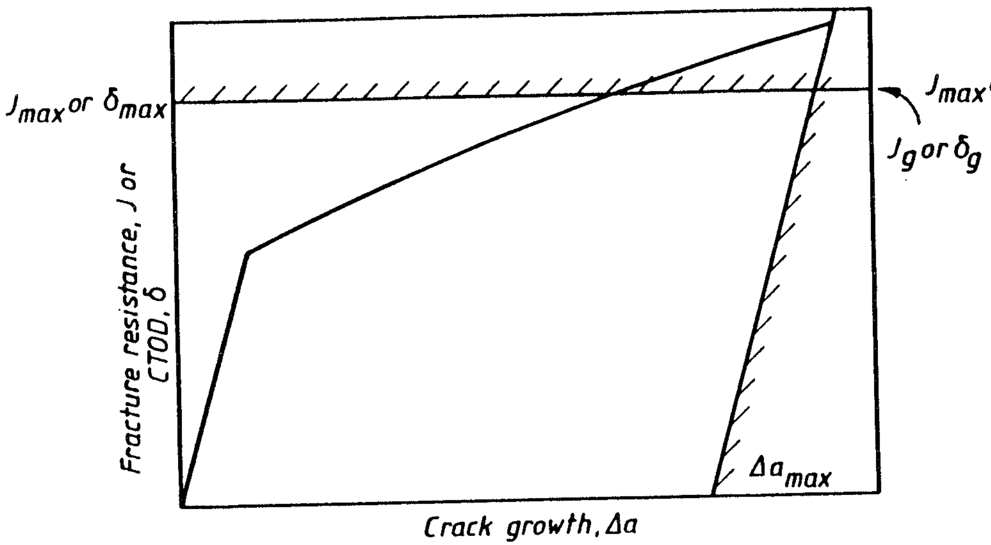


Fig.12 Validity limits.

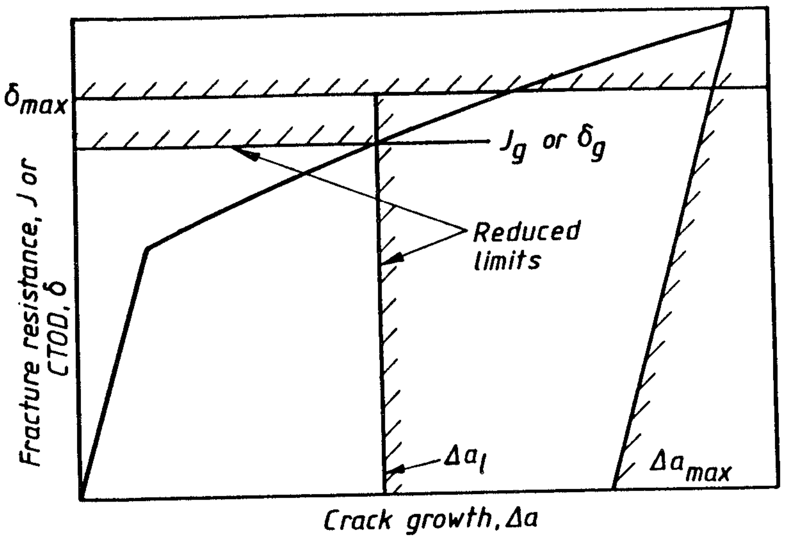


Fig.13 Reduced validity limits.

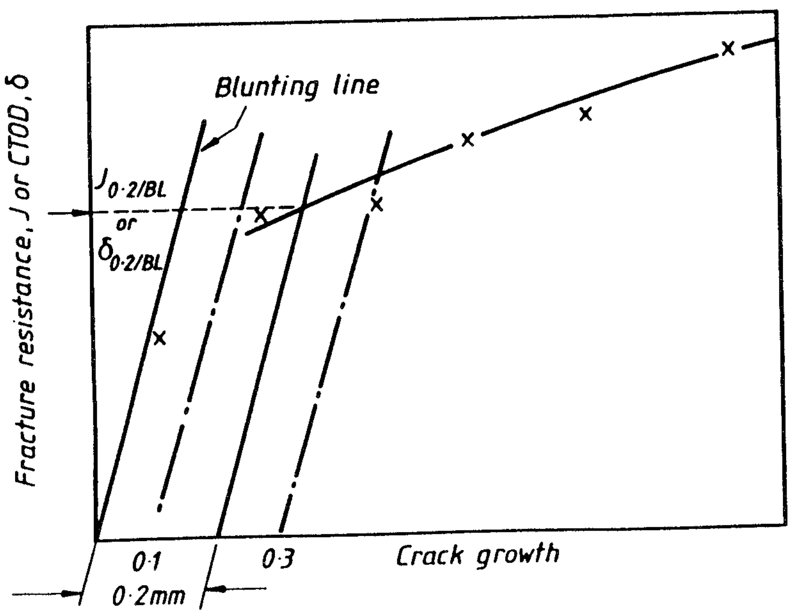


Fig.14 Derivation of $J_{0.2/BL}$ and $\delta_{0.2/BL}$.

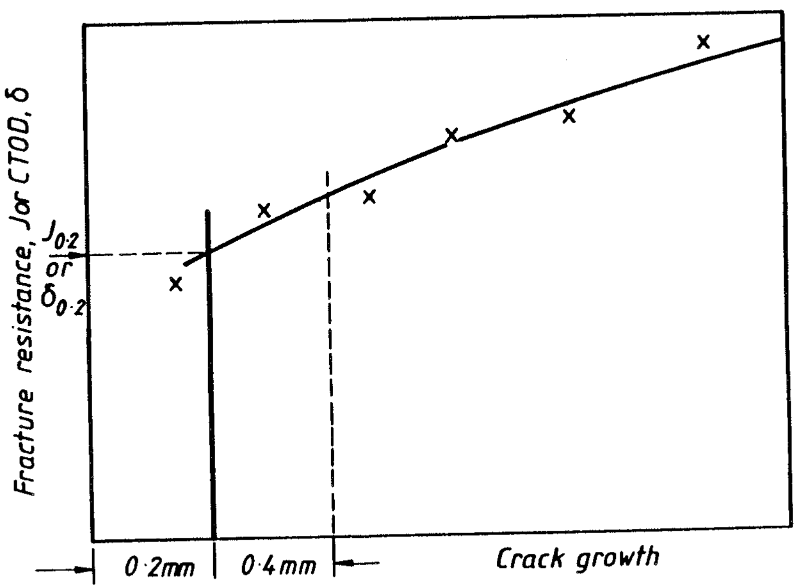
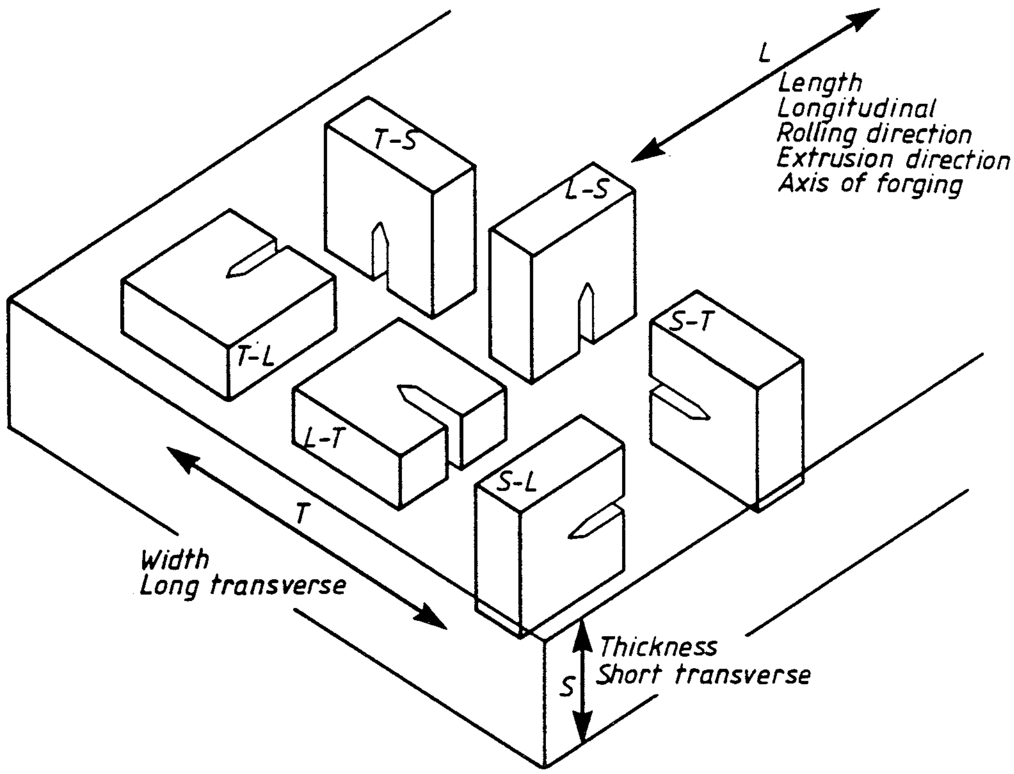


Fig.15 Derivation of $J_{0.2}$ and $\delta_{0.2}$.



Crack plane orientation is defined using a hyphenated letter code, XX-YY. XX is the direction normal to the crack plane. YY is the direction of crack growth.

Fig.16 Crack plane orientation code for rectangular sections.

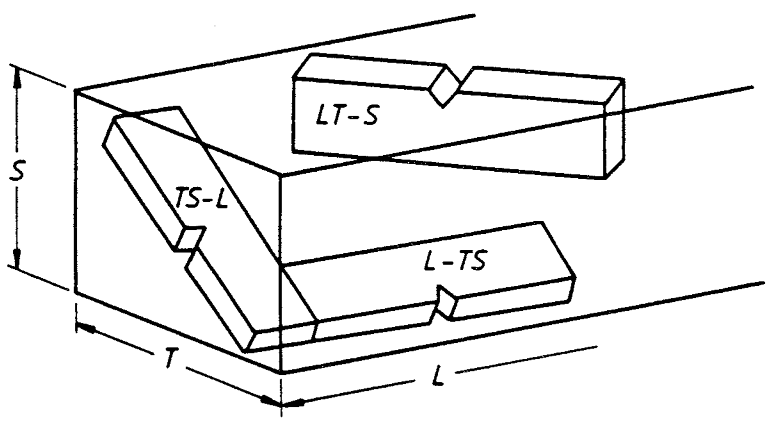


Fig.17 Crack plane orientation code for rectangular sections inclined with respect to the reference directions.

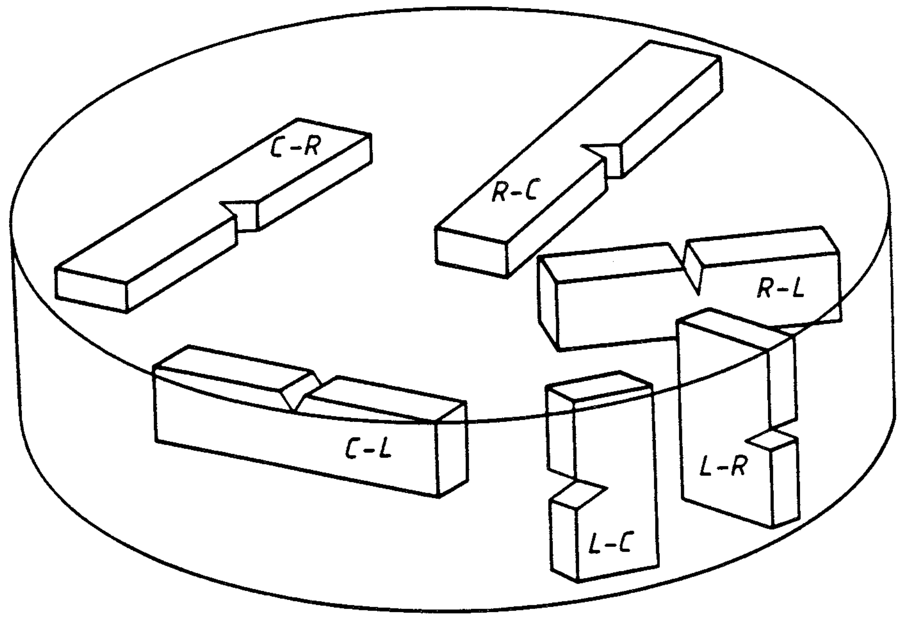


Fig. 18 Crack plane orientation code for bar and hollow cylinder.

APPENDIX 1

Stress Intensity Functions

A1.1 For a compact specimen

$$f(a/W) = \frac{(2+a/W)}{(1-a/W)^{3/2}}[0.886 + 4.64(a/W) - 13.32(a/W)^2 + 14.72(a/W)^3 - 5.6(a/W)^4]$$

A1.2 For a single edge notch bend specimen

$$f(a/W) = \frac{3(a/W)^{1/2}}{2(1+2(a/W))\ (1-a/W)^{3/2}}\ \frac{S}{W}\ \{1.99-a/W\ (1-a/W)\ [2.15 - 3.93(a/W) + 2.7(a/W)^2]\}$$

A1.3 Values of f(a/W) are given in Tables A1.1 and A1.2. For the bend specimen, S/W of 4 has been assumed.

REFERENCE

1. Annual Book of ASTM Standards, E399-83, Standard Test Method for Plane Strain Fracture Toughness of Metallic Materials, Section 3, Vol. 03.01, 1983, 518-553.

TABLE A1.1

Compact Specimen

a/W	f(a/W)	a/W	f(a/W)	a/W	f(a/W)
0.450	8.34	0.535	10.80	0.620	14.80
0.455	8.46	0.540	10.98	0.625	15.11
0.460	8.58	0.545	11.17	0.630	15.44
0.465	8.70	0.550	11.36	0.635	15.77
0.470	8.83	0.555	11.56	0.640	16.12
0.475	8.96	0.560	11.77	0.645	16.48
0.480	9.09	0.565	11.98	0.650	16.86
0.485	9.23	0.570	12.20	0.655	17.25
0.490	9.37	0.575	12.42	0.660	17.65
0.495	9.51	0.580	12.65	0.665	18.07
0.500	9.66	0.585	12.89	0.670	18.52
0.505	9.81	0.590	13.14	0.675	18.97
0.510	9.96	0.595	13.39	0.680	19.44
0.515	10.12	0.600	13.65	0.685	19.94
0.520	10.29	0.605	13.93	0.690	20.45
0.525	10.45	0.610	14.21	0.695	20.99
0.530	10.63	0.615	14.50	0.700	21.55

TABLE A1.2

Bend Specimen

a/W	f(a/W)	a/W	f(a/W)	a/W	f(a/W)
0.450	9.14	0.535	11.94	0.620	16.32
0.455	9.28	0.540	12.15	0.625	16.66
0.460	9.42	0.545	12.35	0.630	17.00
0.465	9.56	0.550	12.57	0.635	17.36
0.470	9.70	0.555	12.79	0.640	17.73
0.475	9.85	0.560	13.02	0.645	18.12
0.480	10.01	0.565	13.25	0.650	18.51
0.485	10.16	0.570	13.49	0.655	18.92
0.490	10.32	0.575	13.74	0.660	19.35
0.495	10.48	0.580	13.99	0.665	19.79
0.500	10.65	0.585	14.25	0.670	20.25
0.505	10.82	0.590	14.52	0.675	20.72
0.510	11.00	0.595	14.80	0.680	21.22
0.515	11.18	0.600	15.09	0.685	21.73
0.520	11.36	0.605	15.38	0.690	22.27
0.525	11.55	0.610	15.69	0.695	22.82
0.530	11.74	0.615	16.00	0.700	23.40

NB For bend specimens, S/W = 4.

APPENDIX 2

Measurement of Load Point Displacement

A2.1 The method of calculating J requires the measurement of the area under the load versus load point displacement record. Unlike the modified compact specimen geometry shown in Figure 2 of the procedure the single edge notch bend specimen does not permit direct measurement of the load point displacement. Consequently the extraneous displacements arising from indentation effects and elastic displacements in the fixture and test machine must be determined and subtracted from the measured displacement. A suitable method of measuring extraneous displacement is described in reference 1.

Alternatively the load point displacement can be measured directly on a single edge notch bend specimen by attaching a comparator bar to the side of the specimen (2,3) or employing a double clip gauge arrangement (4).

If the displacement is measured on the front face of a compact specimen, a suitable relationship to infer load point displacement is given in reference 5.

REFERENCES

1. Buzzard, R.J. and Fisher, D.M., 1978, J. of Testing and Evaluation, Load displacement measurement and work determination in three point bend tests of notched or precracked specimens, 6(1), 35-39.

2. Dawes, M.G., 1977, ASTM STP 668, Elastic-plastic fracture toughness based on the COD and J-contour integral concepts, 307-333.

3. Hellmann, D., Rohwerder, G. and Schwalbe, K.-H., 1984, J. of Testing and Evaluation, Development of a test set up for measuring deflection of single edge notched bend (SENB) specimens, 12(1), 62-64.

4. Willoughby, A.A., 1981, WI Report 153/1981, On the unloading compliance method of deriving single specimen R-curves in three-point bending, The Welding Institute, Cambridge.

5. Saxena, A. and Hudak, S.J. Jnr., 1978, Int. J. of Fracture, Review and extension of compliance information for common crack growth specimens, 14(5), 453-468.

APPENDIX 3

Single Specimen Methods

Any single specimen test method may be used provided sufficient accuracy can be demonstrated.

Methods are described in this Appendix for measuring crack growth in a specimen based on the unloading compliance and potential drop techniques.

In the unloading compliance technique, a specimen is partially unloaded and then reloaded at specified intervals during the test. The unloading slopes, which tend to be linear and independent of prior plastic deformation, are used to estimate the crack length at each unloading from analytical elastic compliance relationships.

The potential drop technique relies on the fact that the potential distribution in the vicinity of a crack changes with crack growth. With suitable instrumentation, the changes in potential can be detected and calibrated to provide an estimate of increase in the crack length. The applied potential is either direct or alternating and is referred to as either the D.C. or A.C. potential drop technique, respectively.

Both techniques are ideally suited to computer control and subsequent analysis of the test data. However, it should be noted that they require careful experimentation and sophisticated test equipment in order to realise their full potential. The tests should be controlled using either the transducer monitoring mouth opening or load point displacement.

There is a fundamental difference between multiple and single specimen test methods. The multiple specimen method gives only an average of the crack growth resistance behaviour and of the initiation parameters. The single specimen method gives individual results which can provide information on material inhomogeneity.

For the first crack growth fracture resistance curve measured in a series of tests using the single specimen methods, at least three specimens are needed. Two of these are required to demonstrate the accuracy of the test equipment at small and intermediate amounts of crack growth. One test should be terminated between 0.1 and 0.3 mm of ductile crack growth, Fig A3.1. The other should be terminated midway between the valid crack growth range, Δa_{max}, Fig A3.1. Suitable termination points can be estimated from data for the specimen covering the Δa_{max} range. If the difference between the estimated and measured crack growth exceeds 15 percent of the measured crack growth or 0.15 mm, whichever is the greater, then the test is invalid and the single specimen technique may require improvement.

In order to characterise the fracture behaviour of a material, all single specimen data must also satisfy the data spacing requirements, Section 6.2, and the appropriate validity limits, Sections 6.4 and 6.5.

The data points from valid tests used to demonstrate the accuracy of the test equipment should be combined to generate a single crack growth fracture resistance curve.

A3.1 Unloading Compliance Technique

Several test procedures have been written for the unloading compliance technique (1-4). None of these has become universally accepted although the ASTM procedures (3,4) are probably the most widely used. The method described here include many aspects of the ASTM procedures. Alternative methods are allowed but any departures from the methodology described here must be given when reporting the results as required in Section 8 of this procedure.

In the unloading compliance test, the elastic compliance C_k is determined at each unloading/reloading event performed during the test from

$$C_k = \left(\frac{\Delta Q}{\Delta F}\right)_k$$

where Q is the appropriate displacement or strain.

The crack length a_k at each unloading is determined from the measured compliance C_k using theoretical or experimental correlations in the form

$$(a/W)_k = f(C_k)$$

Data recording and evaluation of the partial unloadings may be accomplished with a computer or autographically with an x-y recorder.

A3.1.1 Test Requirements

The test requirements given in Section 3 of this procedure must be adhered to in conjunction with the following additional points.

A3.1.1.1 Specimens

Prepare sidegrooved specimens to the specification given in Section 2 of the procedure.

A3.1.1.2 Test Fixtures

For compact specimen testing, the clevis must have a flat bottomed hole, Figure 5. Hardened steel inserts between the loading pin and clevis may help in minimising plastic indentation (5). Steel inserts can also be used between the single edge notch bend specimen and the outer rollers (6). Care must be taken to retain the inserts in place during a test in order to avoid accidents.

A3.1.1.3 Compliance Measurement

Unloading compliance is determined from either mouth opening or load point displacements, Section 3.3.1. If the displacement is measured at an alternative point, then the appropriate compliance function must be evaluated. For bend specimens, compliance can be measured from the load point displacement transducer used to determine J. However, it is recommended that an additional transducer should be used located at the mouth of the crack as for crack opening displacement.

Errors may occur in the compliance measurements as a result of tranducer non-linearity. Significant improvement in accuracy is possible by curve fitting the lowest order polynomial function as possible through the calibration data (7). The maximum deviation of an individual data point to the curve fit should be within ±0.2 percent of the calibrated range.

A3.1.1.4 Digital Signal Resolution

For an unloading compliance measurement, the digitised displacement resolution Δq should be better than

$$\Delta q = \frac{W' R_{p0.2}}{500E}$$

where W′ is the minimum of 50 mm or the specimen width.

The corresponding digital load resolution ΔP should be better than

$$\Delta F = \frac{BW' R_{p0.2}}{15,000}$$

For the duration of a test, stability of the digitised load and displacement signals should be less than $\pm 4\Delta F$ or $\pm 4\Delta q$, whichever is appropriate. The maximum signal noise should be less than $\pm 2\Delta F$ or $\pm 2\Delta q$, whichever is appropriate.

A 16 bit A-D converter will meet the requirements for most applications. It is permissible to amplify the load and displacement signals to attain a satisfactory level for digitisation.

A3.1.1.5 Autographic Signal Resolution

When unloading compliance measurements are derived directly from x-y plots, the pen displacement should be greater than 100mm in both axes. Pen stability should be within ±3mm throughout the duration of the test.

A3.1.2 Procedure

A3.1.2.1 Pre-cycling

Before commencing the test it is recommended that the specimen be cycled several times in the elastic regime at test temperature to allow the specimen to bed-in. During this operation the maximum applied load must not exceed the final fatigue load.

A3.1.2.2 Loading Rate

The loading rate during unload/reload cycles should be as fast as possible to minimise time dependent effects but slow enough to ensure that sufficient data is recorded to enable the compliance of the specimen to be estimated accurately. If possible the loading rate during the unload/reload cycles should not be less than that employed between the unloadings. It is recommended that prior to each unloading the displacement should be held constant until load relaxation caused by time dependent plasticity effects is observed to cease.

A3.1.2.3 Initial Crack Length Measurement

At least three unloading compliance measurements should be made at a load less than the maximum allowable final fatigue load defined in Section 2.3.1.3 of the procedure. No value of the estimated crack length shall differ from the mean by more than ±0.1 mm. The maximum range of the unload/reload cycles should not exceed 50 percent of the actual maximum load used to measure the three initial unloadings.

Non-linear paths of the load displacement record that may occur at low loads from crack closure effects should be excluded from the compliance measurement.

A3.1.2.4 Crack Length Measurements

Partially unload and reload the specimens at intervals during the test. The unloadings should be performed at displacement intervals selected to ensure evenly spaced data points are obtained. Typically 30 unloadings are sufficient to define the crack growth fracture resistance behaviour and meet the data spacing requirement given in Section 6.2. It is recommended that the unloading range should be as small as practicable but not exceed 30 percent of the current load value. To improve the accuracy at lower loads it is permissible to exceed this limit. However, in such cases non-linear parts of the load displacement record that may occur at low loads from crack closure effects should be excluded from the compliance measurement.

At each unloading evaluate the crack length a and J or δ, as appropriate, using the formulae given in Sections A.3.1.5, A3.1.3 and A3.1.4 of the procedure, respectively. The compliance of the specimen C is obtained by dividing the change in crack mouth opening or load point displacement by the corresponding change in load. In the case of computerised test systems, the compliance is generally determined by performing a regression analysis of the recorded data.

A3.1.2.5 <u>Termination of Test</u>

After the final unloading reduce the load to zero ensuring no further increase in displacement. Mark the extent of ductile crack growth as described in Section 4.1.3 of the procedure.

Break open the specimen at or below room temperature to reveal the fracture surfaces. Measure the initial crack length a_o and the total crack growth using the procedure described in Section 4.2.

A3.1.3 <u>Fracture Resistance J</u>

A3.1.3.1 Calculate $J_{o,k}$ at the k th data point on the load displacement record using the relationship

$$J_{o,k} = \frac{\eta\ U_k}{B_n(W-a_o)}$$

where η = 2 + 0.522 (1 - a_o/W) for compact specimens
= 2 for single edge notch bend specimens

and U_k is the area under the load displacement record up to the line of constant displacement at the k th data point.

A3.1.3.2 <u>Fracture Resistance J Allowing for Crack Growth</u>

The J equation used in Section 3.1.3.1 does not allow for crack growth during a test. The errors in J are usually negligible for crack growth less than 0.10(W-a_o). If the crack growth validity limit is extended beyond 0.10(W-a_o) then all data points should be corrected for crack growth. A suitable approximation is given in Section 5.1.2.

A3.1.4 <u>Crack Tip Opening Displacement δ</u>

A3.1.4.1 Calculate $\delta_{o,k}$ at the k th data point on the load displacement record using the relationship

$$\delta_{o,k} = \frac{K^2(1-\nu^2)}{2ER_{p0.2}} + \frac{0.4(W-a_o)}{(0.4W + 0.6a_o + z)} V_{p,k}$$

$$\text{where} \qquad K = \frac{F_k}{\sqrt{(B\,B_n W)}} f(a_o/W)$$

F_k is the load at the k th data point and $V_{p,k}$ is the corresponding plastic component of the mouth opening displacement defined in Figure 10b. $f(a_o/W)$ is the stress intensity function defined in Appendix 1.

A3.1.4.2 Crack Tip Opening Displacement δ Allowing for Crack Growth

The δ equation used in Section A3.1.4.1 does not allow for crack growth during a test. The errors in δ are small for crack growth less than $0.25(W-a_o)$. If the crack growth validity limit is extended beyond $0.25(W-a_o)$, then all data points should be corrected for crack growth. A suitable approximation is given in Section 5.2.2.

A3.1.4.3 In cases where the slope of the elastic loading line is not clearly defined an analytical method for determining $V_{p,k}$ is given in Appendix 4.

A3.1.5 Crack Length Calculation

A3.1.5.1 Compact Specimens

The crack length corresponding to a specimen compliance C determined from the load line displacement is given by

$$a/W = 1.000196 - 4.06319\mu + 11.242\mu^2 - 106.043\mu^3 + 464.335\mu^4 - 650.677\mu^5$$

$$\text{where} \qquad \mu = \frac{1}{[B_{eff}E_M C]^{1/2} + 1}$$

$$B_{eff} = B - (B-B_n)^2/B$$

and E_M, the effective Young's Modulus, is determined from

$$E_M = \frac{1}{C_o B_{eff}} \left(\frac{W+a_o}{W-a_o}\right)^2 [2.163 + 12.219 \left(\frac{a_o}{W}\right) - 20.065\left(\frac{a_o}{W}\right)^2$$

$$- 0.9925\left(\frac{a_o}{W}\right)^3 + 20.609\left(\frac{a_o}{W}\right)^4 - 9.9314\left(\frac{a_o}{W}\right)^5]$$

C_o is the average compliance determined from the unloadings performed in the elastic regime, Section A3.1.2.3.

The effective modulus E_M fits the above equation to the crack length a_o measured in Section A3.1.2.5. The effective modulus E_M is then used to calculate all crack lengths for the specimen under consideration. Should E deviate from a known value of Young's modulus, by more than 10 percent then the test is not valid.

A3.1.5.2 Rotation Correction for Compact Specimens

To account for the change in specimen geometry that occurs from loading, the measured load line compliance should be corrected for rotation according to

$$C_c = \frac{C}{[(\frac{h}{r}\sin\theta - \cos\theta)(\frac{D}{r}\sin\theta - \cos\theta)]}$$

where

C	=	measured compliance
C_c	=	compliance corrected for rotation
h	=	one half of the initial distance between the centres of the loading pin holes, Figure 2.
r	=	radius of rotation given by $r = \frac{W+a}{2}$ where a is the current crack length
D	=	one-half of the initial distance between the displacement measurement points.
θ	=	angle of rotation given by

$$\theta = \arcsin [(\frac{q}{2} + D)/(D^2+r^2)^{1/2}] - \arctan(\frac{D}{r})$$

q	=	total measured load line displacement

A3.1.5.3 SENB Specimens with Crack Mouth Opening Displacement Measured at Specimen Surface

The crack length corresponding to a specimen compliance C determined from mouth opening displacement measured at the surface is given by

$$a/W = 0.999748 - 3.9504\mu + 2.9821\mu^2 - 3.21408\mu^3 + 51.51564\mu^4 - 113.031\mu^5$$

$$\text{where} \quad \mu = \frac{1}{[(\frac{4W}{S}) B_{eff} E_M C]^{1/2} + 1}$$

$$B_{eff} = B - (B - B_n)^2/B$$

and E_M, the effective Young's Modulus, is determined from:

$$E_M = \frac{6S}{B_{eff} W C_o} (\frac{a_o}{W}) \; [0.76 - 2.28(\frac{a_o}{W}) + 3.87(\frac{a_o}{W})^2 - 2.04\;(\frac{a_o}{W})^3 + \frac{0.66}{(1 - a_o/W)^2}\;]$$

C_o is the average compliance determined from the unloadings performed in the elastic regime, Section A3.1.2.3.

The effective modulus E_M fits the above equation to the crack length a_o measured in Section A3.1.2.5. The effective modulus E_M is then used to calculate all crack lengths for the specimen under consideration. Should E_M deviate from a known value of Young's Modulus by more than 10 percent then the test is invalid.

A3.1.5.4 SENB Specimens with Compliance Based on Load Point Displacement

The crack length corresponding to a specimen compliance C determined from load point displacement for S/W of 4 is given by

$$a/W = 0.07204 + 1.25147 \times 10^{-2}\mu - 1.10295 \times 10^{-4}\mu^2 + 5.28088 \times 10^{-7}\mu^3 - 1.26563 \times 10^{-9}\mu^4 + 1.18958 \times 10^{-12}\mu^5$$

$$\text{where} \quad \mu = E_m B_{eff} C$$

$$B_{eff} = B - (B - B_n)^2 / B$$

and E_M, the effective Young's Modulus is, determined from

$$E_M = \frac{1}{B_{eff} C_o} [[0.24 (\frac{S}{W})^3 (1.04 + 3.28 \ (1+\nu)(W/S)^2)]$$

$$+ 2(1-\nu^2) \ (\frac{a_o}{W}) \ (\frac{S}{W})^2 \ [4.21 (\frac{a_o}{W}) - 8.89 (\frac{a_o}{W})^2 + 36.9 (\frac{a_o}{W})^3$$

$$- 83.6 (\frac{a_o}{W})^4 + 174.3 (\frac{a_o}{W})^5 - 284.6 (\frac{a_o}{W})^6 + 387.6 (\frac{a_o}{W})^7$$

$$- 322.8 (\frac{a_o}{W})^8 + 149.8 (\frac{a_o}{W})^9]]$$

C_o is the average compliance determined from the unloadings performed in the elastic regime, Section A3.1.2.3.

The effective modulus E_M fits the above equation to the crack length a_o measured in Section A3.1.2.5. The effective modulus E_M is then used to calculate all crack lengths for the specimen under consideration. Should E_M deviate from a known value of Young's Modulus by more than 10 percent then the test is not valid.

A3.1.5.5 Rotation Correction for SENB Specimens

The measured compliance should be corrected to allow for specimen rotation and changes in the test fixture which occur during a test. No explicit formula is given here because of the lack of an agreed approach although a relationship has been developed for mouth opening displacement (8).

A3.1.6 Crack Growth Fracture Resistance

Ideal crack growth fracture resistance behaviour is characterised by monotonically increasing crack growth, Figure A3.2. However, the unloading compliance often does not give this idealised behaviour. Discrepancies may include positive or negative offset from the original estimate of initial crack length, scatter in the data and apparent negative crack growth. These effects are made worse by problems in the testing fixture, transducer gauge seating, electronic noise and signal non-linearity.

A3.1.6.1 Construction of Resistance Curves

Plot graphs of either J or δ against the predicted crack length.

A3.1.6.2 Estimated Initial Crack Length

In order to determine the crack growth fracture resistance behaviour, it is necessary to define the estimated initial crack length a_i. However, since the unloading compliance technique frequently produces anomalous data no standard method for defining a_i has yet emerged. The three most common methods are:

(i) Defining a_i as the average crack length obtained from the elastic unloading compliance measured in Section A3.1.2.2.

(ii) Defining a_i as the minimum crack length obtained in the test.

(iii) Defining a_i in such a way that the early stages of the crack growth behaviour follow the apparent blunting line equations

$$J = NR_f \Delta a \qquad or \qquad \delta = N\Delta a$$

where $1.0 \leq N \leq 6$.

Alternative methods of defining a_i can be used provided details of the method are reported and justified in Section 8 of the procedure.

It should be noted that the above methods of defining a_i frequently yield similar estimates. However for crack growth fracture resistance behaviour which exhibit apparent negative crack growth, the estimates can be significantly different.

A3.1.6.3 Estimated Crack Growth

Calculate the estimated crack growth Δa_k at the kth unloading from

$$\Delta a_k = a_k - a_i$$

A3.1.6.4 Crack Growth Resistance Curves

Construct plots of J or δ against estimated crack growth Δa_k.

A3.1.6.5 At least 5 data points should remain within 0.2 mm of a_i in order to adequately describe the initial portion of the crack growth fracture resistance curve.

A3.2 Potential Drop Techniques

A3.2.1 AC Potential Drop Method

(i) A typical AC potential drop test system is shown in Figure A3.3. In this system the potential drop measured in the test specimen is compared against that produced by a reference specimen of identical geometry. The method described can only be used if a potential minimum is observed, Figure A3.4.

(ii) Load the test specimen as described in Section 4 of the procedure and obtain test records of both load and potential against either load point or mouth opening displacement. The general form of the test records is illustrated in Figure A3.4.

(iii) On completion of the test mark the extent of ductile crack growth as described in Section 4.1.2 of the procedure.

(iv) Measure the initial crack length a_0 and the total crack growth Δa as described in Section 4.2 of the procedure.

(v) Determine the critical stretch zone width Δa_{SZW} using the measurement technique described in Appendix 7 of the procedure.

A3.2.1.1 Interpretation of Test Records

(i) Identify the potential minimum (ϕ_{min}) on the potential displacement record.

(ii) Measure the potential difference ($\Delta\phi_{end}$) between (ϕ_{min}) and the potential at the end of the test (ϕ_{end}).

(iii) Construct a graph of total crack growth against potential difference as shown in Figure A3.5.

(iv) Plot the points Δa_{SZW}, $\Delta\phi = 0$ and $\Delta a, \Delta\phi_{end}$ and draw a straight line between them, Figure A3.5. This represents the calibration line for the specimen.

(v) To determine the amount of total crack growth corresponding to the point P_x on the load displacement record measure the potential difference between ϕ_{min} and ϕ_x as indicated in Figure A3.4. The amount of total crack growth corresponding to $\Delta\phi_x$ is estimated from the calibrated line similar to that shown in Figure A3.5.

(vi) Determine J or δ for the load P_x using the equations given in Section A3.1.3. or A3.1.4, respectively. Construct plots of either J or δ against estimated crack growth.

A3.2.2 DC Potential Drop Methods

Two DC potential drop methods are described in this section.

A3.2.2.1 Method 1

(i) A typical DC potential drop system (11) for Method 1 is shown in Figure A3.6.

(ii) Load the test specimen as described in Section 4 of the procedure and obtain test records of both load and potential against either load point or mouth opening displacement. The general form of the test records is illustrated in Figure A3.7.

(iii) On completion of the test mark the extent of stable crack growth before breaking the specimen open.

(iv) Measure the initial crack length a_o and the total crack growth Δa as described in Section 4.2 of the procedure.

(v) Determine the critical stretch zone width Δa_{SZW} using the measurement technique described in Appendix 7 of the procedure.

A.3.2.2.1.1 Interpretation of Test Records

(i) The abrupt change in slope of the potential displacement record is used as an estimate of the initiation of ductile tearing.

(ii) Measure the potential difference ($\Delta\phi_{end}$) between estimated initiation of ductile tearing and the potential at the end of the test.

(iii) Construct a graph of total crack growth against potential difference as shown in Figure A3.5.

(iv) Plot the points Δa_{SZW}, $\Delta\phi = 0$ and $\Delta a, \Delta\phi_{end}$ and draw a straight line between them, Figure A3.5. This straight line represents the calibration line for the specimen.

(v) To determine the amount of total crack growth corresponding to a point P_x on the load displacement record measure the potential difference between ϕ_{min} and ϕ_x as indicated in Figure A3.7. The amount of total crack growth corresponding to $\Delta\phi_x$ can be estimated from the calibrated line similar to that shown in Figure A3.5.

(vi) Determine J or δ for the load P_x using the equations given in Section A3.1.3 or A3.1.4, respectively. Construct plots of either J or δ against estimated crack growth.

A3.2.2.2 Method 2

(i) A typical DC potential drop test system for method 2 is shown in Figure A3.8.

(ii) Load the specimen as described in Section 4 of the procedure and obtain records of load against displacement and potential.

The general form of the load potential test record is illustrated in Figure A3.9.

(iii) On completion of the test mark the extent of stable crack growth before breaking the specimen open.

(iv) Measure the initial crack length a_o and the total crack growth Δa as described in Section 4.2 of the procedure.

A3.2.2.2.1 Interpretation of Test Records

(i) Construct a straight line through the steeply rising part of the load potential record as shown in Figure A3.9.

(ii) For any load of interest measure ϕ_o and $\Delta\phi$ as shown in Figure A3.9 and evaluate

$$\phi = \phi_o + \Delta\phi$$

(iii) The crack length corresponding to the selected load can be calculated using the following expression

$$a = \frac{2W}{\pi} \cos^{-1} \left\{ \frac{\cosh(\pi y/2W)}{\cosh[(\phi/\phi_o)\cosh^{-1}(\cosh(\pi y/2W)/\cos(\pi a_o/2W))]} \right\}$$

where y is defined in Figure A3.8.

(iv) The corresponding crack growth Δa is given by

$$\Delta a = a - a_o$$

(v) Determine J or δ for the load of interest using the equations given in Section A3.1.3 or A3.1.4, respectively. Construct plots of either J or δ against estimated crack growth Δa.

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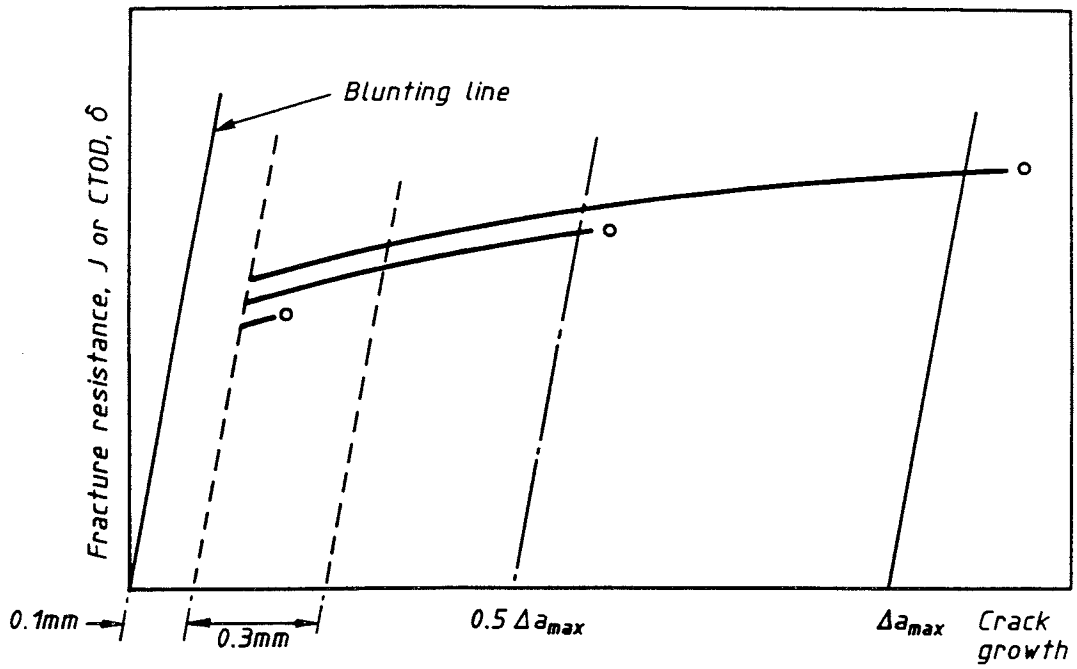

Fig.A3.1 Single specimen crack growth termination requirement.

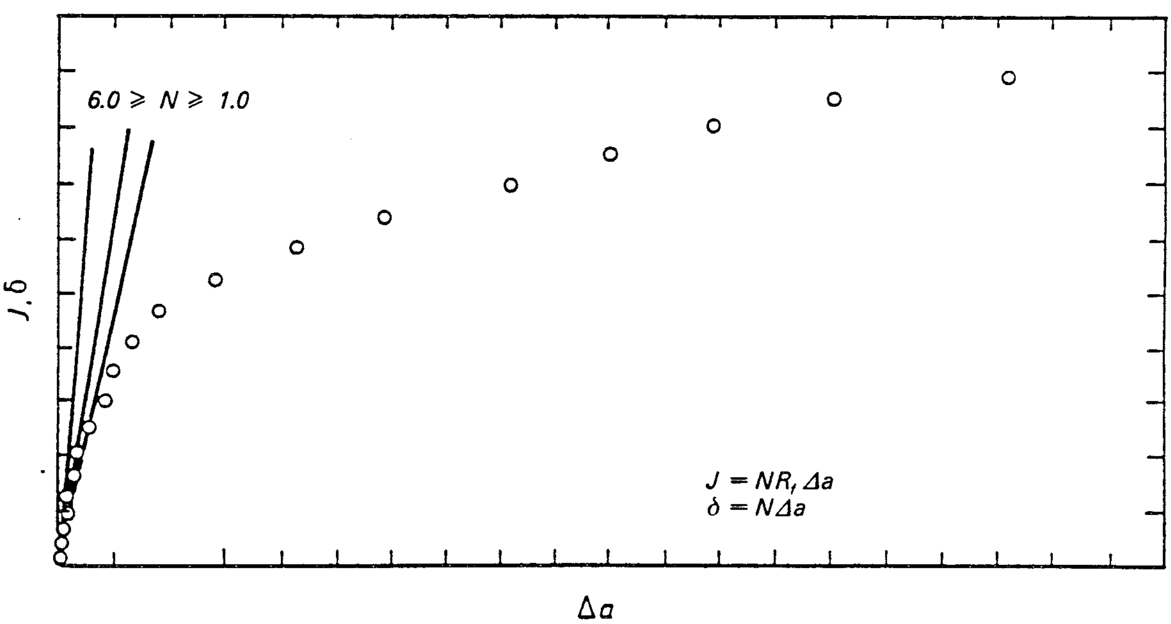

Fig.A3.2 Ideal behaviour of crack growth fracture resistance curve.

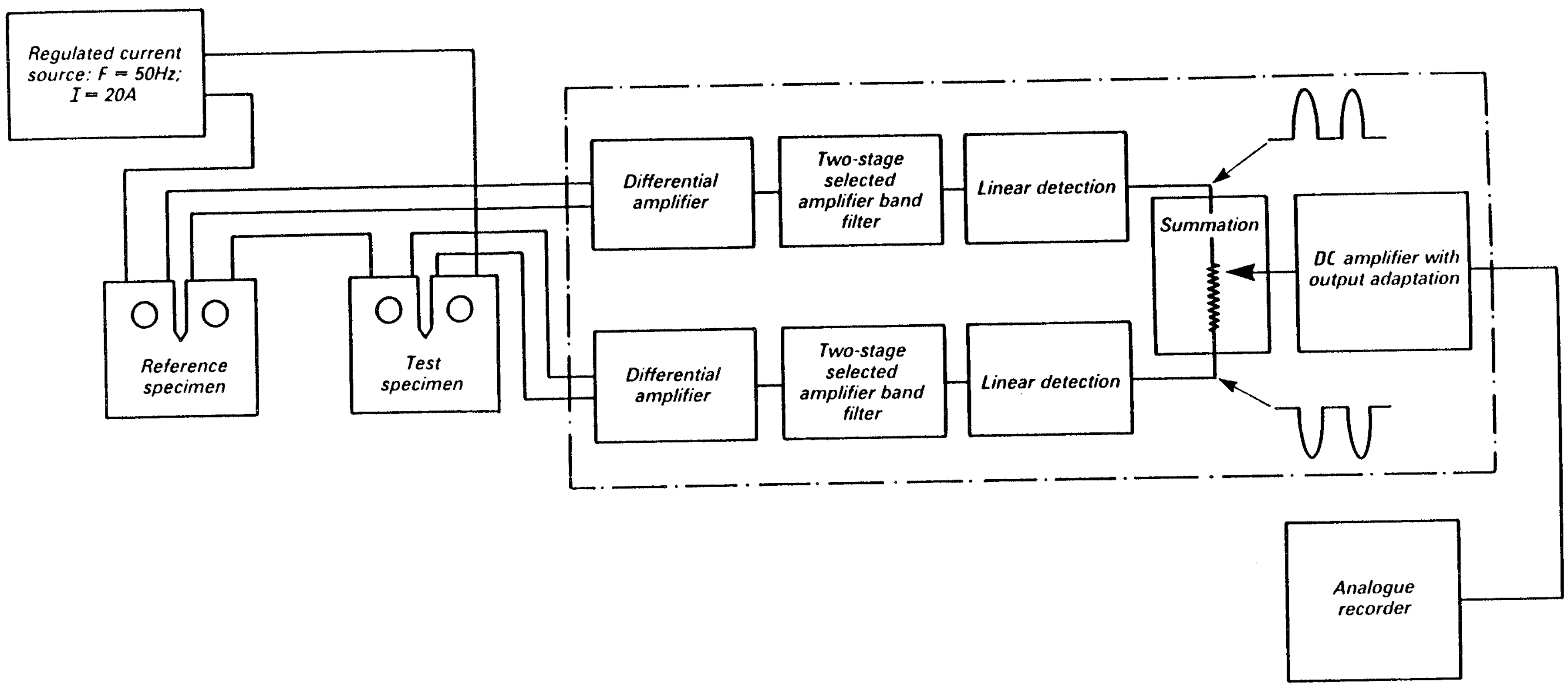

Fig.A3.3 Typical AC potential drop test system.

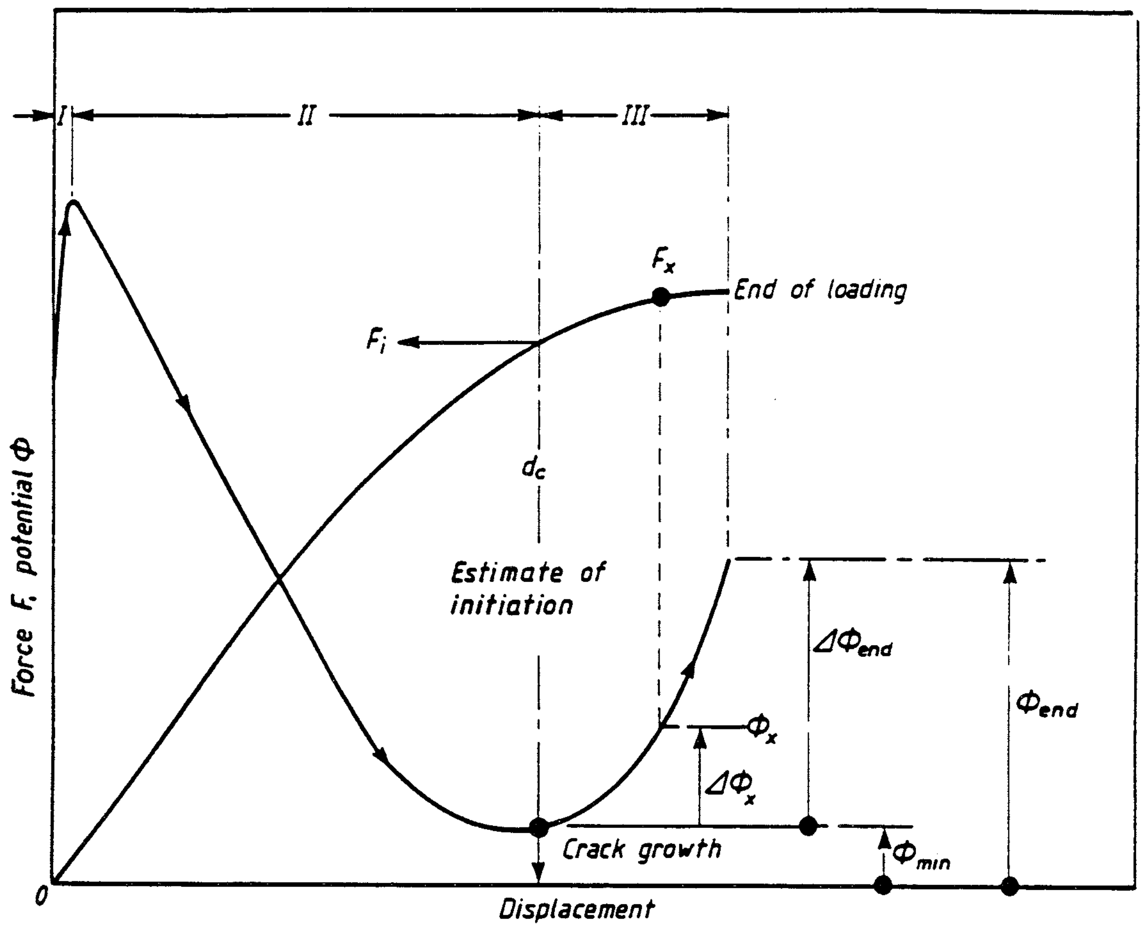

Fig.A3.4 Typical AC potential drop test record.

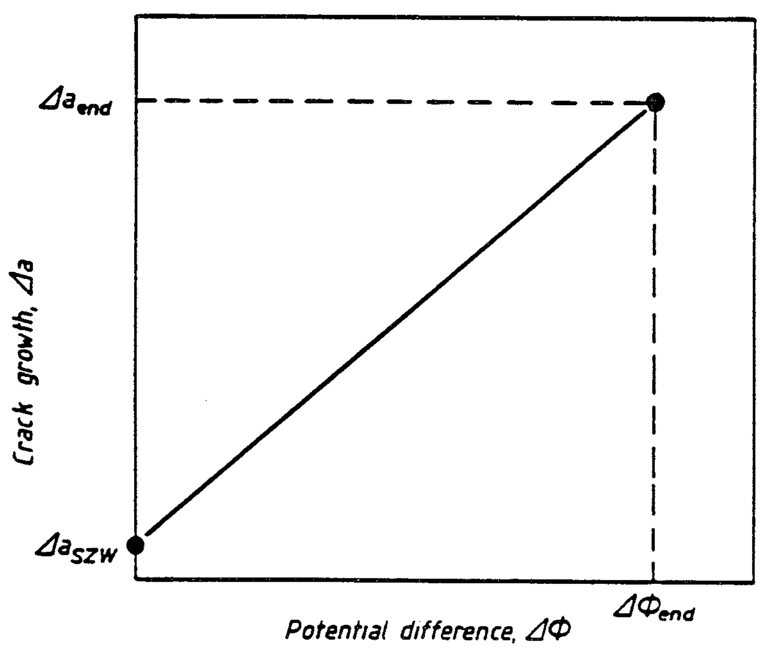

Fig.A3.5 Plot of crack growth against potential difference.

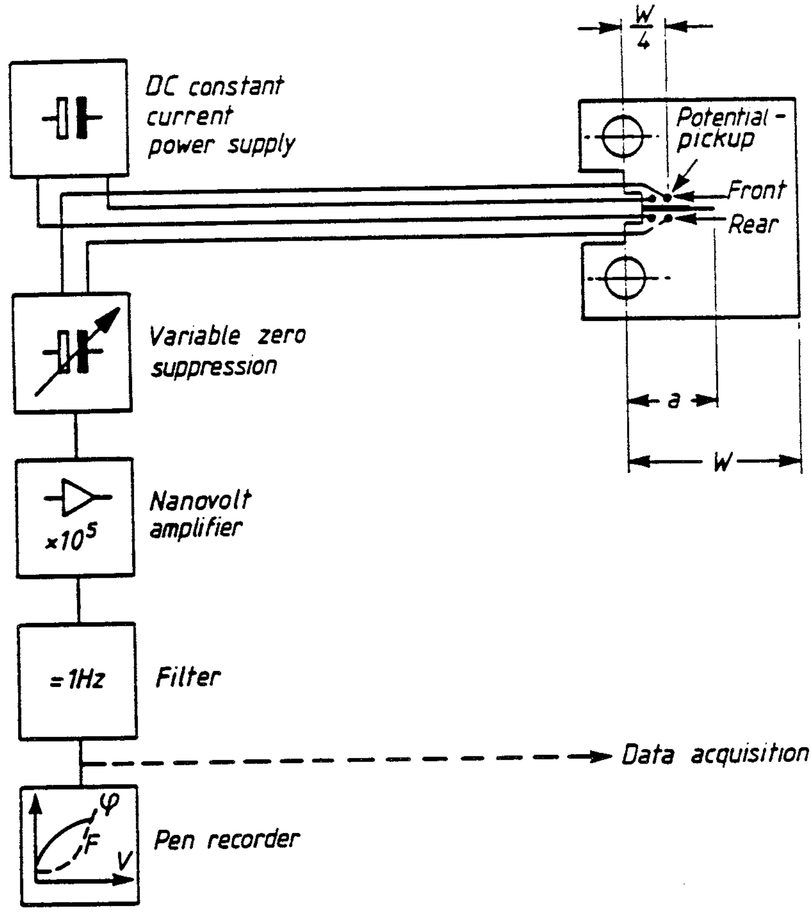

Fig.A3.6 Typical DC potential drop test system.

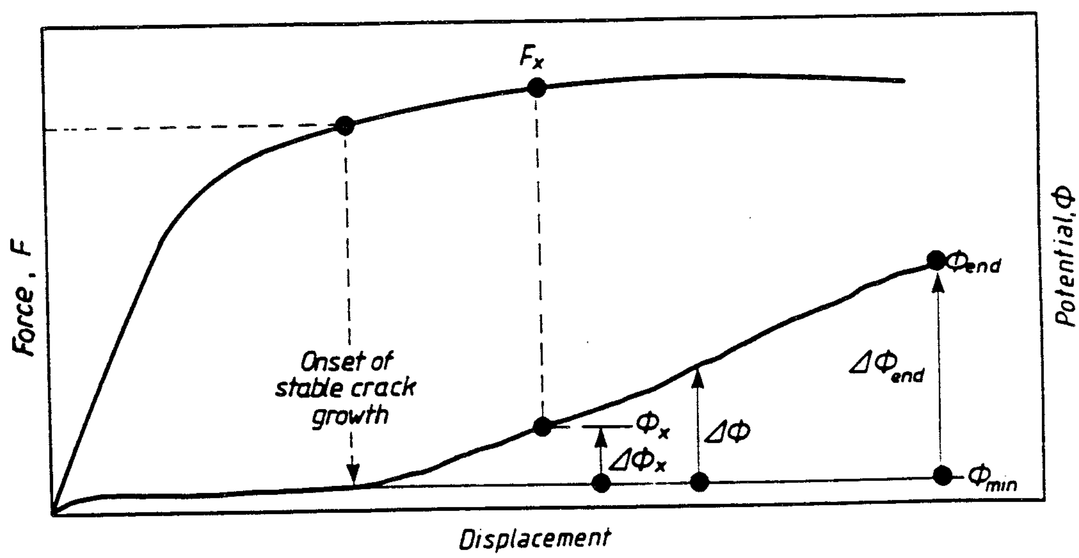

Fig.A3.7 Typical DC potential drop test record for system shown in Fig.A3.6.

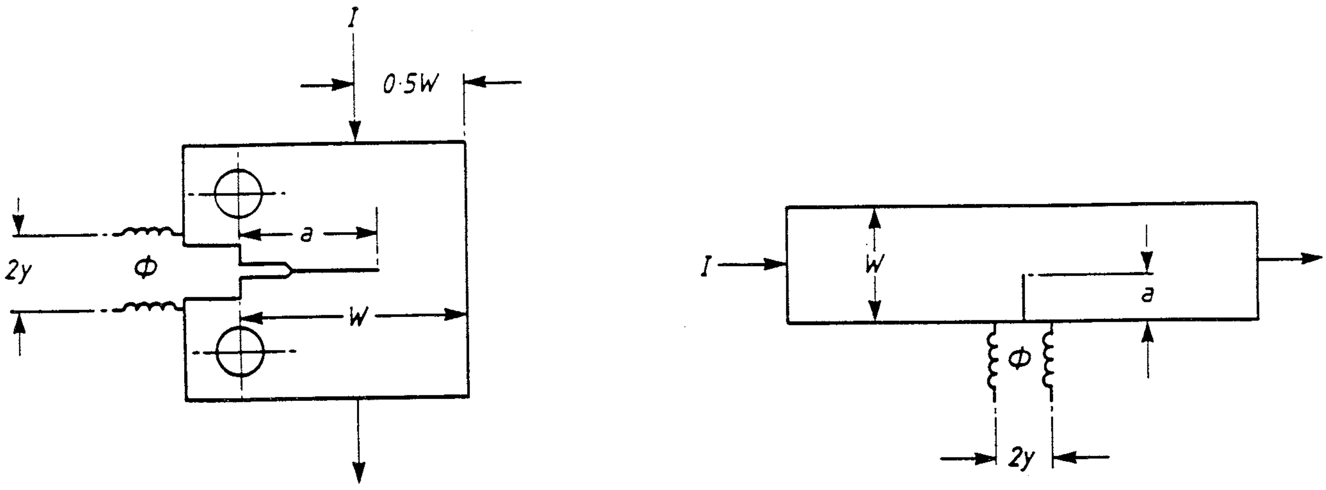

Fig.A3.8 Alternative DC potential drop test system.

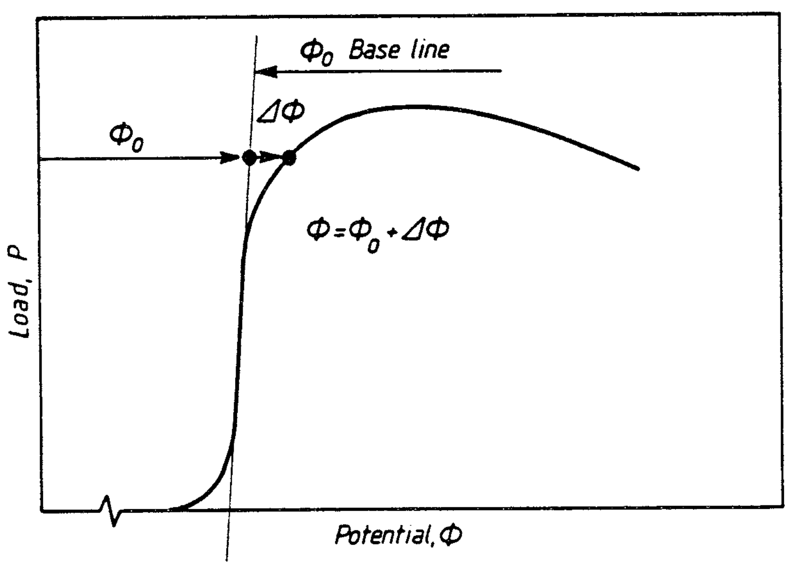

Fig.A3.9 Typical DC potential drop test record for system shown in Fig.A3.8.

APPENDIX 4

Analytical Method for Determining the Plastic Component of Mouth Opening Displacement, V_p

A4.1 The equation used in Section 5.2.1 to calculate the crack tip opening displacement δ_0 is given by

$$\delta_o = \frac{K^2(1-\nu^2)}{2ER_{p0.2}} + \frac{0.4(W-a_o)}{0.4W + 0.6a_o + z} V_p$$

The first term represents the elastic component of δ_0 and is evaluated from the stress intensity factor. The second term represents the plastic component of δ_0 and is evaluated from the plastic component of the mouth opening displacement, V_p, shown in Figure 10b. The method for determining V_p involves measuring the slope of load versus mouth opening displacement record in the elastic regime so that the elastic component of the displacement at termination of the test may be subtracted from the total displacement, V.

A4.2 When the slope of the load displacement record in the elastic regime cannot be easily defined substantial errors can result in the estimate of V_p. In those situations an analytical method can be used to estimate V_e providing surface mouth opening displacement in a bend specimen or load-line displacement in a compact specimen has been measured.

A4.3 For the compact specimen

$$V_e = \frac{F}{BE}\left[\frac{(1+a_o/W)}{(1-a_o/W)}\right]^2 \left[2.163 + 12.219\left(\frac{a_o}{W}\right) - 20.065\left(\frac{a_o}{W}\right)^2 - 0.9925\left(\frac{a_o}{W}\right)^3 + 20.609\left(\frac{a_o}{W}\right)^4 - 9.9314\left(\frac{a_o}{W}\right)^5\right]$$

For the single edge notch bend specimen

$$V_e = \frac{24F(1-\nu^2)}{BE}\left(\frac{a_o}{W}\right)\left[0.76-2.28\left(\frac{a_o}{W}\right)+3.87\left(\frac{a_o}{W}\right)^2 -2.04\left(\frac{a_o}{W}\right)^3+\frac{0.66}{\left(1-\frac{a_o}{W}\right)^2}\right]$$

For side-grooved specimens replace B by

$$B - \frac{(B-B_n)^2}{B}$$

A4.4 The plastic component of mouth opening displacement V_p is given by

$$V_p = V - V_e$$

where V is the total displacement.

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APPENDIX 5

Determination of a Blunting Line from Tensile Properties

The blunting line describes the initial behaviour of the fatigue pre-crack in a fracture specimen under monotonically increasing loads prior to ductile crack growth. The true stress-strain curve of the material is represented by the power law

$$\frac{\epsilon}{\epsilon_o} = \left(\frac{\sigma}{\sigma_o}\right)^{1/n} \qquad \textit{for } \sigma \geq \sigma_o$$

where σ_0 is the reference stress, ϵ_0 is the reference strain equivalent to σ_0/E, n is the strain hardening exponent and E is Young's modulus.

The slope of the blunting line is determined from

$$\Delta a_B = 0.4\, d_n^* \frac{J}{E}$$

where the proportionality constant d_n^* is a function of n and σ_0/E used to describe the stress-strain curve. A method is given in this Appendix for estimating d_n^* assuming plane strain conditions prevail.

A5.1 Measure the stress-strain behaviour of the material at the same temperature as the fracture tests and determine Young's modulus E, yield strength $R_{p0.2}$ and ultimate tensile strength R_m. The longitudinal dimension of the tensile specimen must be normal to the crack plane of the compact and bend specimens and be in the same material condition.

A5.2 Determine the strain hardening exponent n from

$$\frac{R_{p0.2}}{R_m} = \frac{1}{1+\epsilon_{p0.2}} \left\{\frac{2.718 \ln(1+\epsilon_{p0.2})}{n}\right\}^n$$

$$\textit{where} \qquad \epsilon_{p0.2} = \frac{R_{p0.2}}{E} + 0.002$$

A graphical solution for n is given in Figure A5.1.

A5.3 Determine the reference stress σ_0 from

$$\sigma_o = R_{p0.2} 10^t$$

where $$t = \frac{n \lg(E\,\epsilon_{p0.2}/R_{p0.2})}{n-1}$$

A5.4 J blunting line

d_n^* is given graphically in Figure A5.2 for ν of 0.3. Alternatively, d_n^* can be determined using the equation

$$d_n^* = \epsilon_o^{n-1} \cdot D_n$$

where $$D_n = A_o + A_1 n + A_2 n^2 + A_3 n^3 + A_4 n^4 + A_5 n^5$$

and where n is the strain hardening exponent, and the constants of the polynomial are as follows:

A_o = 0.787
A_1 = 1.554
A_2 = -2.45
A_3 = 16.952
A_4 = -38.206
A_5 = 33.13

The slope of the blunting line is given by

$$\Delta a_B = 0.4\, d_n^* \frac{J}{E}$$

An approximation is given by

$$J = 3.75 R_m \Delta a_B$$

A5.5 δ blunting line

Evaluate d_n^* as described in Section A5.4. The slope of the blunting line is given by

$$\Delta a_B = 0.8 d_n^* \left(\frac{R_{p0.2}}{E}\right) \delta$$

An approximation is given by

$$\delta = 1.87\,(R_m/R_{p0.2})\,\Delta a_B$$

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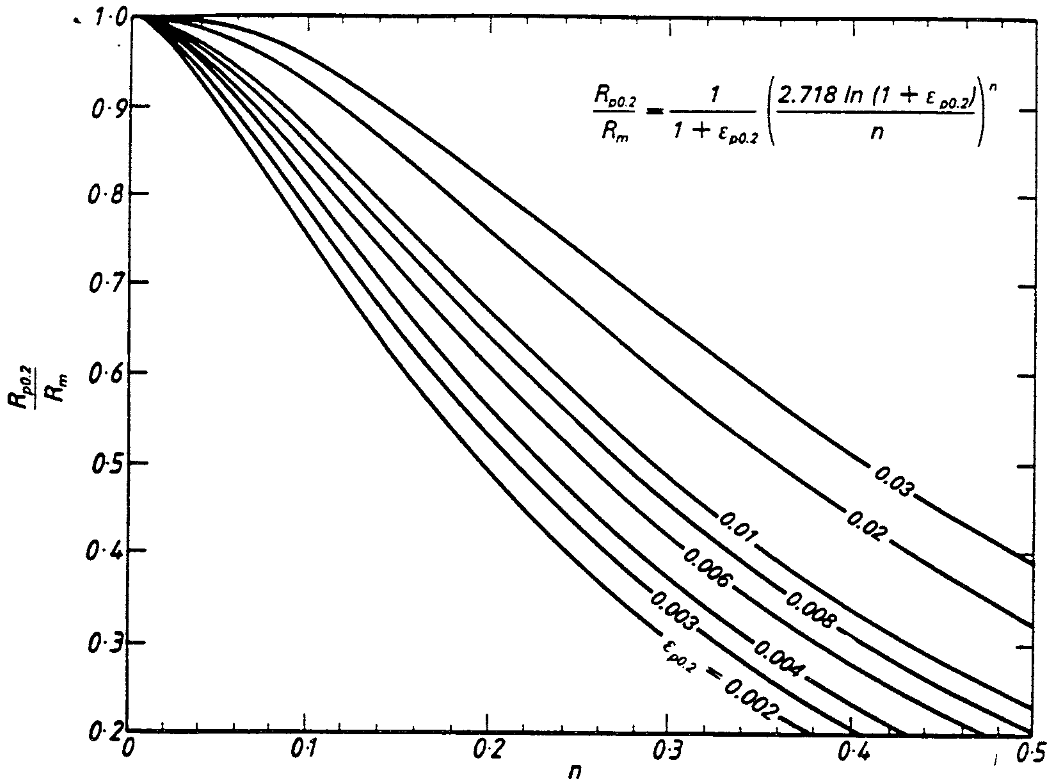

Fig.A5.1 Determination of strain hardening exponent, n.

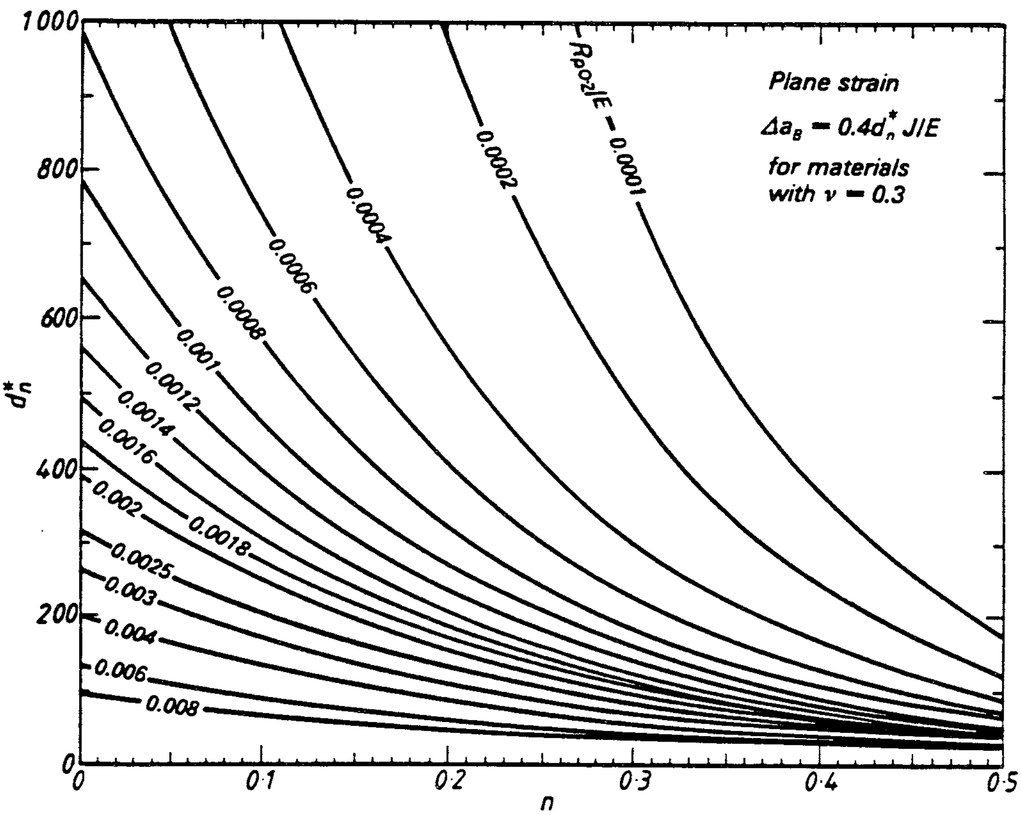

Fig.A5.2 Determination of d_n^*.

An approximation is given by

$$\delta = 1.87\,(R_m/R_{p0.2})\,\Delta a_B$$

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APPENDIX 6

Offset Power Law Fit to Crack Growth Fracture Resistance Data

A6.1 The offset power law to be fitted to crack growth fracture resistance data is of the general form:

$$y = m(x + c)^n \text{ where } c \geq 0$$

and y is either J or δ, x is the crack growth, m, c and n are constants which have to be evaluated. The advantage of the offset power law is that it can degenerate to either a straight line when n is 1 or a power law when c is zero. If m, c and n are all non-zero the fit is of the form shown in Figure A6.1.

A6.2 The constants m, c and n can be determined in the following manner.

A6.2.1 Determine the intercept T of the linear regression line through the x_i, y_i data points as shown in Figure A6.2. T represents an upper limit to the offset.

A6.2.2 Take values of c from 0 in steps of 0.01 mm upto T. For each value of c calculate the correlation coefficient r from

$$r = \frac{\Sigma(\log(x_i+c)\log y_i) - \dfrac{\Sigma \log(x_i+c)\ \Sigma \log(y_i)}{k}}{\left\{\left[\Sigma(\log y_i)^2 - \dfrac{(\Sigma \log y_i)^2}{k}\right]\left[\Sigma\ (\log(x_i+c))^2 - \dfrac{(\Sigma \log(x_i+c))^2}{k}\right]\right\}^{0.5}}$$

of the k data points. The best fit is given by the value of c which maximises the correlation coefficient.

A6.2.3 Having determined c, calculate n and m from

$$n = \left[\frac{\Sigma(\log(y_i)^2 - \dfrac{(\Sigma \log y_i)^2}{k}}{\Sigma(\log\ (x_i + c)^2 - \dfrac{(\Sigma \log(x_i + c))^2}{k}}\right]^{0.5}$$

and $\log m = \{\Sigma \log y_i - n\ \Sigma \log\ (x_i + c)\}/k$

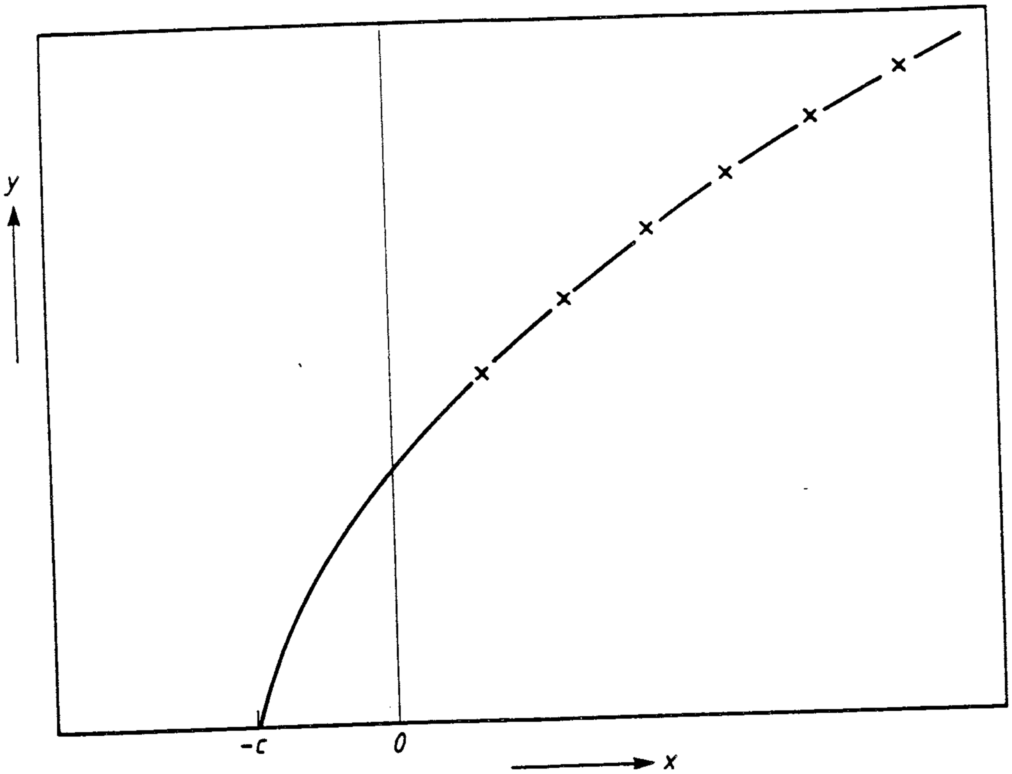

Fig.A6.1 General form of the expression $y = m(x + c)^n$.

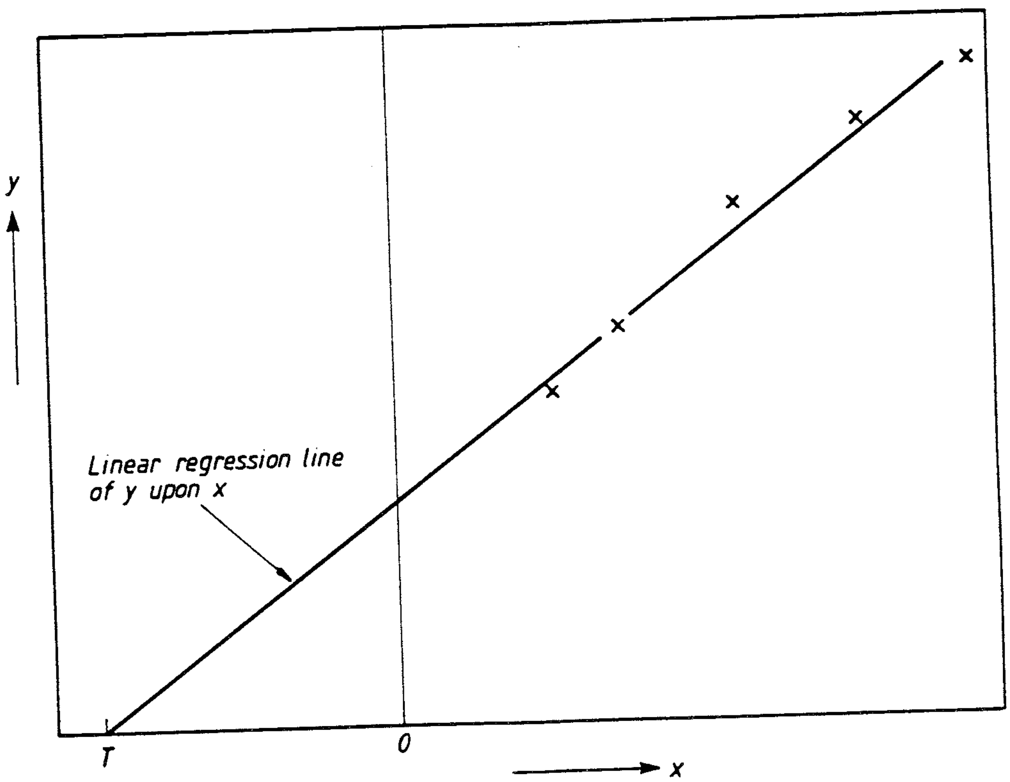

Fig.A6.2 Procedure to determine the maximum offset to the power law.

APPENDIX 7

J_i and δ_i Determination

The determination of J_i and δ_i require the use of a scanning electron microscope (SEM) to measure the stretch zone width on the fracture surfaces of the specimens. The method can produce large scatter in the values of J_i and δ_i as a result of the subjective interpretation and measurement of the stretch zone width. Therefore it is desirable to have experience in interpreting SEM fractographs. If the stretch zone width cannot be distinguished from ductile crack growth, J_i and δ_i cannot be determined.

A7.1 Critical Stretch Zone Width Measurement

A7.1.1 Measure the local critical stretch zone width SZW_L at the 9 positions shown in Figures 8 and 9 using calibrated photographs taken in a SEM. An example is shown in Figure A7.1. At each location the SEM magnification should be adjusted so that both the start and end of the stretch zone are visible at the same time, Figure A7.2. At least 5 measurements are required at each position giving the local stretch zone width

$$\Delta a_{SZW,L} = \frac{1}{k} \sum_{i=1}^{k} \Delta a_{SZW,i} \quad for\ k \geq 5$$

A7.1.2 Determine the critical stretch zone width of the specimen by averaging the nine local measurements

$$\Delta a_{SZW} = \frac{1}{9} \sum_{i=1}^{9} \Delta a_{SZW,L,i}$$

A7.1.3 For each specimen the crack growth Δa measured in Section 4.2 must be greater than Δa_{SZW} + 0.2 mm. Exclude the data points which fail to meet this requirement from those used to determine the mean critical stretch zone width, $\overline{\Delta a}_{SZW}$. At least three data points are required to determine $\overline{\Delta a}_{SZW}$.

$$\overline{\Delta a}_{SZW} = \frac{1}{j} \sum_{i=1}^{j} \Delta a_{SZW,i} \qquad providing\ j \leq 3$$

A7.2 J_i

A7.2.1 Construct a plot of the J-data obtained in Sections 4 and 5 and the critical stretch zone widths Δa_{SZW} as shown in Figure A7.3.

A7.2.2 Construct a line parallel to the J-axis through the mean of the critical stretch zone width data Δa_{SZW} as shown in Figure A7.3. Evaluate and draw the best fit curve through the J-Δa data which exceeds Δa_{SZW} using the equation given in Section 6.3.1. The intercept of the curve with the parallel line defines J_i. Construct a line through the intersection point and the origin. At least one J-Δa point should be within 0.2 mm of this line.

A7.2.3 If J_i exceeds J_{max} determined in Section 6.4, then J is invalid according to this procedure.

A7.2.4 Evaluate the slope of the J-Δa curve at the intersection point using the equation determined in Section 7.2.3. If the slope of the line constructed in Section A7.2.2

$$\left(\frac{dJ}{da}\right)_{BL} < 2 \left(\frac{dJ}{da}\right)_i$$

then J_i is invalid according to this procedure.

A7.3 δ_i

A7.3.1 Construct a plot of the δ-Δa data obtained in Section 4 and 5 and the critical stretch zone widths Δa_{SZW} as shown in Figure A7.3.

A7.3.2 Construct a line parallel to the δ - axis through the mean of the stretch zone width data Δa_{SZW} as shown in Figure A7.3. Evaluate and draw the best fit curve through all the δ - Δa data which exceeds Δa_{SZW} using the equation given in Section 6.3.1. The intercept of the curve with the parallel line defines δ_i. Construct a line through the intersection point and the origin. At least one δ-Δa point should be within 0.2 mm of this line.

A7.3.3 If δ_i exceeds δ_{max} determined in Section 6.5, then δ_i is invalid according to this procedure.

A7.3.4 Evaluate the slope of the δ-Δa curve at the intersection point using the equation determined in Section A7.3.2. If the slope of the blunting line

$$\left(\frac{d\delta}{da}\right)_{BL} < 2 \left(\frac{d\delta}{da}\right)_{i}$$

then δ_i is invalid according to the method of this procedure.

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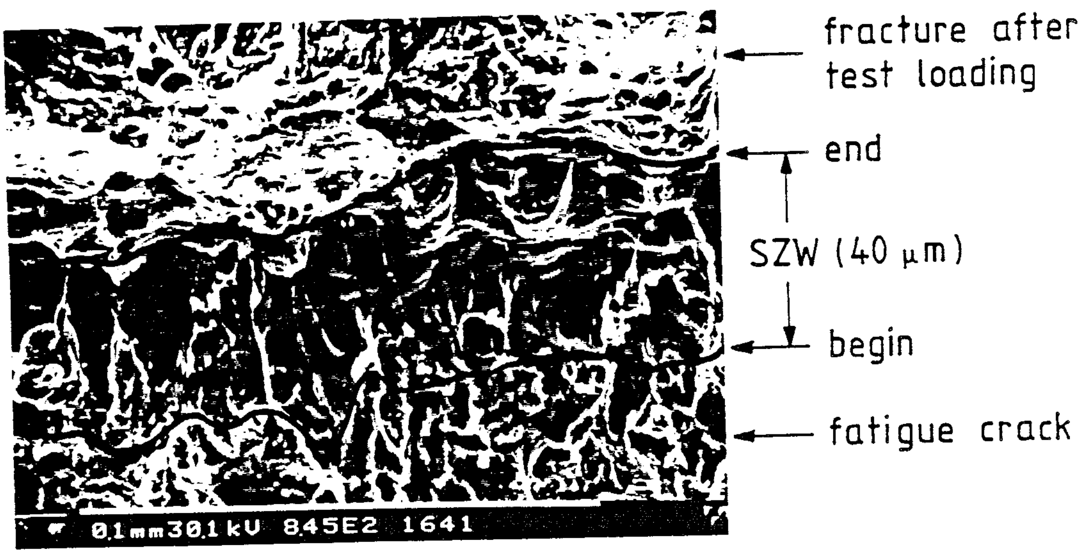

Fig.A7.1 Typical stretch zone width.

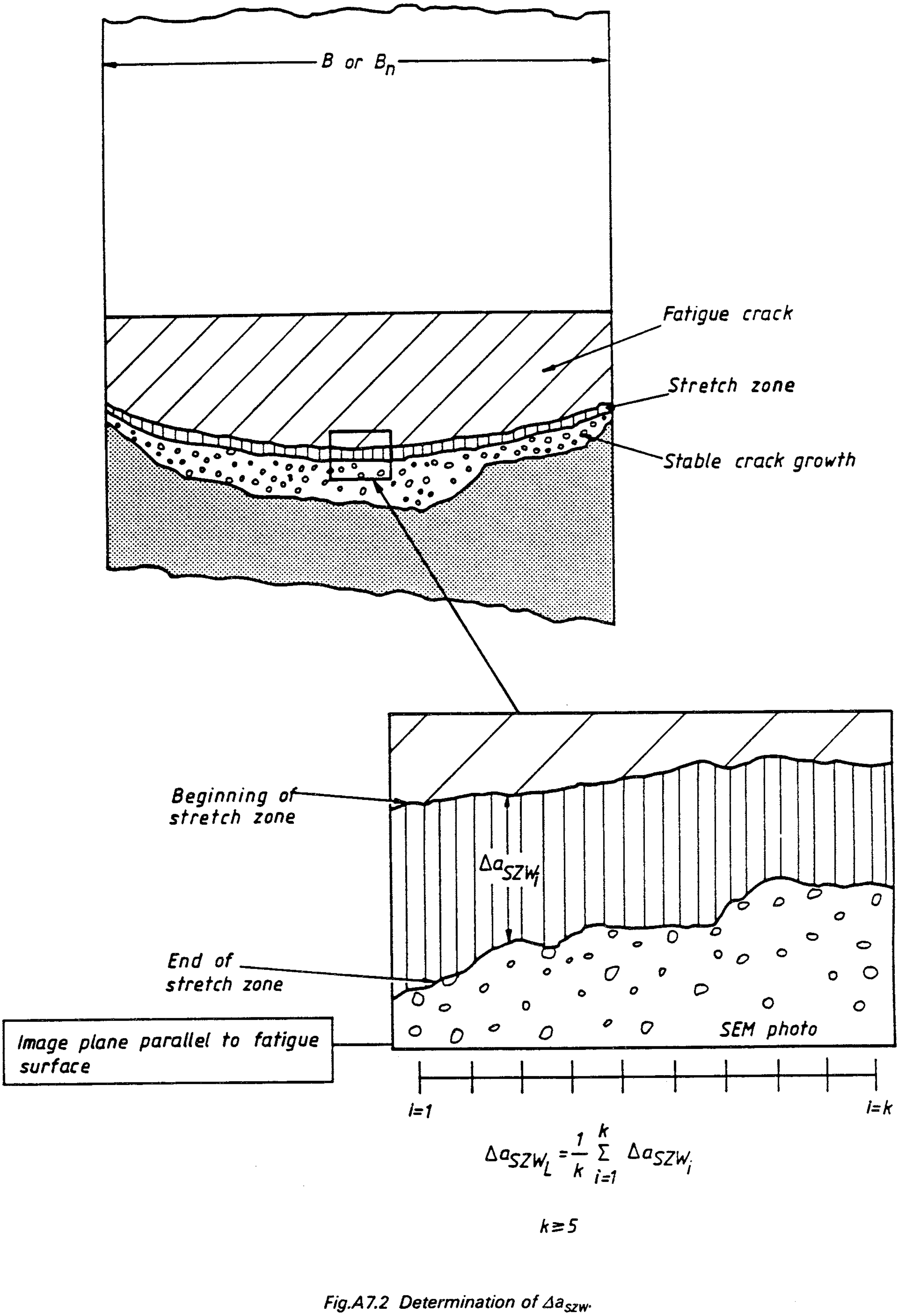

Fig.A7.2 Determination of Δa_{SZW}.

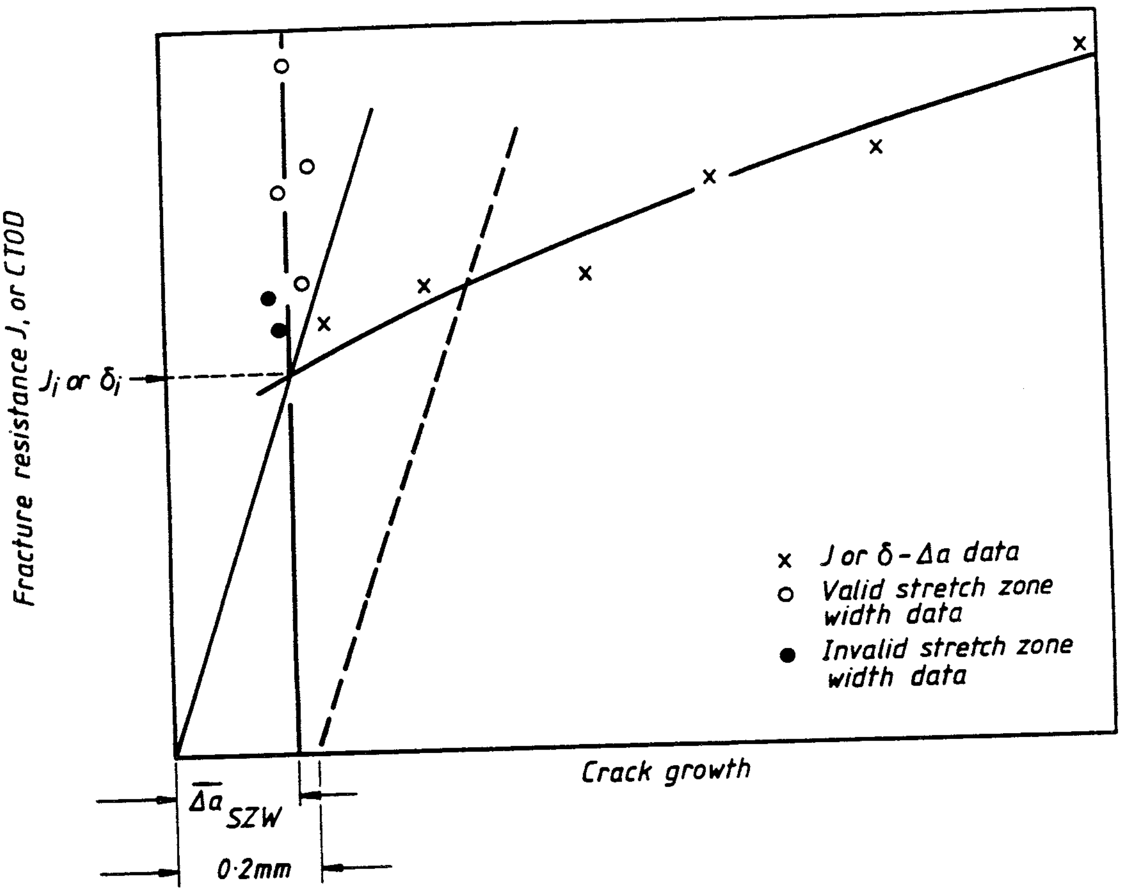

Fig.A7.3 Determination of J_i and δ_i.