GKSS 94/E/60

The GKSS test procedure for determining the fracture behaviour of materials: EFAM GTP 94

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120 pages with 62 figures and 3 tables

Abstract

This document describes a unified fracture mechanics test method in procedural form for quasi-static testing of materials. It is based on the ESIS Procedures P1 and P2 and introduces additional features, such as the δ_5 crack tip opening displacement, centre cracked tensile specimens, shallow cracks, "non-valid" CT and SENB specimen configurations, testing of weldments, and guidance for statistical treatment of scattered data.

Zusammenfassung

Der vorliegende Bericht beschreibt eine vereinheitlichte Bruchmechanik-Versuchsprozedur für die quasi-statische Werkstoffprüfung. Sie beruht auf den ESIS-Prozeduren P1 und P2, führt aber darüberhinaus weitere Aspekte ein, wie die Rißspitzenverschiebung δ_5, Mittenrißscheiben, kurze Risse, „ungültige" CT- und SENB- Probenkonfigurationen, Schweißverbindungen und Berücksichtigung von Streuungen in den Kennwerten.

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SUMMARY

This document describes a Procedure for determining the fracture resistance of materials from the linear elastic regime to the fully plastic regime. The fracture resistance is characterized in terms of either the stress intensity factor, K, the crack tip opening displacement, δ_5,or the J-integral.

Testing requirements and analysis procedures are given which enable K, δ_5, and J to be calculated for compact, single edge notch bend, and centre cracked tensile specimens. Fracture parameters are defined for unstable and stable crack growth which estimate the value of K, δ_5, and J at, or close to, crack initiation.

This procedure closely follows the European Structural Integrity Society Procedure ESIS P2-92 and includes the following features developed at GKSS:

- crack tip opening displacement measured in terms of the parameter δ_5;
- centre cracked tensile specimen;
- use of specimens which do not satisfy validity requirements.

Appendices are also included which provide guidance on the testing of weldments, the evaluation of statistical bounds to the fracture parameters, and the testing of specimens with shallow cracks.

DEFINITIONS

Stable Crack Growth

Crack growth which, under displacement control, stops when the applied displacement is held constant.

Unstable Crack Growth

An abrupt crack growth which occurs with or without prior stable crack growth and which leads to unstable fracture of the specimen.

Fracture Resistance

The resistance a material exhibits against stable or unstable crack growth, expressend in terms of K, δ_5 or J.

Fracture Parameter

Fracture resistance related to unstable crack gowth or initiation of stable crack growth.

NOMENCLATURE

Dimensions

a	Crack length.
a_i	Estimated initial crack length.
a_o	Measured initial crack length, Figures 5, 6, 7, 8, and 9.
B	Specimen thickness.
B_n	Net thickness of sidegrooved specimens.
S	Span of single edge notch bend specimen, Figure 10.
W	Specimen width.
z	Either the distance of the knife edge from the load line. Figures 5 and 6, or the knife edge height defined in Figure 13.

For the centre cracked specimen a, a_i and a_o are the half crack length; and 2W is the specimen width, Figure 8.

Tensile 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 stress $(R_{p0.2}+R_m)/2$.

Forces and Displacements

F	Applied force
F_c	Force defined in Section 5.1.2
F_Y	Yield force calculated using $R_{p0.2}$.
F_L	Ultimate force, calculated using R_m.
F_{max}	Maximum sustained force, Figure 17.
R	Ratio of lower to upper force during fatigue cracking.
q	Load point displacement.
V	Crack mouth opening displacement.

Fracture Parameters and Related Quantities

Δa	Average crack growth including blunting.
Δa_{SZW}	Critical stretch zone width.
Δa_{max}	Crack growth at the limit of J-controlled crack growth.
J	Fracture resistance in terms ot the experimental equivalent of the J-integral, allowing for crack growth.
J_o	J not allowing for crack growth.

J_c	Value of J_0 at unstable crack growth and stable crack growth of less than 0.2 mm.
J_i	Value of J_0 at initiation of stable crack growth.
J_u	Value of J_0 at unstable crack growth and stable crack growth greater than 0.2 mm.
J_{uc}	Value of J_0 at unstable crack growth and an unknown amount of stable crack growth
$J_{0.2/BL}$	Value of J or J_0 at 0.2mm crack growth offset to the blunting line.
$J_{0.2}$	Value of J or J_0 at 0.2mm crack growth including blunting.
dJ/da	Slope of the J-Δa curve.
J_{max}	Value of J or J_0 at the limit for J-controlled fracture behaviour.
J_g	Value of J or J_0 at upper limit of J-controlled crack growth.
η(a/W)	J-calibration function.
δ_5	Fracture resistance in terms of δ_5 as determined according to Appendix 4.
δ_{5c}	Value of δ_5 at unstable crack growth and stable crack growth of less than 0.2 mm.
δ_{5i}	Value of δ_5 at initiation of stable crack growth.
δ_{5u}	Value of δ_5 at unstable crack growth and stable crack growth greater than 0.2 mm.
δ_{5uc}	Value of δ_5 at unstable crack growth and an unknown amount of stable crack growth.
$\delta_{5,0.2/BL}$	Value of δ_5 at 0.2mm of stable crack growth offset to the blunting line.
$\delta_{5,0.2}$	Value of δ_5 at 0.2mm of stable crack growth including blunting.
$d\delta_5$/da	Slope of the δ_5-Δa curve.
$\delta_{5,g}$	Value of δ_5 at upper limit of δ_5-controlled crack growth.
$\delta_{5,max}$	Value of δ_5 at the limit for δ_5-controlled fracture behaviour.
K	Stress intensity factor.
ΔK	Range of stress intensity factor in fatigue.
f(a/W)	Stress intensity function, Appendix 1.
K_{Ic}	Plane strain fracture toughness.

The SI units to be used in this procedure are:

F	Force, kN.
V, q	Displacement, mm.
Δa	Crack growth, mm.
K	Stress intensity factor MPa $m^{1/2}$.
J	Experimental equivalent of J-integral MPa m.
δ_5	Crack tip opening displacement, mm.

1 INTRODUCTION

1.1 Scope and Significance

1.1.1 Objective

This document describes a procedure for determining the fracture resistance of materials using pre-cracked laboratory specimens. It closely follows the ESIS P1-92 and ESIS P2-92 Procedures and encompasses the fracture range from linear elastic through to fully plastic material behaviour. The procedure includes experience gained at GKSS and introduces several additional features not covered by ESIS P1-92 and ESIS P2-92, such as

- the centre cracked tensile specimen;
- the crack tip opening displacement parameter δ_5;
- specimens which do not satisfy the validity requirements.

Guidance is also given for:

- the testing of weldments;
- the evaluation of statistical bounds to fracture toughness data.

The procedure is applicable to a wide range of materials such as ferritic steels, austenitic steels, aluminium alloys, polymers, and weldments.

The test method involves loading a pre-cracked specimen at a slow rate until either sudden unstable fracture occurs with or without significant stable crack growth or ductile stable crack growth ensues.

The fracture resistance is characterized in the procedure in terms of stress intensity factor, K, crack tip opening displacement δ_5, and the J-integral. δ_5 is measured close to the crack tip and is particularly useful for weldments. It avoids problems which may arise with the evaluation of parameters measured remotely from the crack tip region.

In the case of unstable fracture, these parameters are measured at or close to the point of instability. For ductile crack growth, the variation of the fracture resistance with crack growth Δa is measured. The document contains testing requirements and analysis procedures which enable K, δ_5 and J to be calculated for compact, single edge notch bend and centre cracked tensile specimens.

Without prior knowledge of the force-displacement behaviour, it is impossible to know whether a specimen will exhibit unstable fracture or ductile crack growth. The force-displacement behaviour dictates the fracture parameters that can be measured. Figure 1 shows the main fracture parameters derived in the procedure in relation to their broad area of application on an idealised force-displacement diagram. The force-displacement behaviour depends on the material and the specimen size and geometry. Temperature can also affect the behaviour. In the case of ferritic steels a distinct ductile-to-brittle transition is observed with decreasing temperature, Figure 2. The fracture parameters are described in the following two sections.

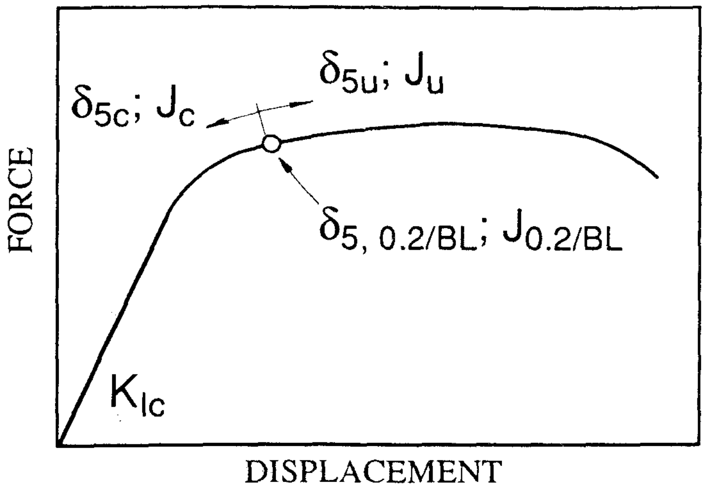


Figure 1:
Fracture parameters relevant to a force-displacement diagram.

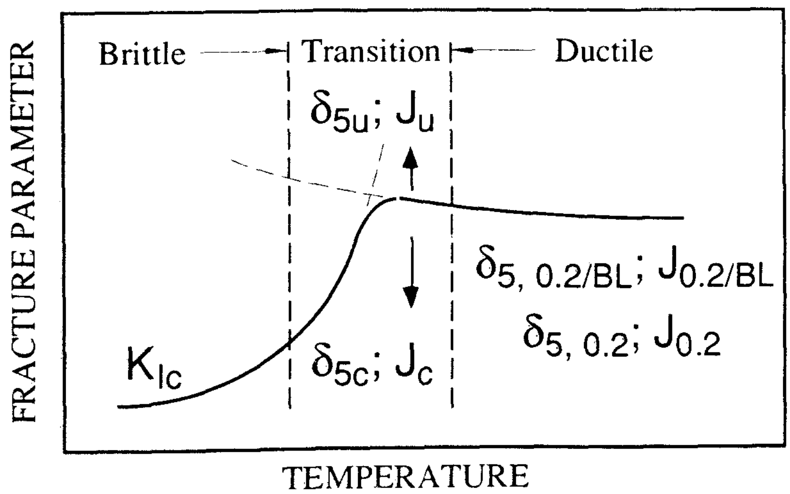


Figure 2:
Fracture parameters relevant to temperature effects on ferritic steels.

1.1.2 Fracture Parameters for Unstable Crack Growth

If the force-displacement record is essentially linear prior to unstable fracture, then the established procedures of linear elastic fracture mechanics are used to determine the plane strain fracture toughness K_{Ic}. This type of test record is exhibited by materials in the brittle regime.

If the force-displacement record is non-linear prior to unstable fracture and crack growth excluding blunting is less than 0.2 mm, then the fracture parameters δ_{5c}

and J_c are determined at the point of instability. This type of test record is usually exhibited by materials in the brittle-ductile transition regime.

If the stable crack growth exceeds 0.2 mm prior to unstable crack growth, then the fracture parameters δ_{5u} and J_u are determined. This type of behaviour is usually associated with materials close to the onset of the ductile regime.

1.1.3 Ductile Crack Growth Parameters

If the force-displacement record is non-linear and only stable crack growth occurs, then the variation in δ_5 or J with crack growth Δa is determined using either the multiple or single specimen method. This type of test record is usually exhibited by materials in the ductile regime. The multiple specimen method requires several nominally identical specimens to be loaded to different displacements. The extent of ductile-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 contains 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 crack growth resistance behaviour of a material. The multiple specimen method measures average fracture properties whereas the single specimen method can provide additional information on material variability.

Three fracture parameters are defined in the Procedure for estimating δ_5 or J close to the onset of initiation of stable crack growth:

- $\delta_{5,0.2/BL}$ or $J_{0.2/BL}$ which measure the material resistance at 0.2 mm of ductile crack growth and provide an engineering definition of initiation. A value of 0.2 mm was chosen as it was felt large enough to allow accurate measurements of crack growth in the test specimens, yet small enough to give material resistance values close to crack initiation.
- $\delta_{5,0.2}$ or $J_{0.2}$ which measure the material resistance at 0.2 mm of total crack growth, including crack tip blunting. For many materials, like low to medium strength steels, these parameters provide useful estimates of the initiation toughness which are generally lower bound estimates of $\delta_{5,0.2/BL}$ and $J_{0.2/BL}$.
- δ_{5i} or J_i which correspond to values of the fracture resistance at crack initiation. The derivation of these parameters requires the measurement of the stretch zone width

using a scanning electron microscope. It is considered to be the most accurate method for measuring δ_5 or J 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 δ_{5g} and J_g are defined which give the maximum fracture resistance values that can be measured from a given test specimen. Also $d\delta_5/da$ and dJ/da which are slopes of the δ_5-Δa and J-Δa curves, respectively, are used to measure the material resistance to crack growth.

In an Appendix to this Procedure a method is described for determining K-based crack growth resistance curves on high strength materials.

1.1.4 Use of Fracture Parameters

The fracture parameters determined according to this procedure characterize the fracture behaviour of brittle and ductile materials. Providing certain procedural validity requirements are satisfied, the parameters evaluated from compact and single edge notch bend specimens in the brittle and ductile regimes may be regarded as a material property independent of size. No such claim can be made for the parameters in the brittle-ductile transition regime where available evidence suggests a considerable size dependence. Scatter may also make it difficult to assess the significance of the fracture parameters. In those situations, bounds may be derived to the fracture data using the statistical treatment described in an Appendix to this Procedure.

Certain combinations of material and test specimen geometry can lead to crack growth resistance curves which do not meet the validity requirements for size independence. In those cases, a thickness dependent resistance curve can be generated which is independent of the in-plane dimensions provided that the remaining ligament is large compared to the thickness. This is of particular interest for thin sheet testing.

For ductile materials, the fracture parameters determined according to this Procedure are generally independent of specimen thickness and geometry. However, the slope of the crack growth resistance curve can be much steeper for the centre cracked tensile specimen compared with the curves for the compact and simple edge notch bend specimens. The difference can be explained in terms of the constraint ahead of the crack tip which is larger for bend specimens than tensile specimens. Consequently, care should be exercised in using the resistance curves of these specimens for structural assessment and material characterization purposes.

The fracture parameters and the crack growth resistance curves can be used to assess the structural integrity of components. They can also be used as an index for material selection and quality assurance purposes or to evaluate the effects of temperature, heat treatment, environment, processing and chemical composition on fracture properties. The choice and applicability of the fracture parameters for structural integrity assessments and materials characterization is at the discretion of the user.

For structural integrity analyses the procedures described in “Engineering Flaw Assessment Methode (EFAM)“ are recommended.

1.2 Selection of Test Method and Analysis Procedure

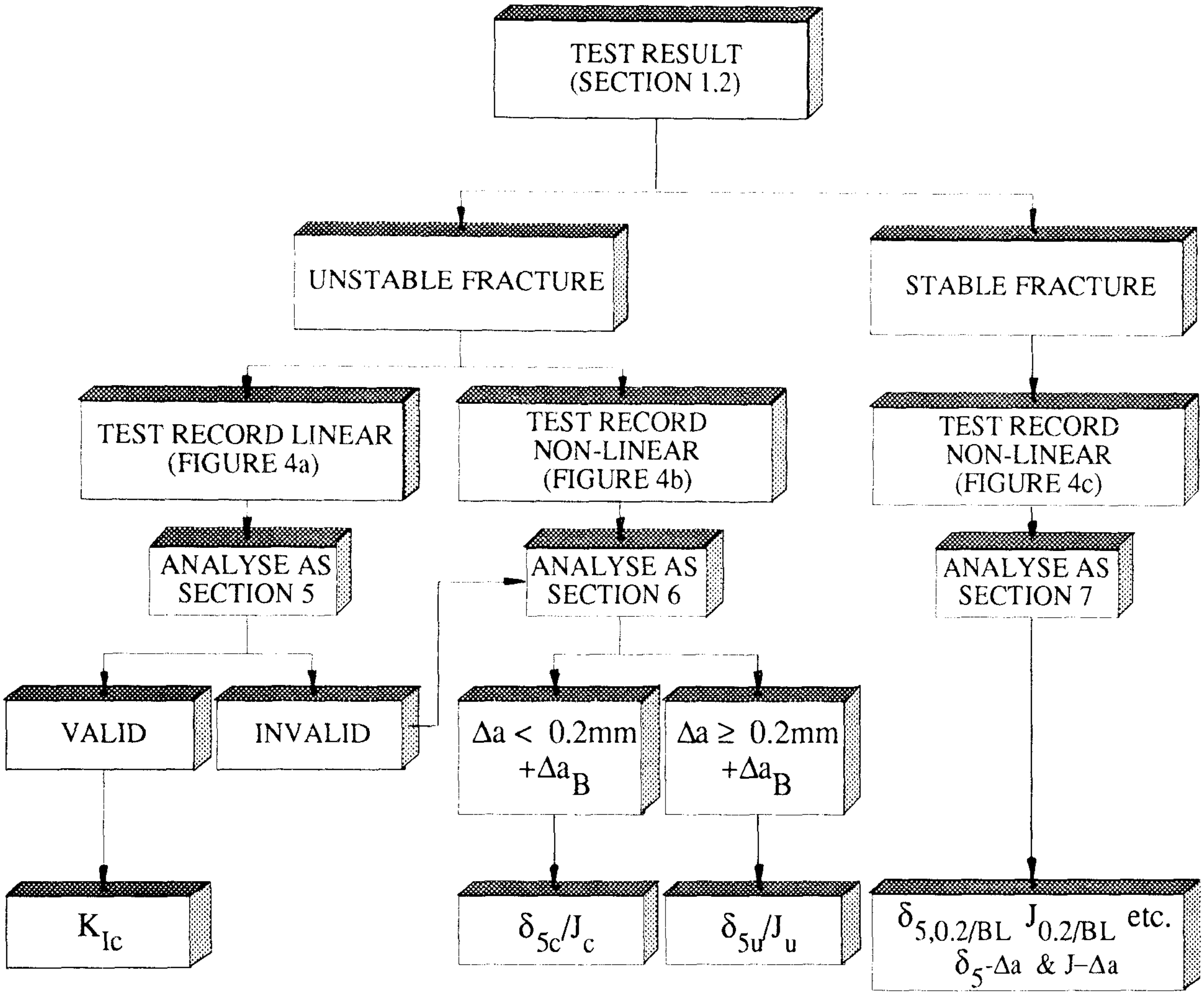
The geometry, dimensions and preparation of the test specimens and the test requirements are given in Sections 2 and 3, respectively. Selection of the test method and analysis procedure depend on the force-displacement behaviour of the test specimen. A specimen of suitable design and size should be tested at the required temperature and loading rate. Load-point displacement should be recorded as a function of applied force. If fracture does not occur the specimen should be unloaded after passing through the maximum force.

Following the test, the force-displacement record should be inspected and the flow diagram in Figure 3a should be consulted for guidance on how to evaluate the fracture behaviour. Figure 3a also gives the relevant section number required in the Procedure to evaluate the appropriate fracture parameter. Figure 3b gives in more detail the evaluation procedure for the ductile fracture parameters. The corresponding test procedures are described in Section 4. Typical force-displacement records and categories of fracture behaviour are shown schematically in Figure 4.

The main part of this Procedure describes the testing of homogeneous materials. If weldments are to be tested, additional steps and requirements are needed, as described in an Appendix to this Procedure.

1.3 Caveat

Testing of replicate specimens in the transition region, Figure 2, under the same nominal conditions can often produce non-linear test records for which both unstable and stable fracture occurs, Figures 4b and 4c respectively. This Procedure enables the appropriate parameters to be determined for the material behaviour. However, care should be exercised in their subsequent use as material characterizing parameters.



Figures 3a: Evaluation of fracture parameters from force-displacement record.

2 SPECIMEN GEOMETRY, DIMENSIONS AND PREPARATION

2.1 Specimen Geometries

The Procedure allows the use of either compact, single edge notch bend, or centre cracked tensile specimens. The suggested compact specimens are shown in Figures 5 and 6. The step notched specimen is recommended for measuring load-point displacement directly, Figure 6. 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 7. Figure 8 shows the centre cracked tensile specimen.

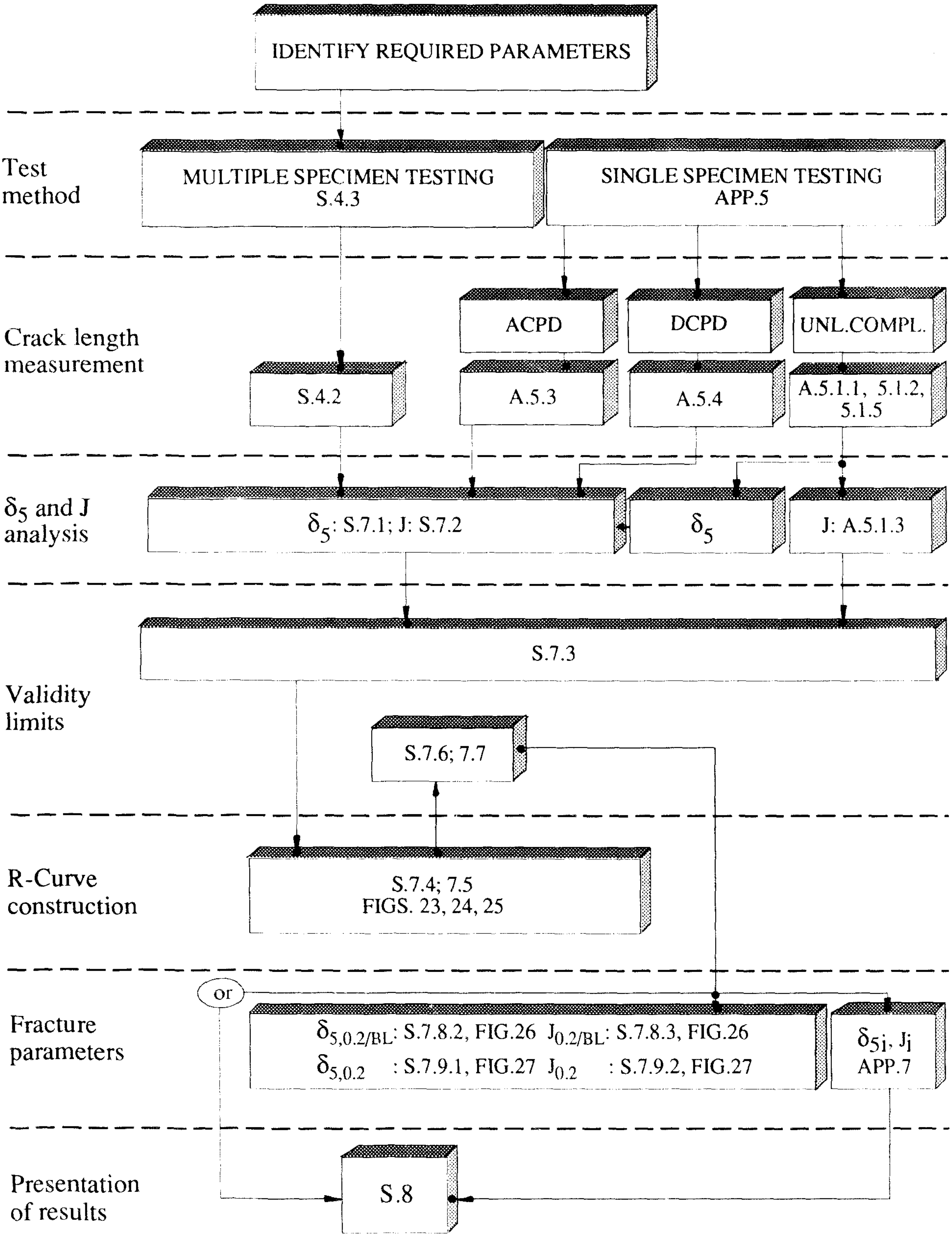


Figure 3b: Flow chart for determining stable crack growth and related fracture parameters.

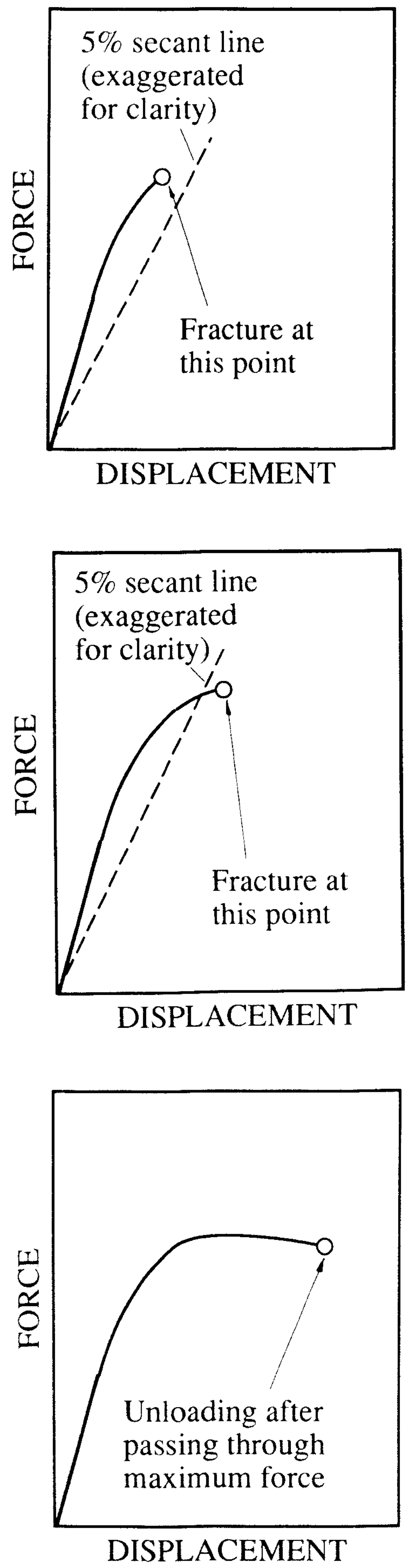


Figure 4:

Schematic force-displacement records and associated fracture behaviour:

a) Fracture unstable and test record linear (brittle),

b) Fracture unstable and test record non-linear (ductile/brittle),

c) Fracture stable and test record non-linear (ductile).

2.2 Dimensions

2.2.1 Geometrical Considerations

The dimensions of the test specimens shown in Figures 5 to 8 are characterized by the specimen width W. For the compact and single edge notch bend specimen the preferred thickness B is 0.5 W. It is recommended that the specimen should be as large as practicable. For the centre cracked tensile specimen, W is usually much greater than B. In those situations, the use of antibuckling guides is recommended. The specimen dimensions should satisfy the validity requirements appropriate to the parameter being measured. Since these requirements 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 value of the fracture parameter.

All test specimens must be machined to within the tolerances given in Figures 5 to 8.

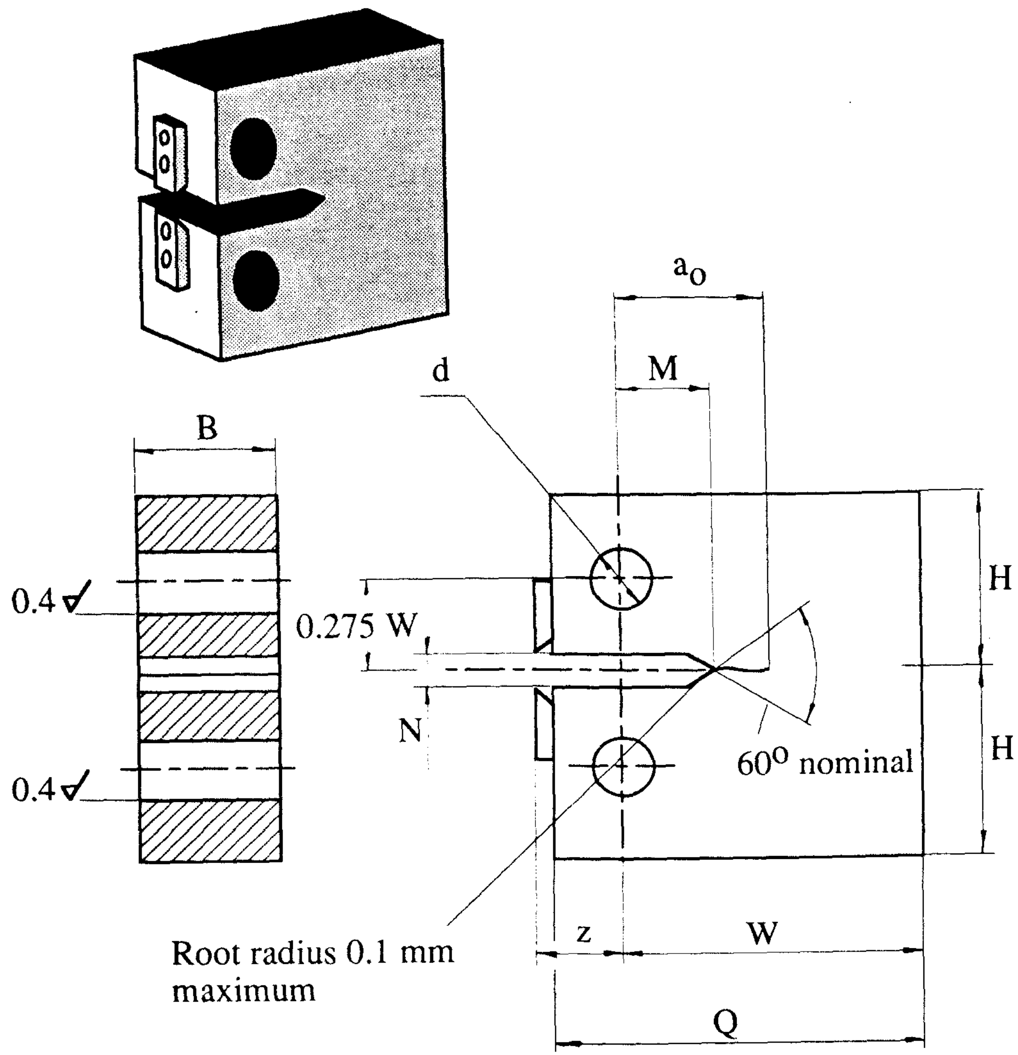
2.3 Preparation

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, Figures 5 to 8, to give an initial crack length a_0 in the range $0.45 \le a_0/W \le 0.65$ for compact and single edge notched bend specimens, and $0.25 \le a/W \le 0.40$ for the centre cracked tensile specimen. Test specimens should contain initial crack lengths which are in reasonably close agreement with each other. If the crack length range exceeds 0.05 W, then report the discrepancy in Section 8.3. Guidance for testing compact and single edge notched bend specimens with shallow cracks when $a_0/W \le 0.45$ is given in an Appendix to this Procedure.

It is recommended that for those materials in which the ultimate to yield strength ratio, $R_m/R_{p0.2}$ exceeds 2, and stable crack growth is excepted to occur, Section 1.1.3, the initial crack length in compact and single edge notched bend specimens should tend towards the upper limit of a_0/W to ensure that plastic deformation is limited to the uncracked ligament.

2.3.1.2 The fatigue pre-crack, or pre-cracks for the centre cracked specimen, must exceed the larger of 0.05 a_0 or 1.5 mm. The notch geometry must be enclosed within a 30° included angle from the fatigue pre-crack tip, Figure 9. For the centre cracked specimen, the fatigue pre-cracks should also be within 0.05 a_0 or 1.5 mm, whichever is the greater, of each other.



$\overset{x}{\nabla}$ is the surface finish to x µm

Figure 5: Straight notched compact specimen.

Width W   Thickness B

Total width $Q = 1.25W \pm 0.01W$

Half height $H = 0.6W \pm 0.005W$

Hole diameter $d = 0.25W \,^{+0.004W}_{-0}$

Notch width $N = 0.06W$ max. or

1.5mm max. if $W \leq 25mm$

Effective notch length

$M = 0.4W$ min

Effective crack length

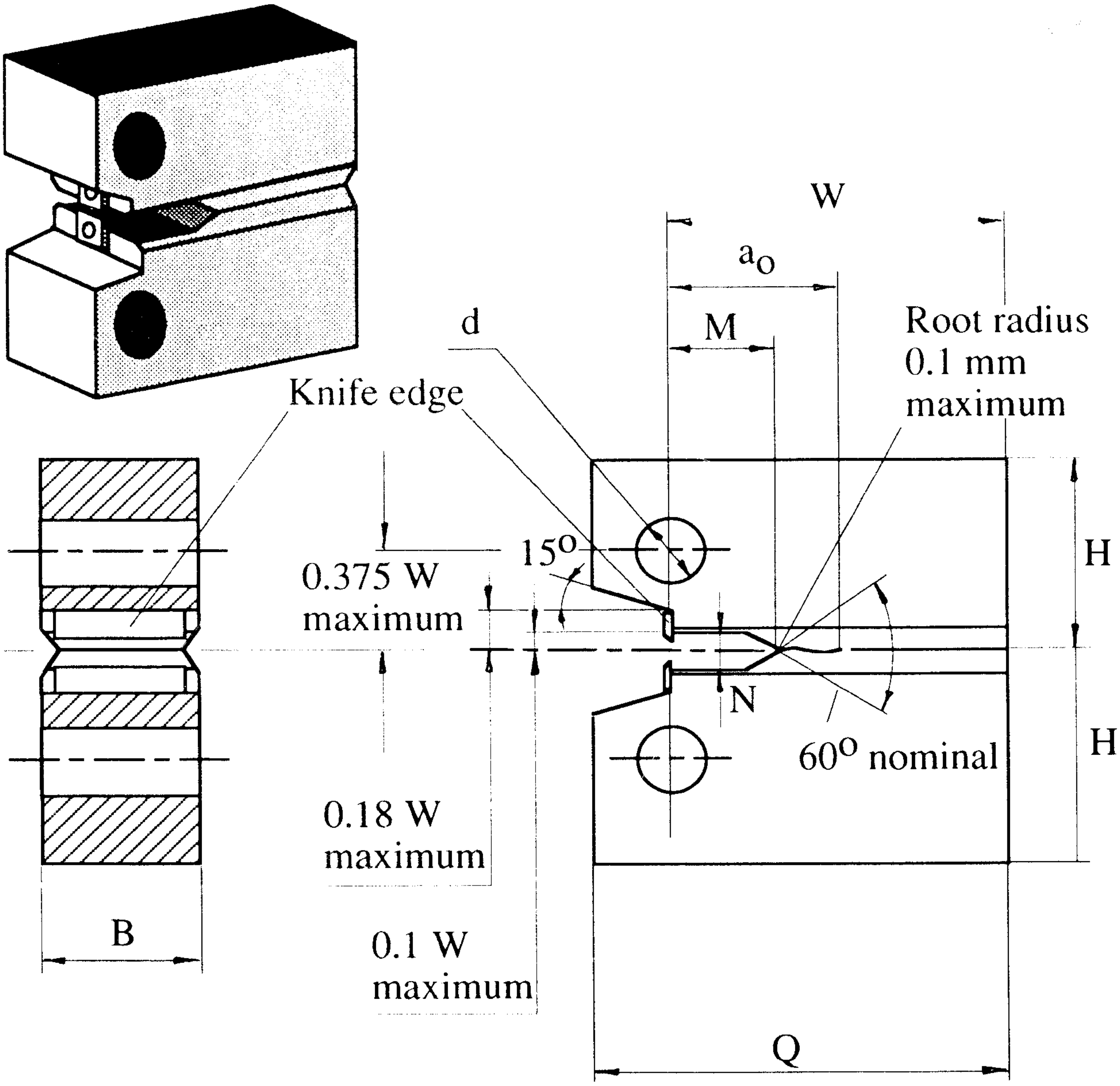
$a_o = 0.45W$ to $0.65W$

Notes:

1. A spark eroded or machined slit can be used instead of the V-notch profile.
2. Squareness and parallelism to be within 0.002W.

   Holes to be square with faces and parallel.

$\overset{x}{\nabla}$ is the surface finish to x µm

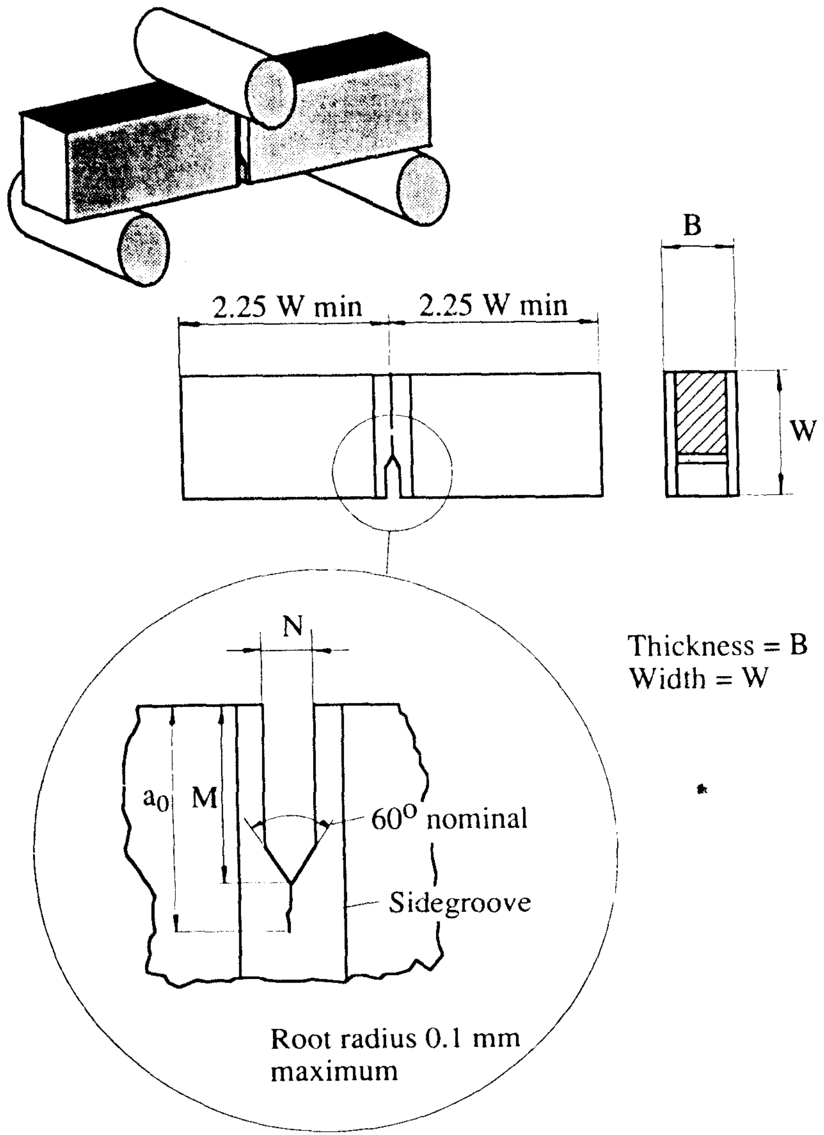


Tolerances, surface finish and dimensions as Fig. 5

Additional notes:

1. Spacing between knife-edges depends on type of clip gauge to be used.
2. Side grooves are recommended for tests in the ductile regime, see Section 2.3.2

Figure 6: Step notched compact specimen.



Width W Thickness B

Notch width N = 0.06W max. or
1.5mm max. if $W \leq 25$mm

Effective notch length
M = 0.4W min.

Effective crack length
$a_o = 0.45W$ to $0.65W$.

Notes:

1. A spark eroded or machined slit can be used instead of the V-notch profile.
2. Squareness and parallelism to be within 0.002W.
   Notch to be square with specimen faces and notch faces to be parallel.
3. Side grooves are recommended for tests in the ductile regime, see Section 2.3.2

$\overset{x}{\checkmark}$ is the surface finish to x µm

Figure 7: Single edge notch bend specimen.

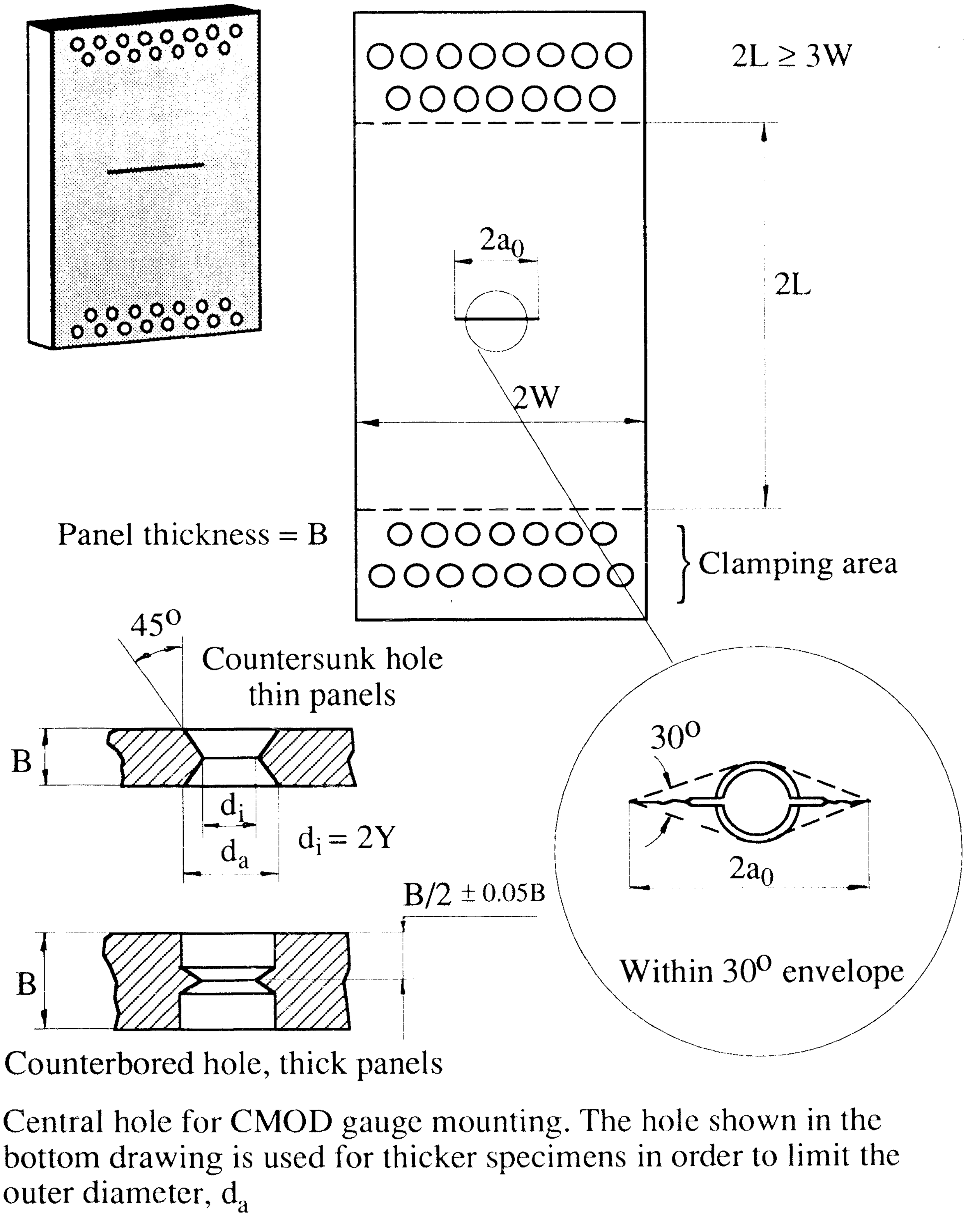


Figure 8: Centre cracked tensile specimen.

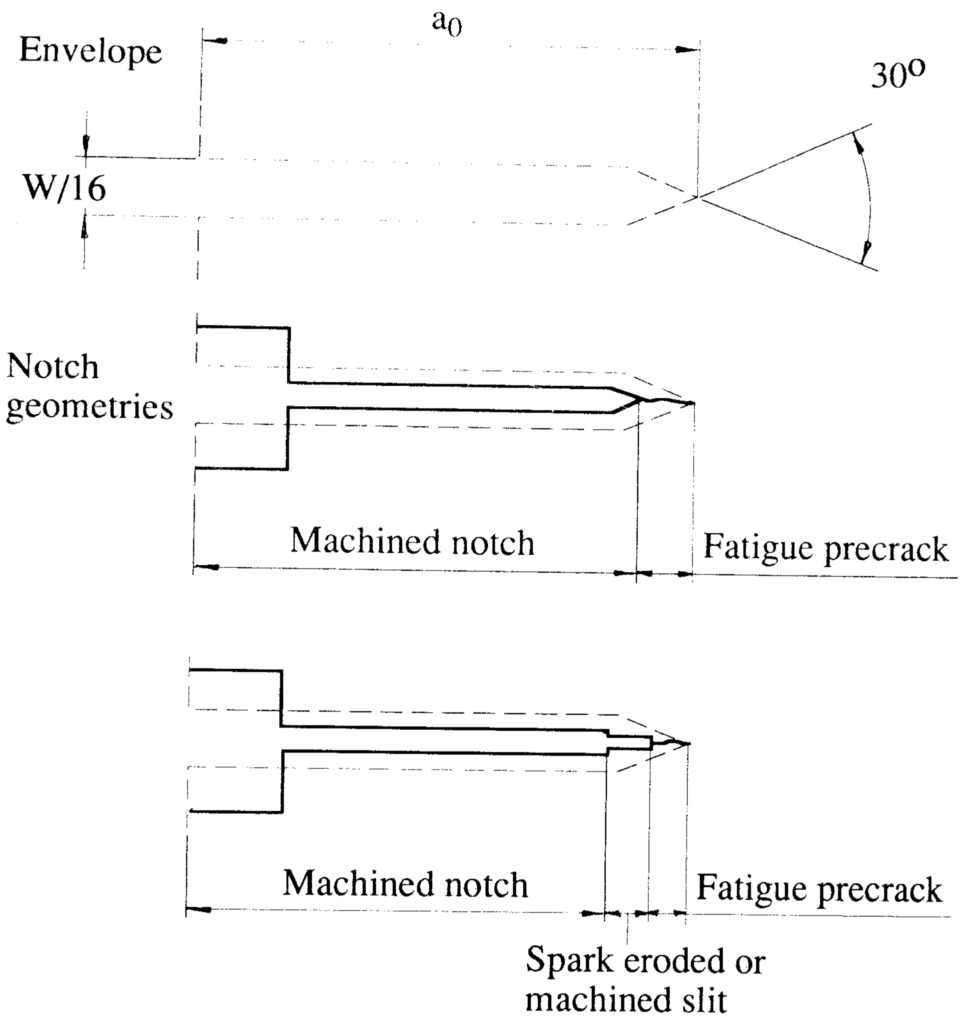


Figure 9: Acceptable machined notch geometries.

Notes:
1. Machined notch width must not exeed 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

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

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

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

for the single edge notch bend specimen by

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

and for the centre cracked tensile specimen by

$$F_Y = 2(W-a)B \quad R_{p0.2}$$

2.3.1.4 When the fatique precracking of a specimen is performed at a temperature T_1, and then tested a temperature T_2, K_{max} given in Section 2.3.1.3 should be factored by the ratio $(R_{p0.2})_1/(R_{p0.2})_2$ where $(R_{p0.2})_1$ and $(R_{p0.2})_2$ are the yield strengths at the temperatures T_1 and T_2, respectively. In addition, F_Y should be evaluated from the lowest value of $(R_{p0.2})$ at the two temperatures.

2.3.1.5 For materials which exhibit a linear force-displacement test record, Figure 4a, use F_c defined in Section 5.1.2, instead of F_Y to check the fatigue precracking requirements. F_c is only available after the test.
The stress intensity factor K at force 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 Sidegrooving

Sidegrooving is only recommended for those compact and single edge notched bend specimens which are expected to exhibit stable crack growth and non-linear force-displacement record, Figure 4c. When the test specimen thickness is less than the component thickness, it is recommended that the specimens are sidegrooved. Sidegrooving is not recommended for centre cracked tensile specimens.

2.3.2.1 Sidegrooving promotes straight fronted ductile crack growth during a test. Specimens should be sidegrooved after fatigue pre-cracking.

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 0.10 B and must not exceed 0.25 B where B_n is the net section thickness. For most materials, 20 percent total sidegrooving is recommended.

2.3.3 Measurements

Prior to testing, measure the thickness B, net section thickness B_n, if applicable, and W, as shown in Figures 5 to 8 to an accuracy of 0.05 mm.

3 TEST REQUIREMENTS

3.1 Test Machine

The test machine must incorporate a rigid loading frame, and a force transducer to provide an autographic recording of the force applied to the specimen. The test machine should be capable of operating at both constant force and displacement rates.

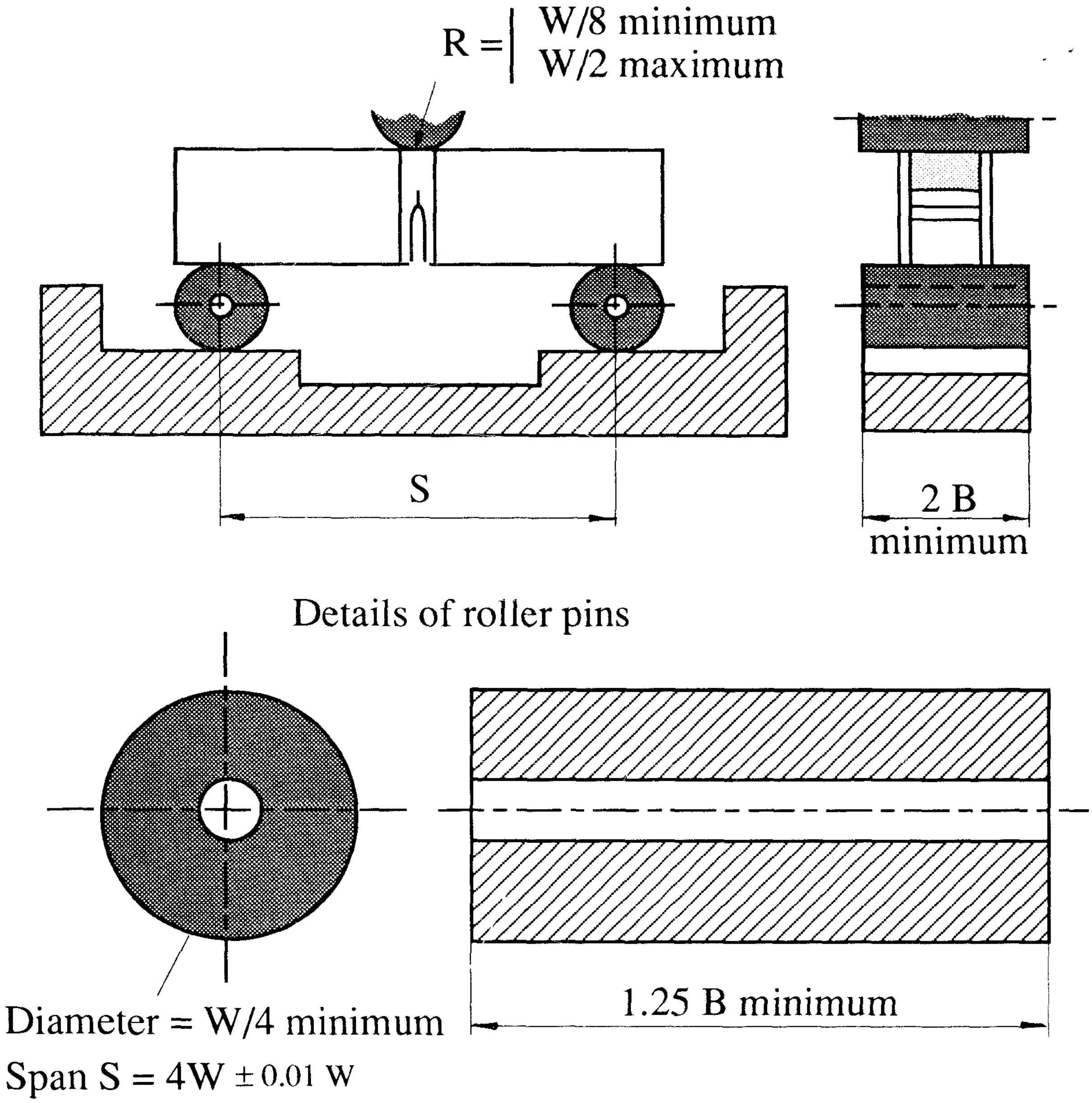
3.2 Test Fixtures

The test fixtures must be designed to be as rigid as practicable. Figure 10 shows a suitable loading frame for a single edge notch bend specimen. The lower support rollers must be free to move outwards. Figure 11 shows a suitable clevis design for the compact specimen. Other testing fixtures can be used providing care is taken to minimise indentation and frictional effects between the specimen and fixture.

The fixture for the centre cracked tensile specimen should be designed to distribute the load uniformly over the cross-section of the specimen. The fixture may be rigidly connected to the machine if uniform loading of the specimen in the machine can be achieved at all loads. Otherwise, pin-loading via detachable grips is recommended, Figure 12a.

3.3 Prevention of Buckling

It is recommended that anti-buckling plates should be attached to both sides of a centre cracked tensile specimen covering the expected path of the crack. Frictional forces between the specimen and the plates should be reduced to a minimum with the use of a non-corrosive lubricant such as Teflon applied to the mating surfaces. An access hole is required in one of the plates for mounting the displacement CMOD and δ_5 gauges onto the specimen or, if the potential method is used, for the attachment of cables. A suitable arrangement is shown in Figure 12b.



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.

Figure 10: Fixture for single edge notch bend specimen testing.

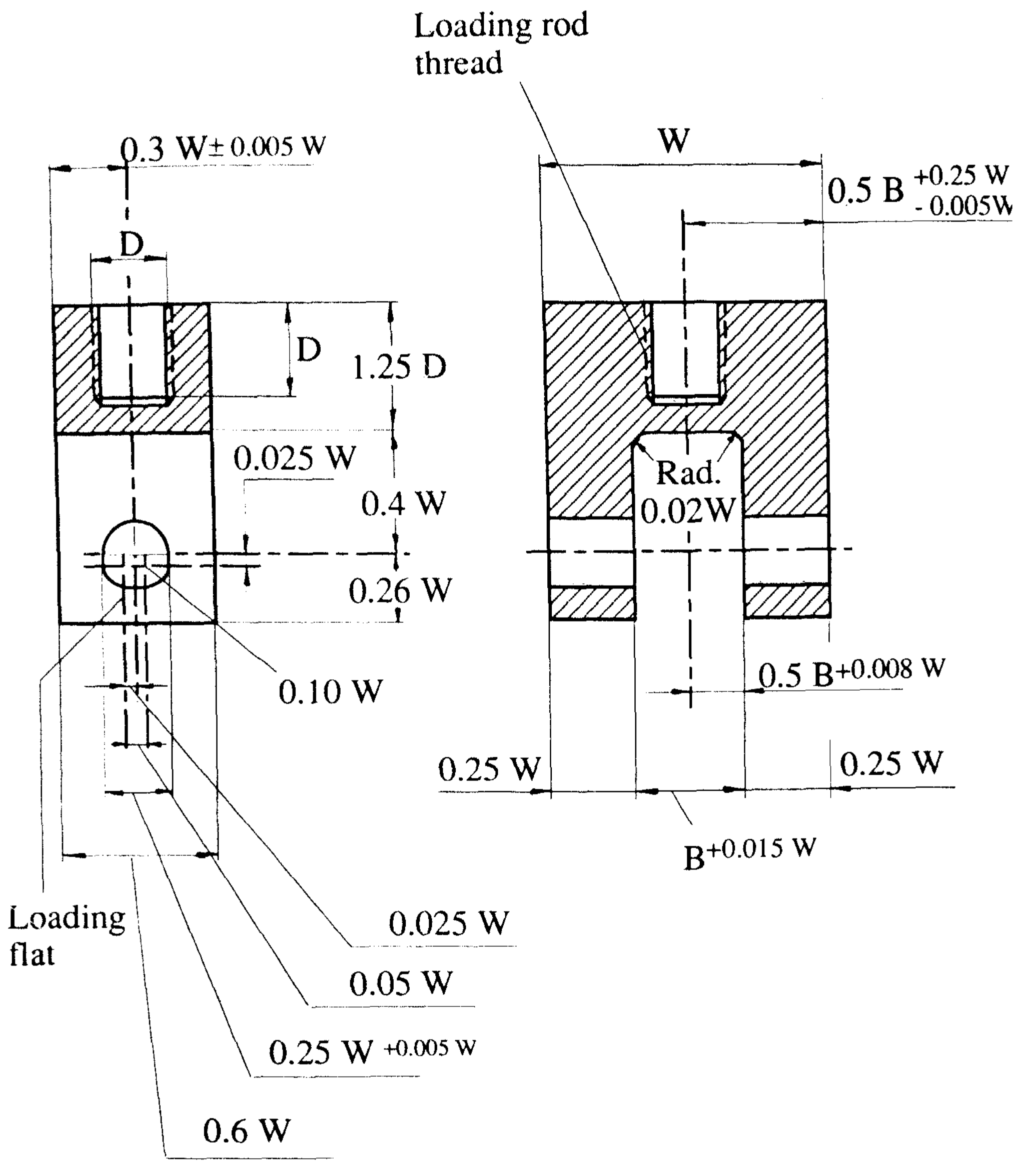


Figure 11: Clevis for compact specimen testing.

Notes:

1. Thickness B usually 0.5W, see Section 2.2.1.
2. Loading pin diameter = $0.24W^{+0}_{-0.005W}$
3. Surface 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.

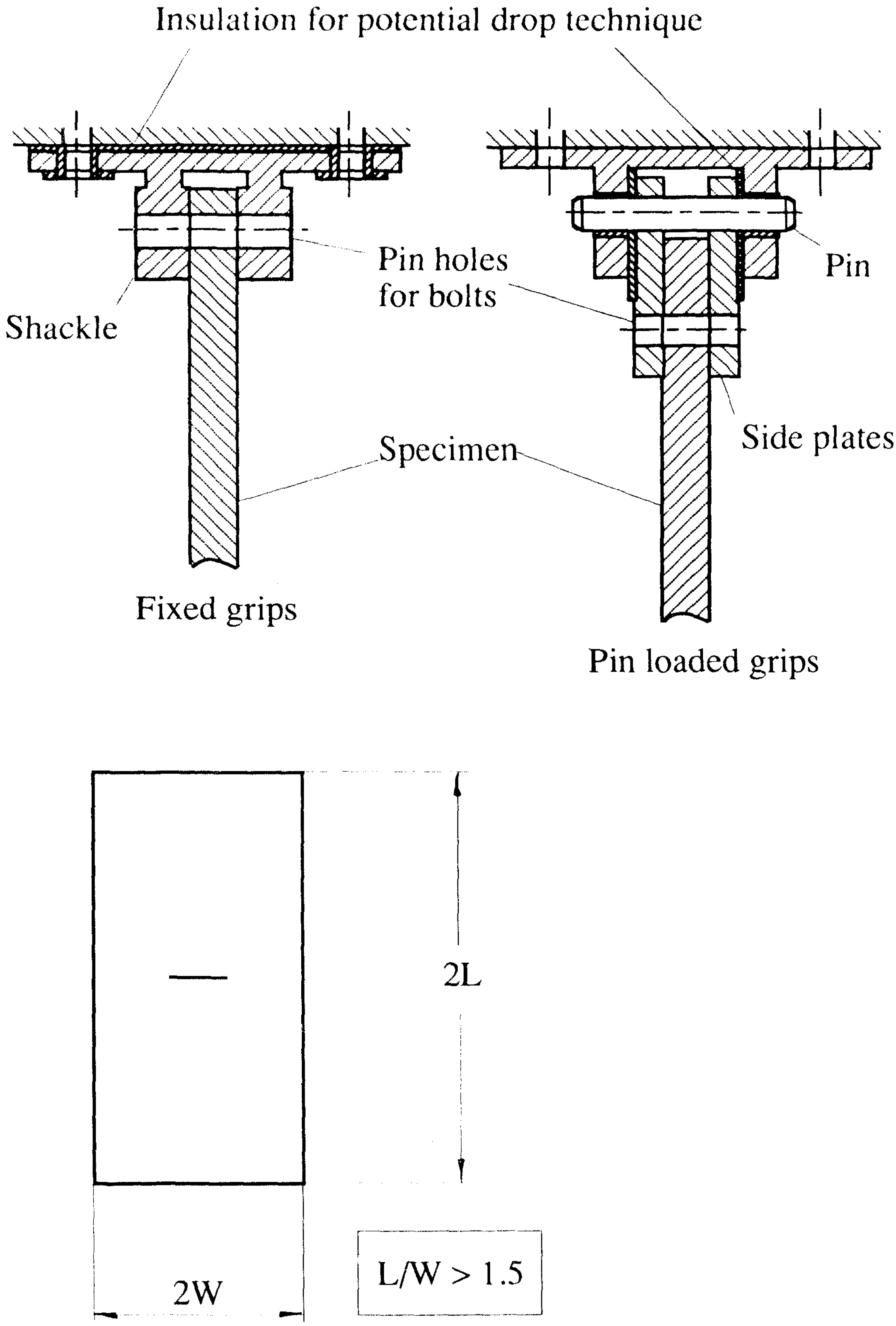


Figure 12a: Examples of fixed and pin-loaded grips for centre cracked tensile specimen.

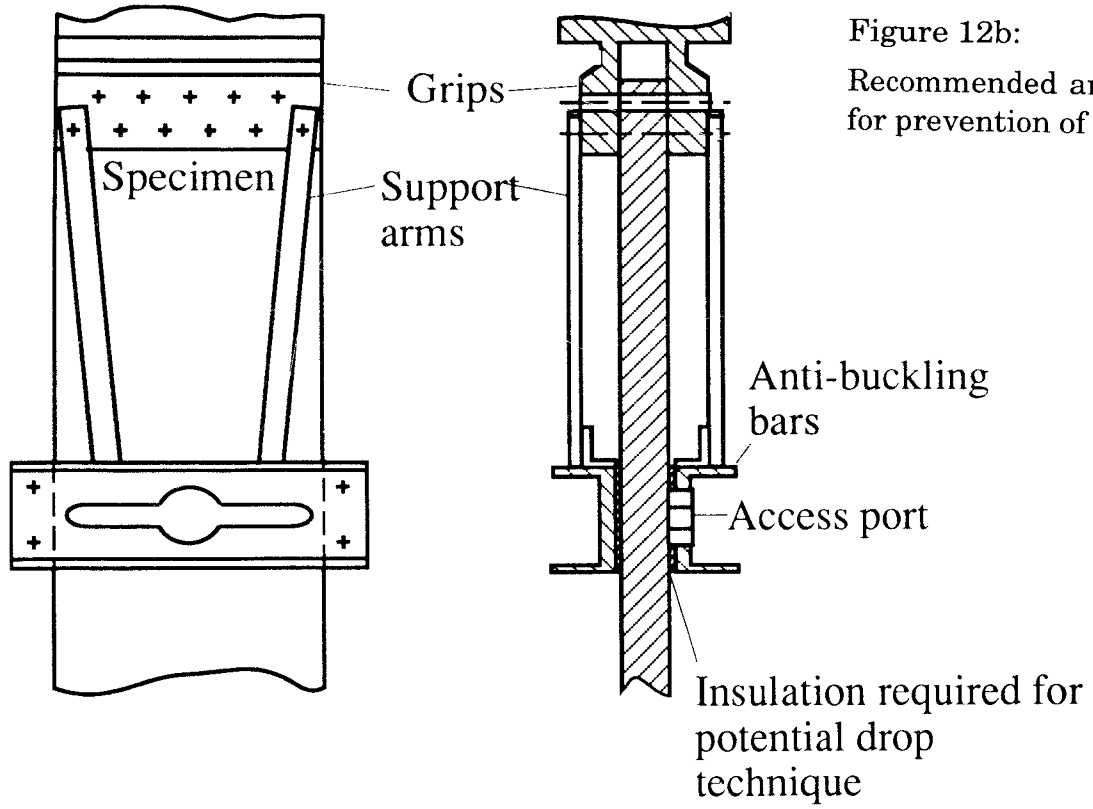


Figure 12b:
Recommended arrangement for prevention of buckling.

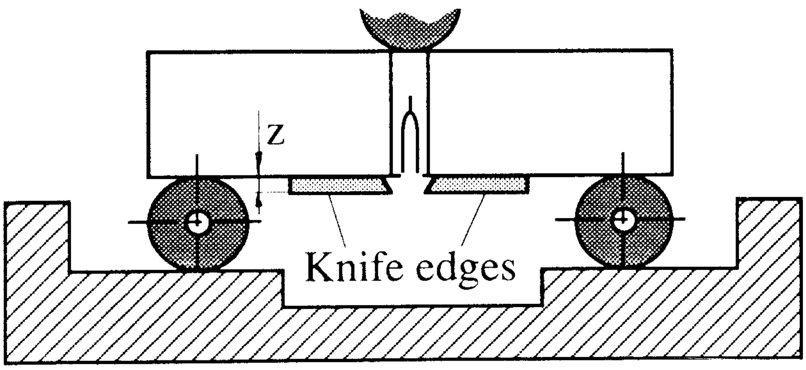


Figure 13:
Position of knife edges for measuring mouth opening displacement in the bend specimen.

3.4 Displacements

The fracture toughness K is evaluated from the applied force F. The force can be measured relative to either the load-point displacement q, or the crack, mouth opening displacement V.
The fracture resistance J is evaluated from load-point displacement q.
The crack tip opening displacement δ_5 is obtained explicitly in this Procedure.

3.4.1 Load-Point Displacement

When testing compact specimens, usually, the load-line displacement measured between knife edges placed between the pin holes, Figure 6, is taken as a measure of load-point displacement. For compact specimens which do not permit measurement of the load-line displacement, Figure 5, the relationship between the measured displacement and the load-line displacement must be established so that load-line values can 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 on the fixture are determined and subtracted from the measured displacement.

When testing centre cracked tensile specimens the load-point displacement is measured between two points close to the grip attachment area, Figures 12b and A 4.3. The fracture resistance J can also be determined from the crack mouth opening displacement, Appendix 3.

3.4.2 Crack Mouth Opening Displacement (CMOD)

For the step notched compact specimen shown in Figure 6, the CMOD corresponds to the load-point displacement. If the knife edges are not located at the load-line, the CMOD is measured between knife edges at a distance z from the load-line in the direction away from the crack tip, Figure 5.

In the case of the single edge notch bend specimen, the CMOD can be measured between knife edges at a distance z from the specimen surfaces, Figure 13.

For the centre cracked tensile specimen, the CMOD can be measured between the circular knife edge in the countersunk hole shown in Figure 8. Further details are given in Appendix 3.

3.4.3 Crack Tip Opening Displacement (CTOD)

The crack tip opening displacement, δ_5, is measured directly between two points indented in the surface of the specimen close to the crack tip. The points are located 5 mm apart across the crack plane and normal to the tip position. Further details are given in Appendix 4.

3.5 Accuracy of Transducers

The force 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 linearitiy should be evaluated at the temperatures experienced by the transducers during the test.

3.6 Test Temperature

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.

3.7 Specimen and Fixture Alignment

For compact specimen testing, the centre-lines of the upper and lower clevises must be within the smaller of 0.03 B or 1 mm of each other and within the smaller of 0.03 B 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 perpendicular to the axes of the rollers.

For centre cracked tensile specimen testing, the centre lines of the upper and lower loading shackle, Figure 12a, must be within the smaller of 0.03 B or 1 mm of each other and within the smaller of 0.03 B or 1 mm of the specimen mid-thickness centre line. The anti-buckling guides should be supported at the grips by means of linking rods, Figure 12b to avoid interference with the gauges. To avoid load being transferred via the anti-buckling guides to the specimen, the rods must not be rigidly fixed to the grips.

4 TEST PROCEDURE

The test shall be carried out under crack mouth opening, load-line or cross-head displacement control. The force-displacement data and the amount of crack growth are required to evaluate the fracture behaviour of a specimen.

4.1 Test Method

4.1.1 Measure and record the force displacement behaviour of the specimen at a rate such that the rate of the initial increase of the stress intensity is in the range 0.55 to 2.75 MPa $m^{1/2}/s$. Use the stress intensity factor defined in Section 2.3.1.3 of this Procedure to determine the rate.

4.1.2 Continue the test until the specimen can either sustain no further increase in displacement or unstable fracture occurs.

4.1.3 If unstable fracture occurs, measure the initial crack length and stable crack growth as described in Section 4.2. Evaluate the fracture parameters, as appropriate, using the procedures given in Sections 5 and 6.

4.1.4 If only stable crack growth occurs, then the crack growth must be measured from additional test specimens using either the multiple specimen method described in Section 4.3 or inferred from single specimen methods described in Appendix 5. Evaluate the fracture parameters using the procedure given in Section 7.

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 such as 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.

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 14. 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 15.

In centre cracked tensile specimens the initial crack length a_0 corresponds to half of the distance between the ends of the two fatigue pre-cracked zones, Figure 16.

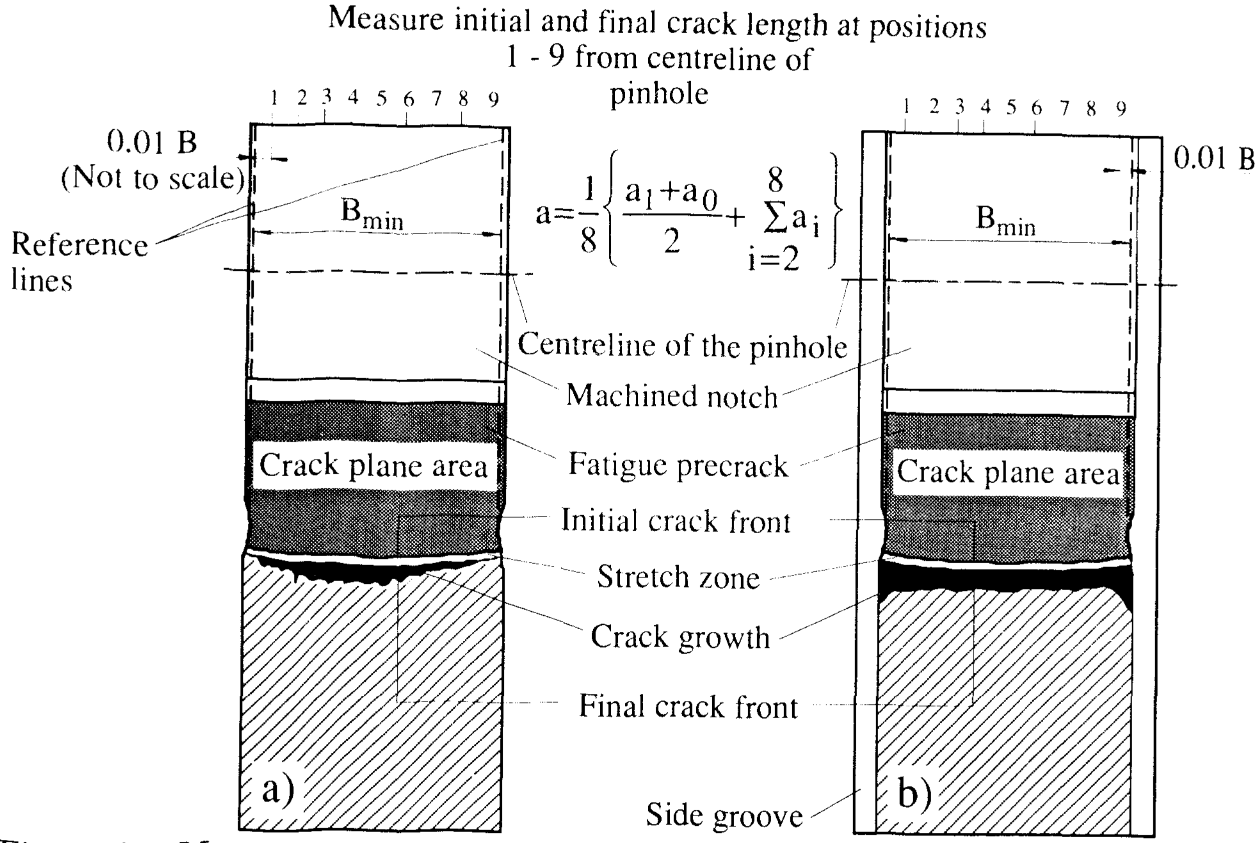


Figure 14: Measurement of crack lengths on compact specimens:
a) plain sided specimens, **b) side grooved specimens.**

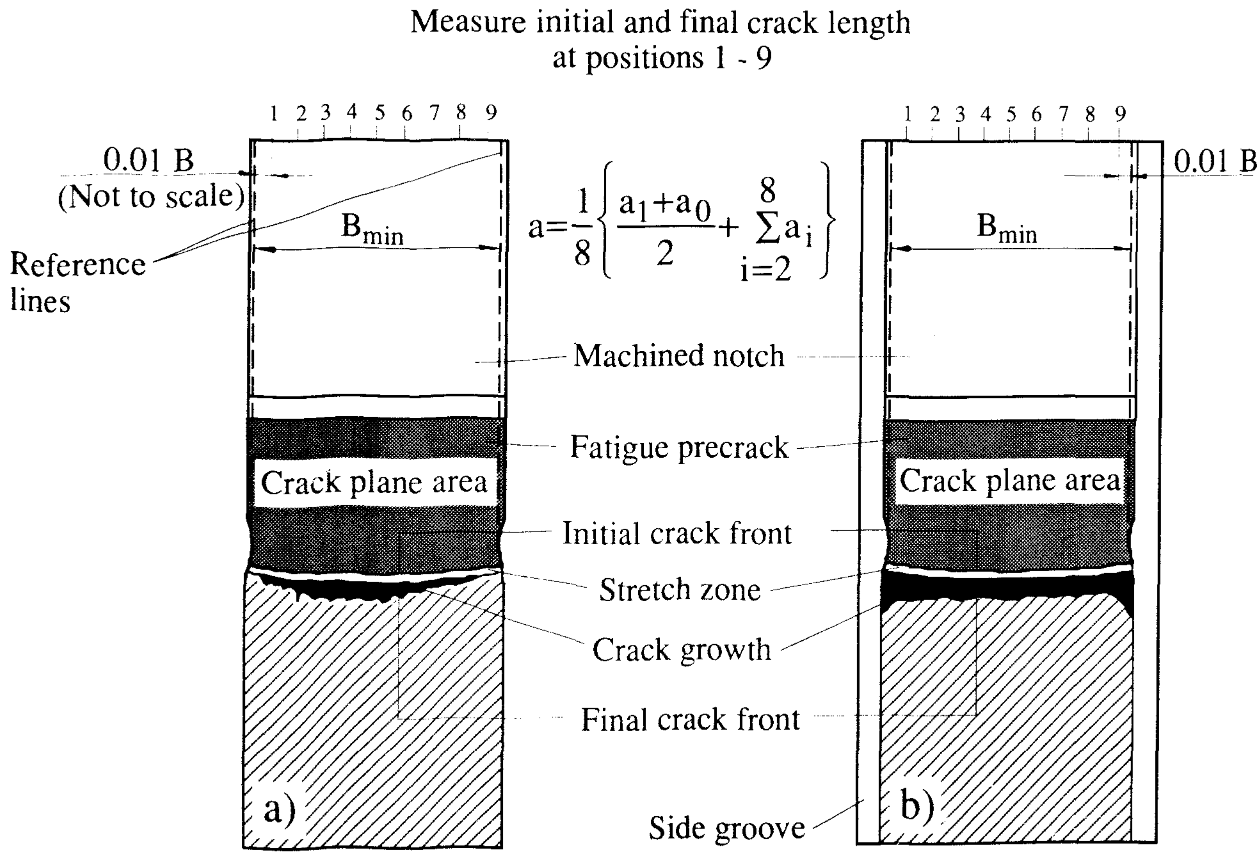
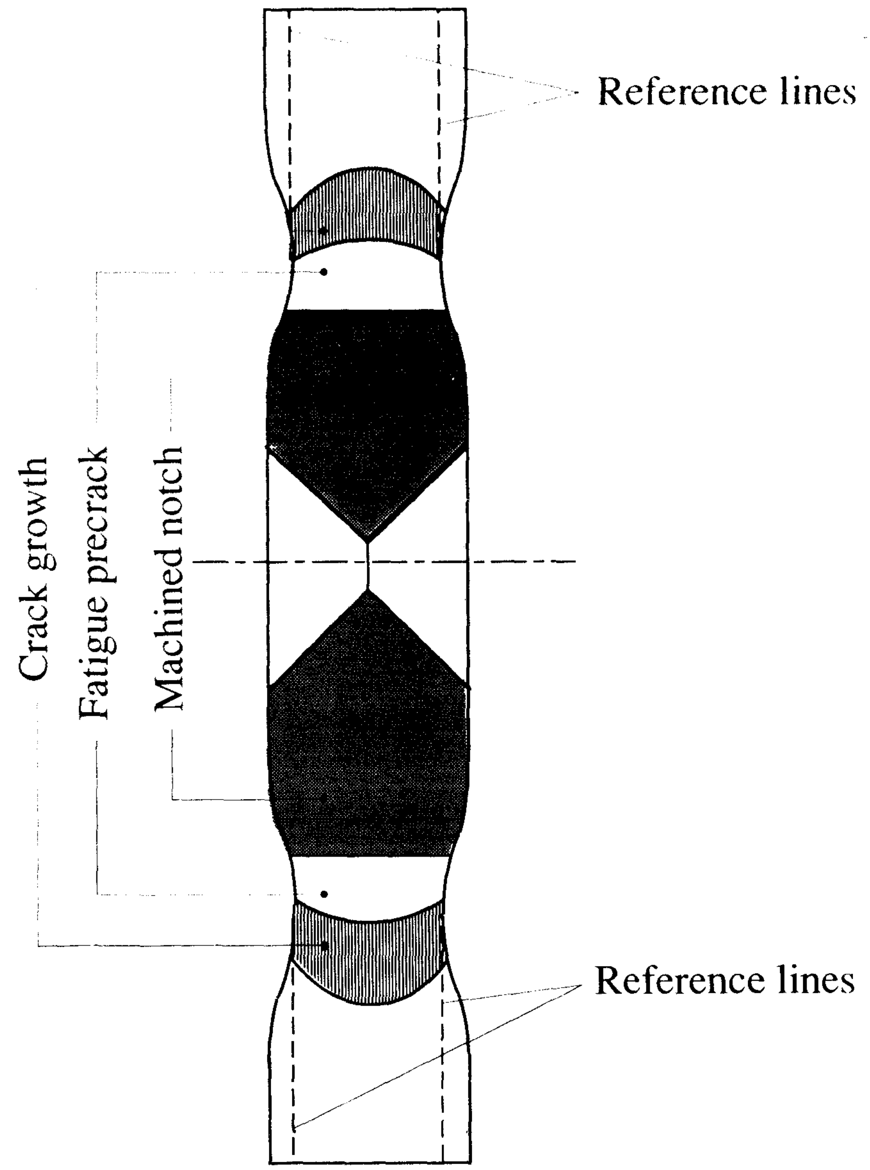


Figure 15: Measurement of crack lengths on single edge notch bend specimens:
a) plain sided specimens, **b) side grooved specimens.**

Figure 16:

Measurement of crack length on centre cracked tensile specimens. The same procedure is used as outlined in Figures 15 and 16. The average of both cracks represents the crack lengths of the centre cracked tensile specimen.



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 14 to 16. 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 ± 10 percent, then report non-uniform fatigue pre-crack growth as required in Section 8.3.

4.2.3 Measure to an accuracy of 0.25 percent or 0.05 mm, whichever is the greater, the minimum difference between the initial crack length and the start of each fatigue pre-cracked zone, as appropriate. If a zone does not exceed the larger of 0.05 a_0 or 1.5 mm, then report insufficient fatigue pre-crack growth as required in Section 8.3. For centre cracked tensile specimens, if the difference between the two zones exeeds the larger of $0.05a_0$ or 1.5 mm, then report non-symmetric fatigue pre-crack growth as required in Section 8.3.

4.2.4 If appropriate 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. For the centre cracked tensile specimen the crack growth Δa is the average value obtained ahead of both initial crack fronts. If the difference between the growth ahead of the crack fronts exceeds 30%, then report non-symmetric crack growth in Section 8.3.

4.2.5 Measure the maximum and minimum crack growth between measurement positions 1 to 9, Figures 14 to 16. 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. For the centre cracked tensile specimen, treat the growth ahead of each crack front separately.

4.2.6 Examine the fracture surfaces for evidence of arrested unstable crack growth regions ahead of the fatigue pre-crack and any other unusual features on the fracture surfaces. Record the number of regions and associated fracture appearance as required in Section 8.3.

4.3 Multiple Specimen Method

The multiple specimen method is used to measure stable crack growth, Figure 4c. The method requires the testing of several nominally identical specimens to provide the data distribution specified in Sections 7.4, 7.8, and 7.9, as appropiate. Usually one specimen is required to give an indication of the displacement needed to obtain the maximum crack growth allowed by this procedure.

4.3.1 Load a specimen to a displacement just beyond the maximum force attainable, then reduce the force 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.

4.3.2 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 force should not exceed three quarters of the final force measured during the test.

4.3.3 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, if required, using the procedure given in Section 7.2.

4.3.4 Repeat the test procedure with further specimens terminating each test at the displacement judged to give crack growth satisfying the requirement given in Section 7.4, 7.8, and 7.9, as appropriate.

4.3.5 Only data satisfying the crack growth criteria, Δa_{max}, given in Section 7.3, can be used in subsequent analysis of the data.

5 PLANE STRAIN FRACTURE TOUGHNESS K_{IC}

The procedure to evaluate the plane strain fracture toughness K_{Ic} from compact and single edge notch bend specimens which exhibit an essentially linear force-displacement record, Figure 4a, prior to unstable fracture is described in this section. K_{Ic} is believed to represent a lower limiting value of fracture toughness in a material. An equivalent requirement for the centre cracked tensile specimen has not yet been established. Consequently, the centre cracked specimen cannot be used to evaluate K_{Ic} of a material.

5.1 Interpretation of Test Record

Examples of three typical force-displacement records are shown in Figure 17.

5.1.1 Construct a tangent OA to the linear portion of the force-displacement record, ignoring any slight initial non-linearity, and measure the slope, m, of OA. Construct a line of reduced slope 0.95 m through the intercept of the tangent and the displacement axis. The intercept of the tangent with the test record is defined as F_5, Figure 17.

5.1.2 The force F_c used to evaluate K_c is defined in relation to F_5 depending on the type of test record, Figure 17. For type I and II test records, F_c is the highest force that precedes F_5. For type III record F_c equals F_5.

5.1.3 Calculate the ratio F_{max}/F_c where F_{max} is the maximum sustained force, Figure 17. If the ratio exceeds 1.10, then the test record is considered non-linear and either the fracture parameters δ_{5c}, δ_{5u} or J_c, J_u should be evaluated, Section 6.

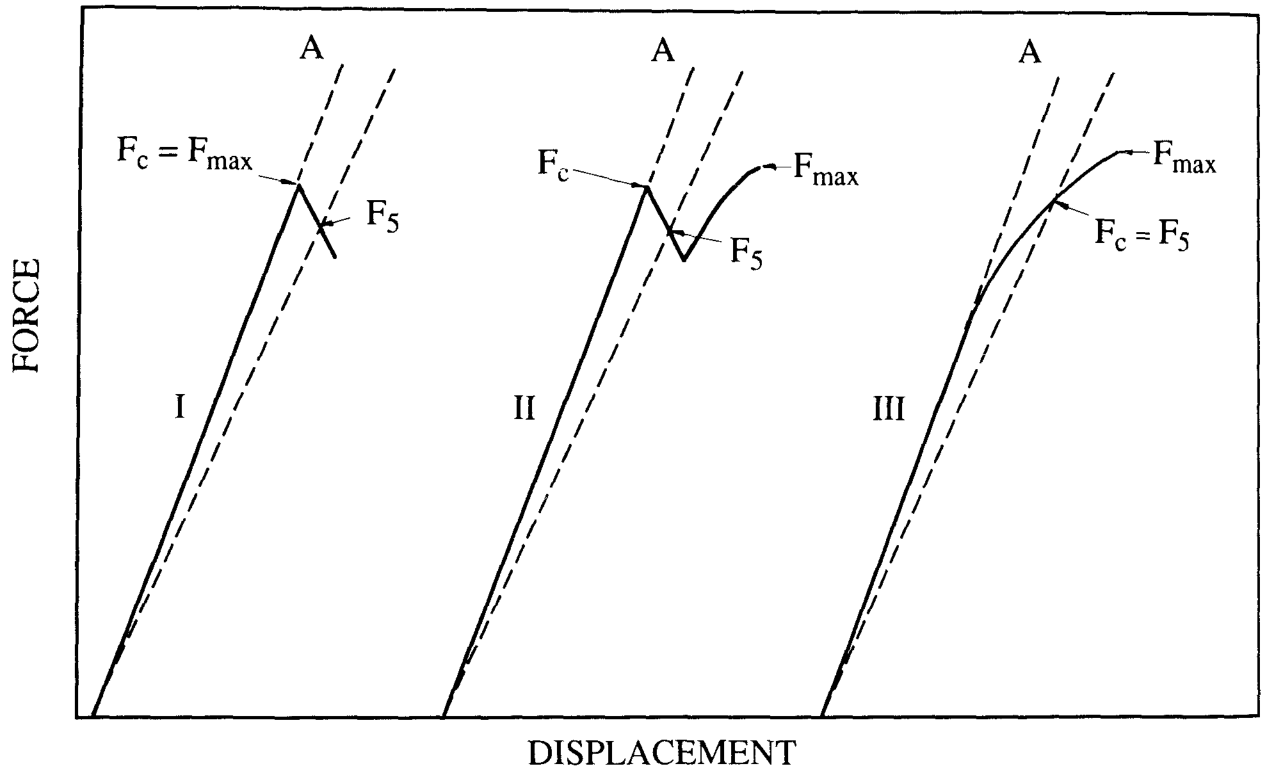


Figure 17: Typical force-displacement records.

5.2 Parameter K_c

If F_{max}/F_c is less than or equal to 1.10, then calculate K_c from

$$K_c = \frac{F_c}{B\sqrt{W}} f(a_0 / W)$$

where the stress intensity function $f(a_0/W)$ is defined in Appendix 1. For side grooved specimens replace B with $\sqrt{BB_n}$ where B_n is the net section thickness.

5.3 Validity Requirement

The validity requirement can only be applied to K_c values obtained from compact and single edge notch bend specimens.

5.3.1 Calculate K_{max} from the smaller of

$$K_{max} = R_{p0.2}\sqrt{\frac{a_0}{2.5}}$$

$$K_{max} = R_{p0.2}\sqrt{\frac{W - a_0}{2.5}}$$

and

$$K_{max} = R_{p0.2}\sqrt{\frac{B}{2.5}}$$

5.3.2 If K_c is less than K_{max}, then K_c can be designated K_{Ic}, the plane strain fracture toughness.

5.3.3 If K_c is greater than K_{max}, then a fracture parameter according to Section 6 can be determined.

6 FRACTURE PARAMETERS δ_{5c}, J_c AND δ_{5u}, J_u

The procedure to evaluate δ_{5c}, J_c and δ_{5u}, J_u from specimens which exhibit a non-linear force-displacement record, Figure 4b, prior to unstable fracture, is described in this section. This type of test record is usually exhibited by materials in the ductile-brittle transition region.

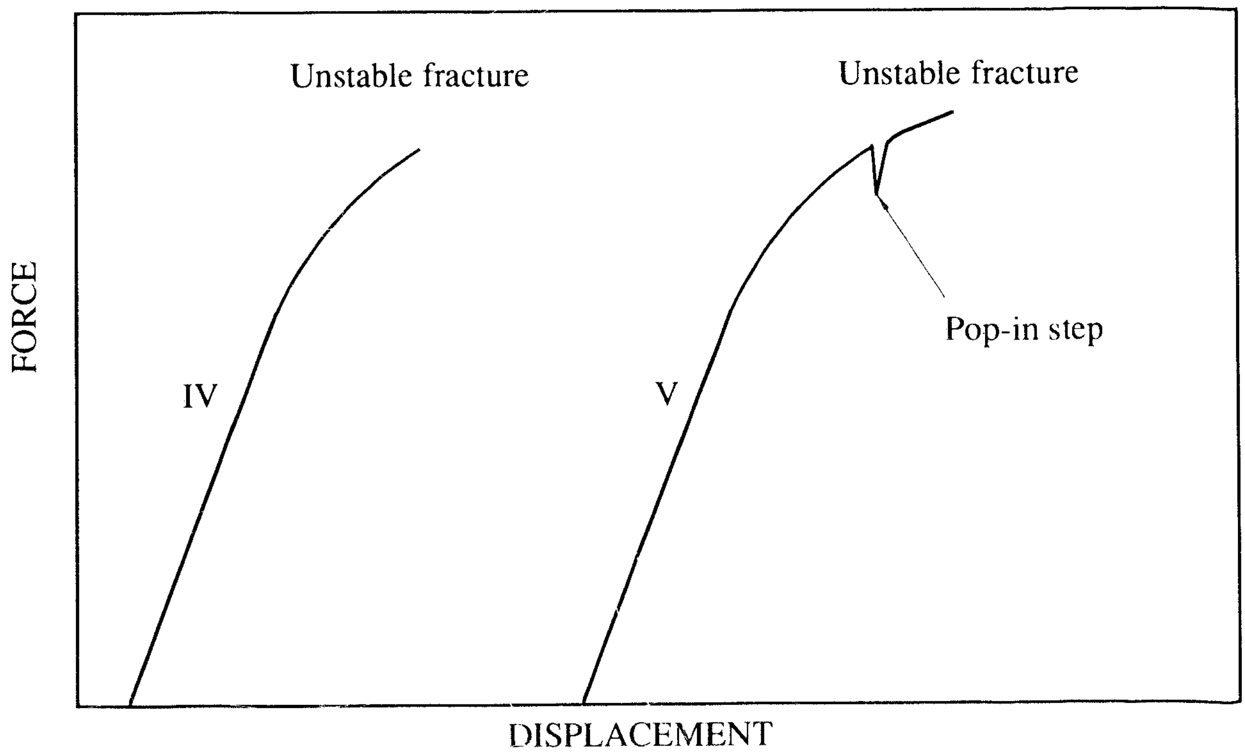


Figure 18: Typical force-displacement records.

Examples of typical test records are shown in Figure 18. Type V has a pop-in step in the force-displacement record prior to unstable fracture. The pop-in step is usually characterized by an abrupt force drop and a small increase in displacement. The behaviour is associated with the arrest of a rapidly moving crack during unstable crack growth which often appears as a distinct brittle thumbnailed region on the fracture surface of a specimen. In order to interpret type V test records, Figure 18, it is necessary to assess the significance of a pop-in step and relate the number of pop-in steps to the number of thumbnailed regions on the fracture surface, Section 4.2.6.

For those cases where the amount of stable crack growth cannot be measured prior to unstable fracture, δ_5 and J are designated δ_{5uc} and J_{uc}, respectively. The subscript uc means the parameter is evaluated for an unknown amount of crack growth.

Fracture in this regime may result in large scatter. Guidance for statistical treatment is given in Appendix 10.

6.1 Significance of a Pop-in

6.1.1 Evaluate the load drop f_i/F_i and displacement increase d_i/D_i, Figure 19, at each pop-in. If both the force drop and displacement increase are less than 1 percent, then the pop-in step is considered insignificant.

6.1.2 For those pop-in steps not satisfying the requirement given in Section 6.1.1, calculate the percentage force drop at the i^{th} pop-in using the equation

$$\frac{fd_i}{F_i} = 1 - \frac{D_i}{F_i}\left\{\frac{F_i - f_i}{D_i + d_i}\right\}$$

where the terms are defined in Figure 19. If fd_i/F_i exceeds 5 percent then the pop-in step is considered significant.

6.1.3 Record the number of insignificant and significant pop-in steps as required in Section 8.3.

6.2 Fracture Parameter δ_5

6.2.1 The crack tip opening displacement, δ_5 is measured directly in this Procedure, Section 3.4.3.

6.2.2 Calculate $\delta_{5,max}$ from the smaller of

$$\delta_{5,\max} = \frac{(W - a_0)}{30}$$

and

$$\delta_{5,max} = \frac{B}{30}.$$

6.2.3 If δ_5 does not exceed $\delta_{5,max}$, then δ_5 characterizes the fracture process for the specimen tested.

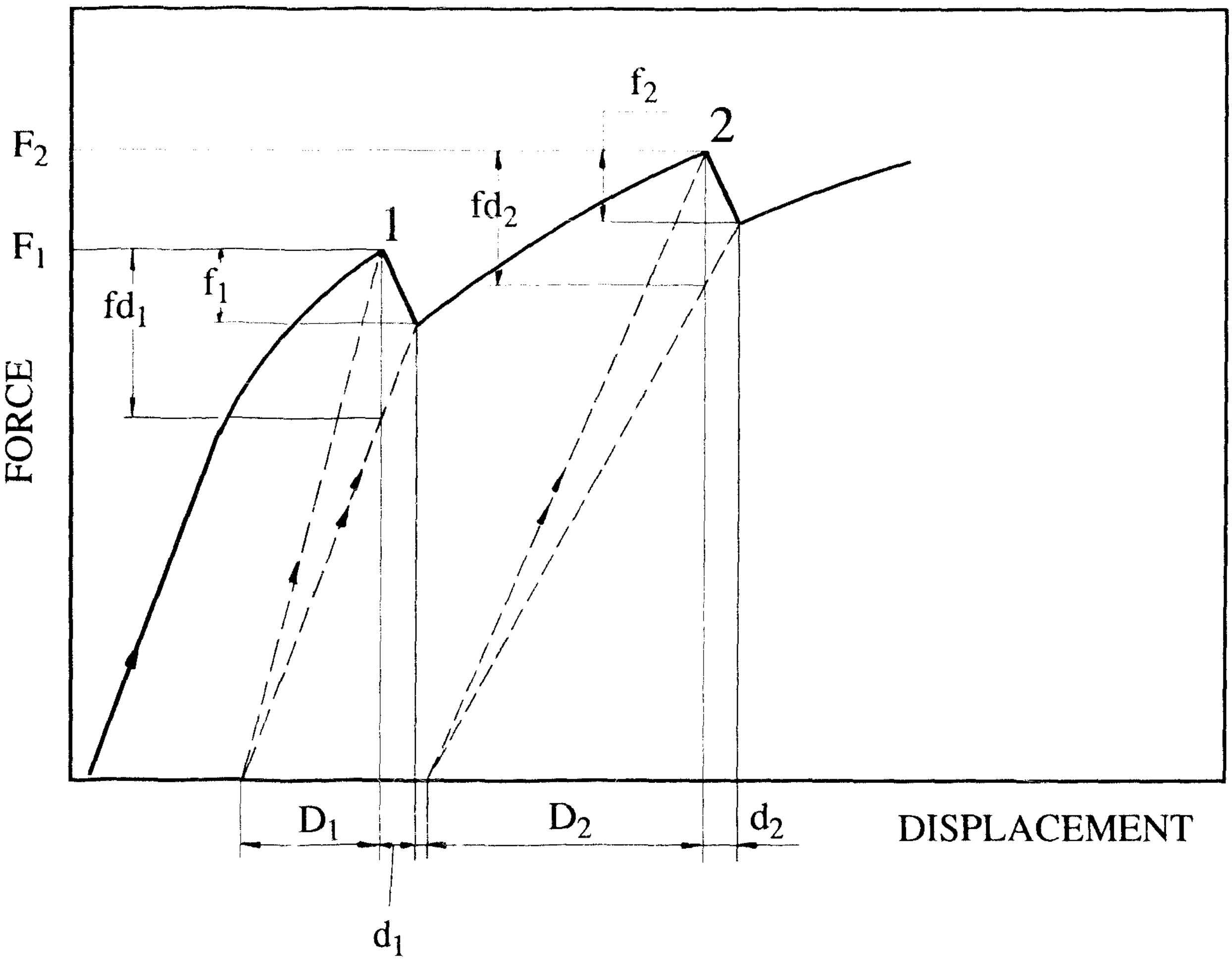


Figure 19: Assessment of pop-in step behaviour.

6.3 Fracture Parameter J

6.3.1 CT and SENB specimens

6.3.1.1 Measure the area U under the force versus load-point displacement record up to the line at constant displacement, Figure 20, corresponding to either the unstable fracture point or the first significant pop-in step.

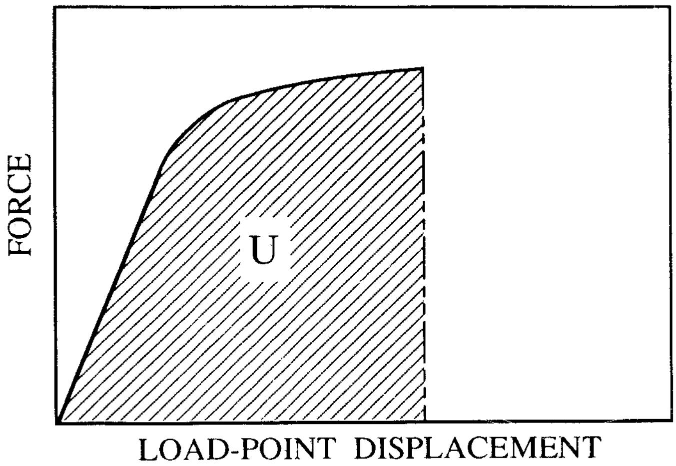


Figure 20:

Definition of absorbed energy, U.

6.3.1.2 Calculate J_0 using the relationship

$$J_0 = \frac{\eta U}{B(W - a_0)}$$

where

$\eta.$	$= 2 + 0.522\,(1 - a_0/W)$	for compact specimens,
	$= 2$	for single edge notch bend specimens.

For sidegrooved specimens replace B with the net section thickness B_n.

6.3.1.3 Calculate J_{max} from the smaller of

$$J_{max} = (W - a_0)\frac{R_f}{20}$$

and

$$J_{max} = \frac{BR_f}{20}$$

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

6.3.1.4 If J_0 does not exceed J_{max}, then J_0 characterizes the fracture process for the thickness tested.

6.3.2 CCT specimens

6.3.2.1 Measure the area U* under the force versus load-point displacement record up to the point corresponding to either unstable fracture or the first significant pop-in step,

Figure 21. Alternatively, U* can be determined from the force versus CMOD diagram, Figure 22.

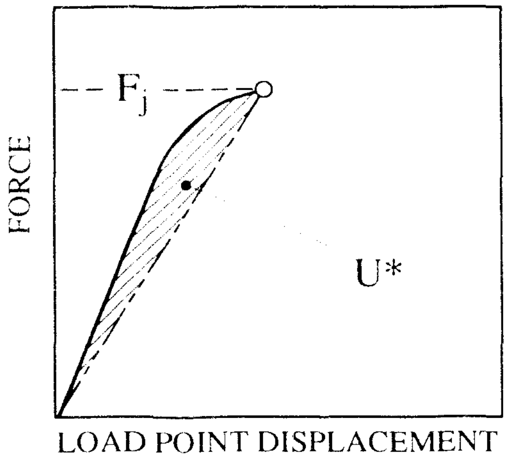


Figure 21: Definition of U*.

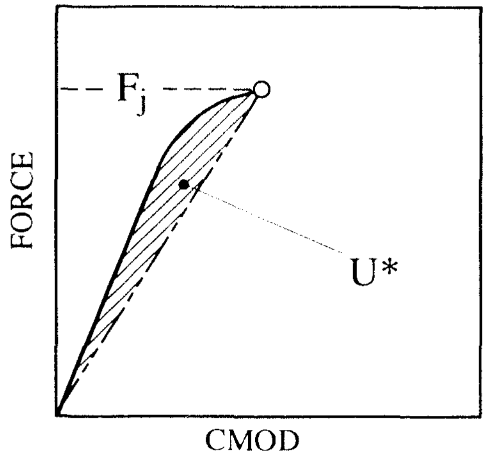


Figure 22: Determination of U* from force-CMOD diagram.

6.3.2.2 Calculate J_o using the relationship

$$J_0 = \frac{K^2}{E} + \frac{U^*}{B(W - a_0)}$$

where,

$$K = \frac{F_j}{B\sqrt{W}} f(a_o / W)$$

and F_j is the force at unstable fracture or the first significant pop-in, Figure 21, $f(a_o/W)$ is the stress intensity function defined in Appendix 1, E is Young's modulus.

J_o should only be evaluated from this relationship if $F_j < 1.8\ R_{p0.2}$ BW. If F_j exceeds this limit, then J_o may be severely overestimated and is therefore regarded as invalid.

6.4 δ_{5c}, J_c and δ_{5u}, J_u

6.4.1 If the total measured stable crack growth prior to unstable fracture or to the first significant pop-in is less than 0.2 mm + $(\delta_5/1{,}87)\ (R_{p0.2}/R_m)$ or 0.2 mm+$(J/3.75\ R_m)$, then δ_5 and J_0 are designated δ_{5c} and J_c, respectively.

Note: $R_{p0.2}$ and R_m are the yield strength and ultimate tensite strength at test temperature respectively!

6.4.2 If the total measured stable crack growth prior to unstable fracture or to the first significant pop-in is greater than or equal to the values specified in Section 6.4.1, then δ_5 and J_0 are designated δ_{5u} and J_u, respectively. δ_{5u} and J_u values must be reported with the corresponding Δa value as required in Section 8.4.

6.4.3 If the amount of stable crack growth cannot be measured prior to unstable fracture or to the first significant pop-in then δ_5 and J_0 are designated δ_{5uc} and J_{uc}, respectively.

6.4.4 If these parameters have been determined using CCT specimens, then they must be reported with the superscript CCT, e.g. δ_{5c}^{CCT}.

7 CRACK GROWTH FRACTURE RESISTANCE CURVES AND RELATED FRACTURE PARAMETERS $\delta_{5,0.2/BL}$, $J_{0.2/BL}$, $\delta_{5,0.2}$, $J_{0.2}$

The procedures to evaluate the fracture behaviour of specimens which exhibit only stable crack growth and a non-linear force-displacement record, Figure 4c, are described in this section. The fracture behaviour is characterized in terms of either the variation in crack tip opening displacement δ_5 or fracture resistance J with crack growth, Δa. Methods are given for interpreting the δ_5-Δa and J-Δa behaviour in terms of the fracture parameters $\delta_{5,0.2/BL}$, $J_{0.2/BL}$, $\delta_{5,0.2}$, $J_{0.2}$. The analysis procedures given in the section for determining either δ_5 or J are based on multiple specimen data.

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 δ_5 and J characterize the fracture behaviour of ductile materials.

The validity limits are expressed in terms of the maximum δ_5, J and Δa values which can be measured for a given test specimen size. Data satisfying the validity limits are 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.

If these limits are exceeded then the crack growth resistance data are only relevant to the thickness tested. In such cases, it may be possible with the use of the Δa_{max} limit together with a width-to-thickness requirement to ensure that the data are independent of the in-plane dimensions of the specimen.

Three fracture parameters are described for estimating δ_5 and J close to the onset of crack initiation from crack growth fracture resistance data.

These parameters are:

(1) $\delta_{5,0.2/BL}$ or $J_{0.2/BL}$ which measure the fracture resistance at 0.2 mm crack growth beyond crack initiation. 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) $\delta_{5,0.2}$ or $J_{0.2}$ 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 $\delta_{5,0.2/BL}$ and $J_{0.2/BL}$. High toughness materials may be ranked unduly low.

(3) A more accurate estimate of the fracture resistance at crack initiation, δ_{5i} or J_i, requiring the use of a scanning electron microscope is given in Appendix 6.

Note: For valid parameters the data points used for the R-curve fit do not have to meet the $\delta_{5,\,max}$ or J_{max} requirements.

Additionally, parameters δ_{5g} and J_g are defined which give the maximum fracture resistance values that can be measured from a given test specimen. Also $d\delta_5/da$ and dJ/da, which are the slopes of the δ_5-Δa and J-Δa curves, respectively, are used to measure the material resistance to crack growth.

A flowchart of the procedure to follow in order to determine the fracture parameters described in this section is given in Figure 3b.

In an Appendix to this Procedure a method is described for determining K-based crack growth resistance curves on high strength materials.

7.1 Fracture Resistance δ_5

The crack tip opening displacement, δ_5, is measured directly in this Procedure, Section 3.4.3.

7.2 Fracture Resistance J

7.2.1 CT and SENB specimens

7.2.1.1 Measure the area U under the force versus load-point displacement record up to the line at constant displacement corresponding to the termination of the test, Figure 20.

7.2.1.2 Calculate J_o for each sidegrooved specimen using the relationship

$$J_0 = \frac{\eta U}{B_n(W - a_0)}$$

where

$\eta = 2 + 0.522\,(1\text{-}a_0/W)$ for compact specimens,

$= 2$ for single edge notch bend specimens.

For non-sidegrooved specimens replace B_n with B in the above formula.

7.2.1.3 Fracture Resistance J allowing for Crack Growth

The J-equation used in Section 7.2.1.2 does not allow for crack growth during a test. The errors in the J-values are usually negligible for crack growth less than 0.1 ($W\text{-}a_0$). If the crack growth validity limit is extended beyond 0.1 ($W\text{-}a_0$) then all data points should be corrected for crack growth. A suitable approximation is

$$J = J_0\left\{1 - \frac{(0.75\eta - 1)\Delta a}{(W - a_0)}\right\}$$

where η is defined in Section 7.2.1.2.

7.2.2 CCT Specimens

7.2.2.1 Measure the area U* under the force versus load-point displacement record up to the point corresponding to the termination of the test, Figure 21. Alternatively, U* can be determined from the force versus CMOD record, Figure 22.

7.2.2.2 Calculate J_o using the relationship

$$J_0 = \frac{K^2}{E} + \frac{U^*}{B(W - a_0)}$$

where

$$K = \frac{F_j}{B\sqrt{W}} f(a_o / W)$$

and F_j is the force at termination of the test, Figure 21,

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

E is Young's modulus.

J_o should only be evaluated if $F_j < 1.8\, R_{p0.2}\, BW$. If F_j exceeds this limit, then J_o may be severely overestimated and is therefore regarded as invalid.

7.2.2.3 Fracture Resistance J allowing for Crack Growth

The J-equation used in Section 7.2.2.2 does not allow for crack growth during a test. The errors in the J-values are usually negligible for crack growth less than 0.1($W-a_0$). If crack growth is analyzed beyond this value, then all data points should be corrected for crack growth. A suitable approximation is

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

where $\eta = 0.5$.

7.3 Δa_{max} Crack Growth Limit

7.3.1 Construct a plot of fracture resistance against crack growth using the data obtained in Sections 4.2, 7.1 and 7.2.

7.3.2 CT and SENB Specimens

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

$$\Delta a_{max} = 0.25(W\text{-}a_o) \qquad \text{for } \delta_5$$

or

$$\Delta a_{max} = 0.1(W\text{-}a_o) \qquad \text{for J.}$$

7.3.3 CCT Specimens

For each specimen, calculate Δa_{max} from either

$$\Delta a_{max} = W\text{-}a_o\text{-}B \qquad \text{for } \delta_5$$

or

$$\Delta a_{max} = 0.4\,(W\text{-}a_o) \qquad \text{for J.}$$

7.3.4 Determine the slope of the blunting line as described in Appendix 7. Plot the blunting line on a graph containing the crack growth fracture resistance data. Report the slope of the blunting line as required in Section 8.4.

7.3.5 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 either Section 7.3.2 or Section 7.3.3, Figure 23.

7.3.6 Construct an exclusion line parallel to the blunting line at an offset of 0.10 mm, Figure 23.

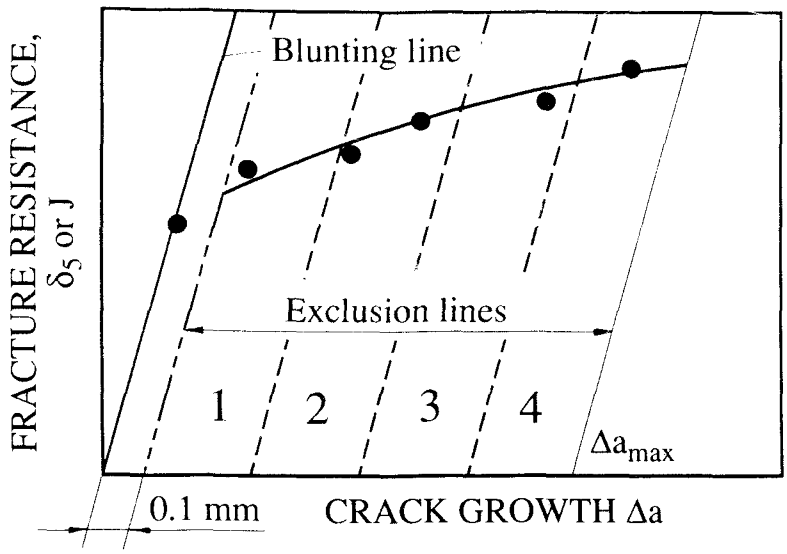


Figure 23:
Data point distribution for determining fracture parameters.

7.3.7 If only the crack growth fracture resistance curve is to be determined, the blunting line construction can be avoided by the use of a vertical exclusion line at Δa_{max}, Figure 24.

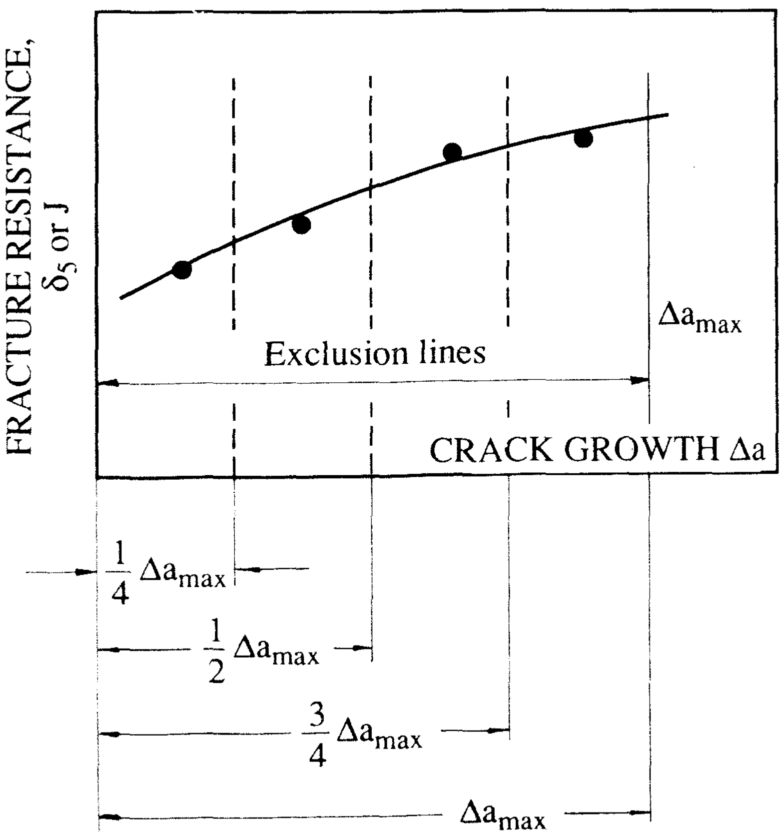


Figure 24:
Data distribution.

7.4 Data Spacing Requirement

7.4.1 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 Figures 23 and 24. The data spacing requirement shown in Figure 23 must be used for the evaluation of the fracture parameters $\delta_{5,0.2/BL}$, $J_{0.2/BL}$, δ_{5i}, and J_i. The alternative data spacing shown in Figure 24 can be used if only the crack growth fracture resistance curve is determined.

7.4.2 Any specimen which exhibits cleavage fracture shall be reported as required in Section 8.3. If the amount of prior stable crack growth can be measured, then the data can be used to describe the crack growth fracture resistance curve. Any cleavage data points shall be clearly identified on the fracture resistance curve as required in Section 8.4.

7.5 Curve Fit

7.5.1 Determine the best fit curve through the data points which lie within the Δa_{max} exclusion lines shown in either Figure 23 or Figure 24, whichever is appropriate, using the equation

$$\delta_5 \text{ or } J = A + C\Delta a^D,$$

where A and C ≥ 0 and O ≤ D ≤ 1.

A method for evaluating the constants A, C and D is given in Appendix 8. If A or C are less than zero the curve fit is unacceptable and additional tests or the use of single specimen test techniques, Appendix 5, are recommended.
The crack growth resistance curve can also be represented as the series of data points.

7.6 δ_5 Validity Limits

7.6.1 CT and SENB Specimens

7.6.1.1 For each specimen calculate $\delta_{5,max}$ from the smaller of

$$\delta_{5,max} = \frac{(W - a_0)}{30}$$

and

$$\delta_{5,max} = \frac{B}{30}.$$

7.6.1.2 Construct an exclusion line to the δ_5-Δa data at the minimum calculated $\delta_{5,max}$ value, Figure 25.

7.6.1.3 The crack growth resistance curve enclosed by the $\delta_{5,max}$ and Δa_{max} exclusion lines may be regarded as a material property independent of specimen size.

7.6.1.4 The intersection of the curve with either the $\delta_{5,max}$ or Δa_{max} exclusion lines defines δ_{5g}, Figure 25. δ_{5g} is the upper limit to δ_5-controlled crack growth behaviour for the test specimen size.

7.6.1.5 If δ_5 is greater than B/30, then the crack growth resistance curve may be thickness dependent. If $(W-a_o)/B$ is equal to or greater than 4 and the δ_5-Δa curve is within the Δa_{max} exclusion line, then the crack growth resistance curve is independent of the in-plane dimensions.

7.6.2 CCT Specimens

The crack growth resistance curve is in general thickness dependent. If $(W-a_o)/B$ is equal to or greater than 4 and the δ_5-Δa curve is within the Δa_{max} exclusion line, then the crack growth resistance curve is independent of the in-plane dimensions.

Note: An established $\delta_{5,max}$ limit for CCT specimens is not yet available.

7.7 J Validity Limits

7.7.1 CT and SENB Specimens

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

$$J_{max} = (W - a_0)\frac{R_f}{20}$$

and

$$J_{max} = B\frac{R_f}{20}$$

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

7.7.1.2 Construct an exclusion line to the J-Δa data at the minimum calculated J_{ma}, value, Figure 25.

7.7.1.3 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.

7.7.1.4 The intersection of the best fit curve with either the J_{max} or Δa_{max} exclusion line defines J_g, Figure 25. J_g is the upper limit to J-controlled crack growth behaviour for the test specimen size.

7.7.1.5 If J is greater than $(B \cdot R_f)/20$, then the crack growth resistance curve may be thickness dependent. If $(W-a_0)/B$ is equal to or greater than 4 and the J-Δa curve is within the Δa_{max} exclusion line, the crack growth resistance curve is independent of the in-plane dimensions.

7.7.2 CCT Specimens

The crack growth resistance curve is in general thickness dependent. If $(W-a_0)/B$ is equal or greater than 4 and the J-Δa curve is within the Δa_{max} exclusion line, the crack growth resistance curve is independent of the in-plane dimensions.

Note: An established J_{max} limit for CCT specimens is not yet available. Numerical evidence suggests under plane stress conditions J_{max} is given by

$$J_{max} = (W - a_0)\frac{R_{p0.2}}{10}.$$

7.8 Fracture Parameters at 0.2 mm of Ductile Tearing

The following procedure applys to CT and SENB specimens. It can also be applied to CCT specimens, but the resulting values of $\delta_{5,0.2/BL}$ and $J_{0.2/BL}$ may be thickness dependent.

7.8.1 $\delta_{5,0.2/BL}$

7.8.1.1 Construct a plot of the blunting line, Section 7.3.4, and the best fit curve, Section 7.5.1, through the δ_5-Δa data.

7.8.1.2 Construct a parallel line offset to the blunting line at 0.2 mm crack growth, Figure 26. The intersection of the best fit curve with the offset line defines $\delta_{5,0.2/BL}$. At least one δ_5-Δa data point should be within 0.1 mm of the parallel offset line.

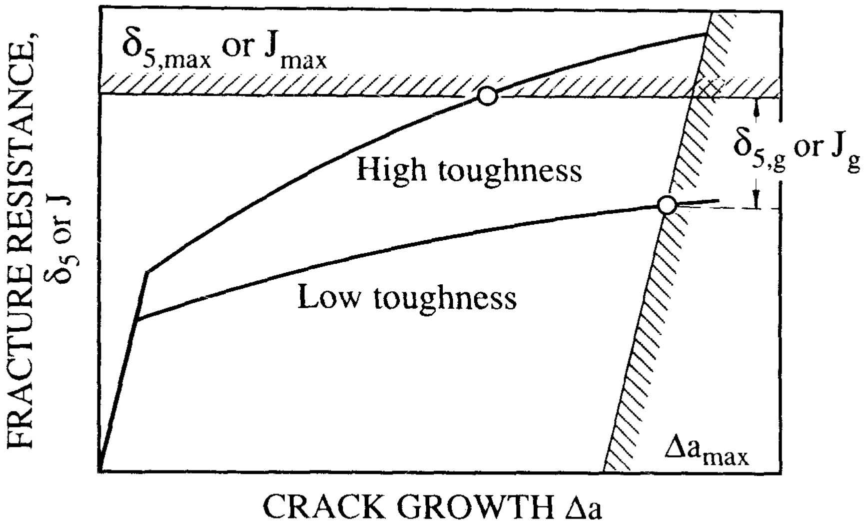


Figure 25: Validity limits.

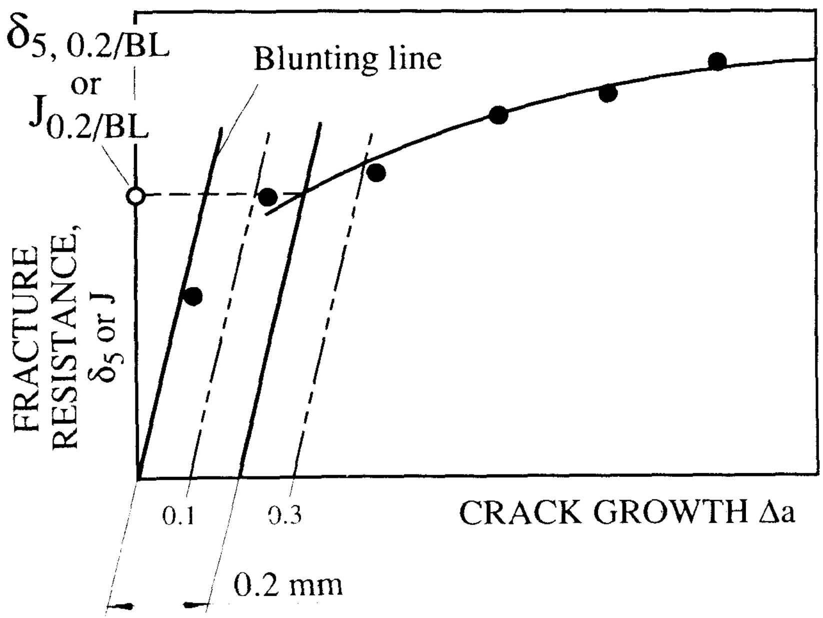


Figure 26: Determination of $\delta_{5,0.2/BL}$ and $J_{0.2/BL}$.

7.8.1.3 If $\delta_{5,0.2/BL}$ exceeds $\delta_{5,max}$ determined in Section 7.6.1, then $\delta_{5,0.2/BL}$ is invalid according to this Procedure.

7.8.1.4 Evaluate the slope of the δ_5-Δa curve, $\left(\frac{d\delta_5}{da}\right)_{0.2/BL}$ at the intersection point from the equation determined in Section 7.8.1.1. If the slope of the blunting line

$$\left(\frac{d\delta_5}{da}\right)_{BL} < 2\left(\frac{d\delta_5}{da}\right)_{0.2/BL},$$

then $\delta_{5,0.2/BL}$ is invalid according to this procedure.

7.8.2. $J_{0.2/BL}$

7.8.2.1 Construct a plot of the blunting line, Section 7.3.4, and the best fit curve, Section 7.5.1 through the J-Δa data.

7.8.2.2 Construct a parallel line offset to the blunting line at 0.2 mm crack growth, Figure 26. 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.

7.8.2.3 If $J_{0.2/BL}$ exceeds J_{max} determined in Section 7.7.1 then $J_{0.2/BL}$ is invalid according to this procedure.

7.8.2.4 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 7.8.1.1. 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.

7.9 Fracture Parameters at 0.2 mm of Crack Growth Including Blunting

The following procedure applys to CT and SENB specimens. It can also be applied to CCT specimens , but the resulting values of $\delta_{5,0.2}$ and $J_{0.2}$ may be thickness dependent.

7.9.1 $\delta_{5,0.2}$

7.9.1.1 Construct a line corresponding to constant total crack growth of 0.2mm on a plot of the δ_5-Δa data. The intersection of this line with the best fit curve through the data obtained in Section 7.5.1 defines $\delta_{5,0.2}$, Figure 27. At least one data point should be between within 0.2 and 0.4 mm.

7.9.1.2 If $\delta_{5,0.2}$ exceeds $\delta_{5,max}$ determined in Section 7.6.1, then $\delta_{5,0.2}$ invalid according to this procedure.

7.9.2 $J_{0.2}$

7.9.2.1 Construct a line corresponding to constant total crack growth of 0.2 mm on a plot of the J-Δa data. The intersection of this line with the best fit curve through the data obtained in Section 7.5.1 defines $J_{0.2}$, Figure 27. At least one data point should be between 0.2 and 0.4 mm crack growth.

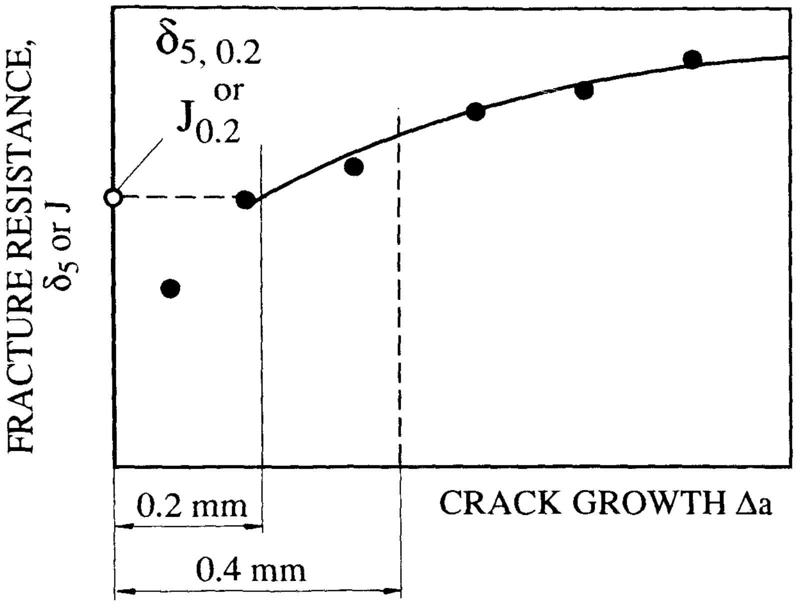


Figure 27: Determination of $\delta_{5,0.2}$ and $J_{0.2}$.

7.9.2.2 If $J_{0.2}$ exceeds J_{max} determined in Section 7.7.1, then $J_{0.2}$ 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 stress 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 sidegrooved specimens, if applicable, and crack plane orientation from either a drawing or the notation given in Figures 28 to 30.

8.3 TEST DETAILS – maximum stress intensity factor and force during final stages of fatigue pre-cracking, temperature, single or multiple specimen method, loading rate and machine control. If applicable, total number of significant and insignificant pop-in steps on the load-displacement test record. Time at test temperature. Method of measuring initial crack length and, if applicable, crack growth. Measured initial crack length. If the multiple specimen method is used, the initial crack length range. If applicable, non-uniform, non-symmetric and insufficient fatigue pre-crack growth. Stable or unstable crack growth. Non-symmetric crack growth. Specimens exhibiting cleavage fracture. If applicable, number of brittle thumbnailed regions ahead of the fatigue pre-crack. If non-uniform or non-symmetric 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 – Force versus load-point displacement or CMOD, as appropriate. Record K_c, K_{Ic}, F_{max}/F_c, δ_{5u}, δ_{5c}, δ_{5uc}, J_c, J_u, and J_{uc}, whichever is applicable. If either J_u or δ_{5u} is applicable, the corresponding crack growth Δa. Record either the δ_5-Δa or J-Δa curve and all data points including details of the exclusion lines, the constructional procedure and equations used to derive the fracture parameters $\delta_{5,0.2/BL}$, $\delta_{5,0.2}$, $J_{0.2/BL}$, $J_{0.2}$, whichever is applicable. Identify on the curve any data points exhibiting cleavage fracture. If applicable, report and provide justification for the use of extended validity limits. If applicable, report the slope of the 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.

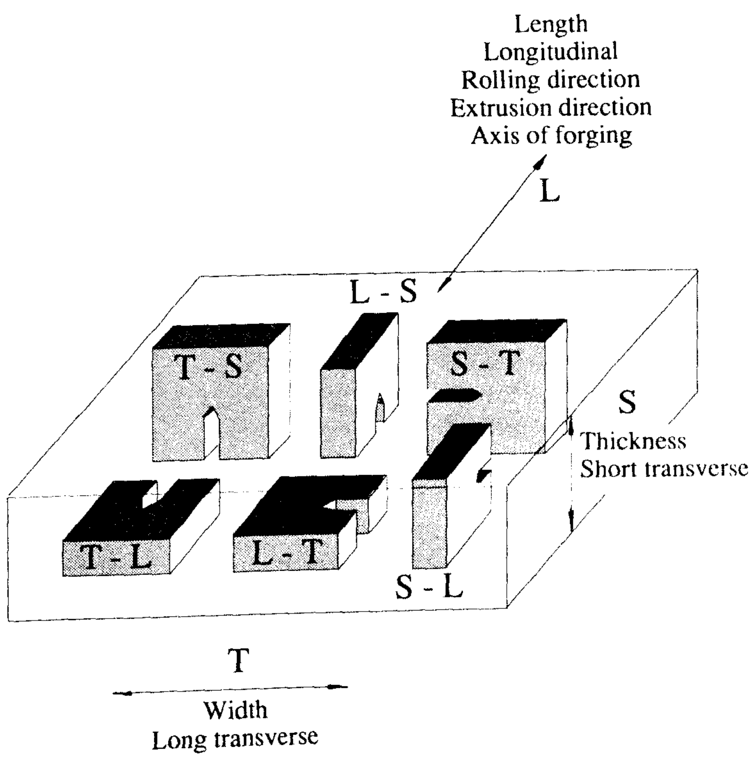


Figure 28:
Crack plane orientation
code for rectangular sections.

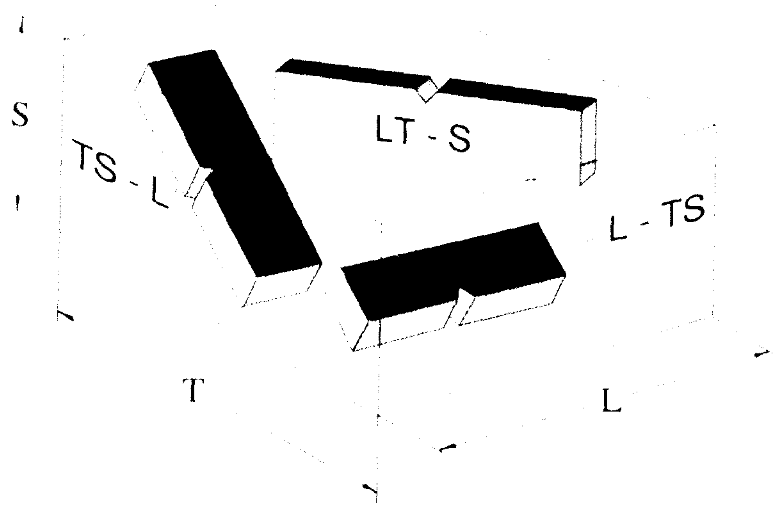


Figure 29:

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

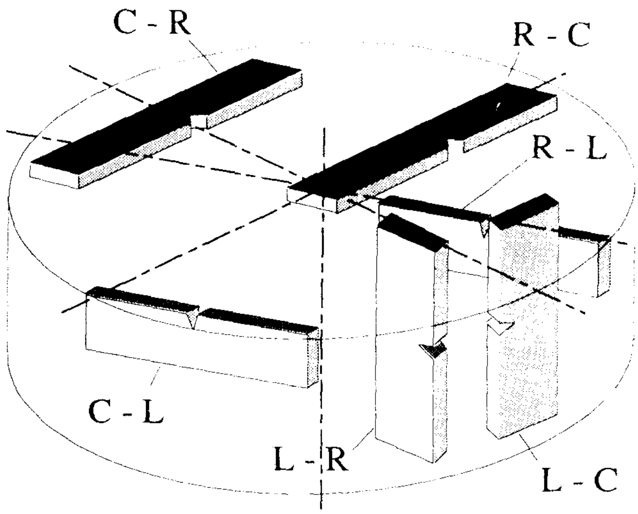


Figure 30:

Crack plane orientation code for bar and hollow cylinder.

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]	Fracture appearance *	
Fracture toughness K_{Ic}	[MPa$\sqrt{m}$]	Crack growth, Δa Stable/Unstable	[mm]
CTOD, δ_5	[mm]	Fracture resistance, J	[MPam]

* for example brittle/ductile crack growth regions; any unusual features on fracture surface, non-symmetric crack growth.

NB If a single specimen method has been used, tabulate all the intermediate values of δ_5, J and Δa.

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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.

EFAM 94, Engineering Flaw Assessment Method (EFAM), GKSS-Forschungszentrum Geesthacht, 21502 Geesthacht, Germany, 1994.

APPENDIX 1

Stress Intensity Functions

A1.1 For a compact specimen

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

A1.2 For a single edge notch bend specimen

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

A1.3 For a centre cracked tensile specimen

$$f(a/W) = \frac{1}{2}\sqrt{\frac{\pi a}{W}\sec\frac{\pi a}{2W}}$$

where a is the half crack length and 2W is the specimen width.

A1.4 Values of f(a/W) are given in Tables A1.1 and A1.2 for the compact and single edge notch bend specimen, respectively. For the bend specimen, S/W of 4 has been assumed.

REFERENCES

[1] Annual Book of ASTM Standards, E399-83, Standard Test Method for Plane Strain Fracture Toughness of Metallic Materials, Section 3, Vol. 03.01, 1990, 488–512.

[2] Annual Book of ASTM Standards, E561-86, Standard Practice for R-Curve Determination, Section 3, Vol. 03.01, 1991, pp. 577–588.

[3] C. Wheeler, J.N. Eastabrook, D.P. Rooke, K.-H. Schwalbe, W. Setz, and A.U. de Koning, Recommendations for the measurement of R-curves using centre cracked panels, J, strain Analysis, Vol. 17, 1982, pp. 205–213.

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 force versus load-point displacement record. Unlike the step notched compact specimen geometry shown in Figure 6 of the Procedure, the single edge notch bend specimen, Figure 10, and the straight notched compact specimen, Figure 5, do not permit direct measurement of the load-point displacement. Consequently the extraneous displacements arising from indentation effects and elastic displacement 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 [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], Figure A2.1 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 [5].

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[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.

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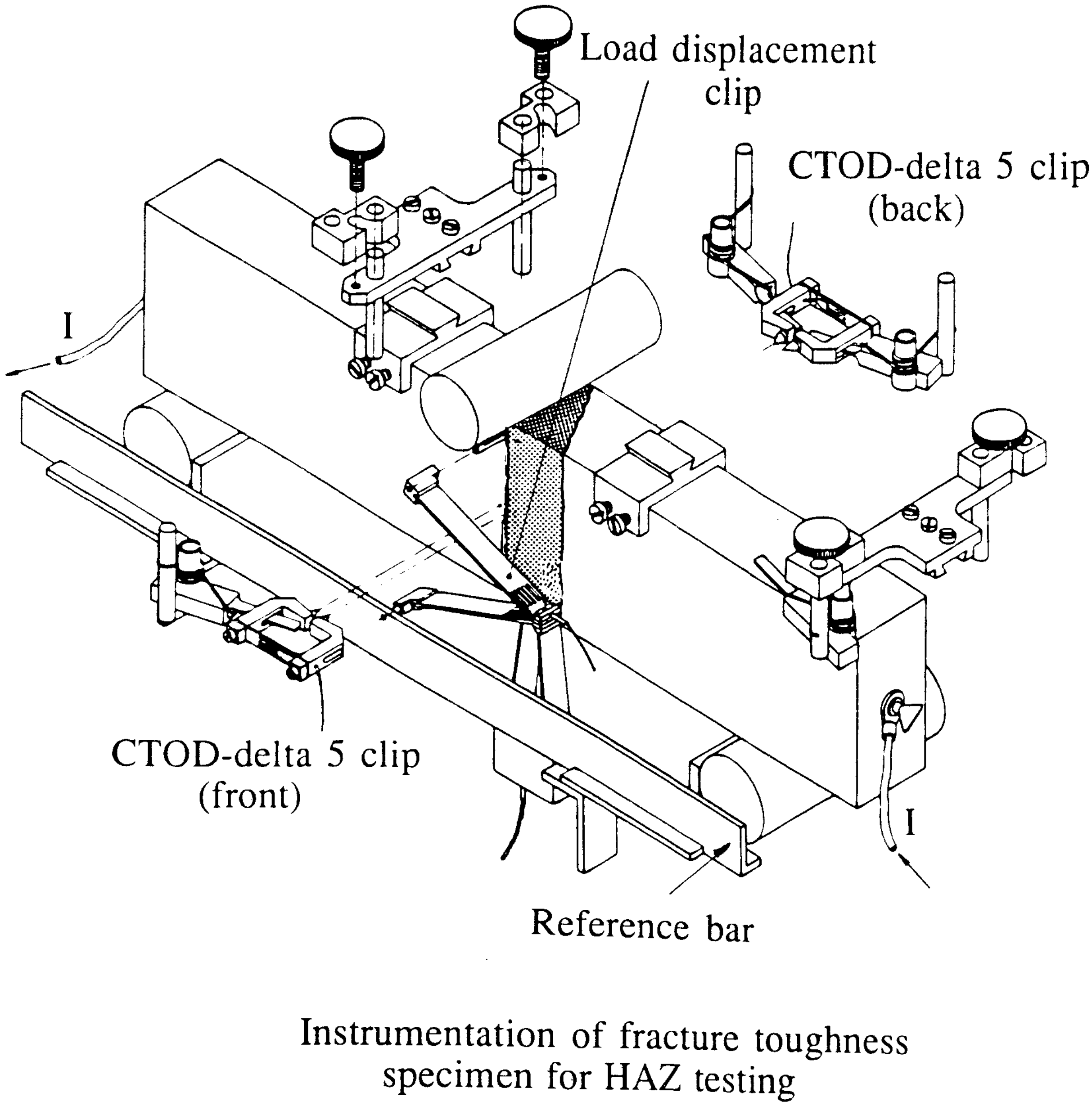

Figure A2.1: Single edge notched bend specimen with comparator bar for measuring the load-point displacement. The specimen is also equipped with two δ_5 gauges and a CMOD gauge.

APPENDIX 3

Measurement of Crack Mouth Opening Displacement on Centre Cracked Tensile Specimens

A recommended arrangement is shown in Figure A3.1 for the measurement of crack mouth opening displacement, V, on centre cracked tensile specimens. It makes use of the circular knife edge hole detailed in Figure 8. The gauge tips shown in Figure A3.1 have rounded end-pieces with a circular notch of radius r and an included angle Ø. The radius r must be less, and the angle Ø greater, than the corresponding dimensions of the knife-edge. In additions Ø must be chosen to ensure free movement of the gauge. The rigid arms of the gauge are connected to an elastic beam, and the rotation of the beam is measured by strain gauges. Detailed drawings are given in Figure A3.2.

Note: The plastic portion of the crack mouth opening displacement can be used for determining the J-integral on a centre cracked tensile specimen.

Note: The diameter of the knife edge, d_i, is identical with the gauge length which appears in analytical linear elastic solutions for the crack mouth opening displacement.

REFERENCE

[1] C. Wheeler, J.N. Eastabrook, D.P. Rooke, K.-H. Schwalbe, W. Setz, and A.U. de Koning, Recommendations for the measurement of R-curves using centre cracked panels, J. Strain Analysis, Vol. 17, 1982, pp. 20–213.

[2] Annual Book of ASTM Standards, E561-86, Standard Practice for R-Curve Determination, Section 3, Vol. 03.01, 1991, 57–588.

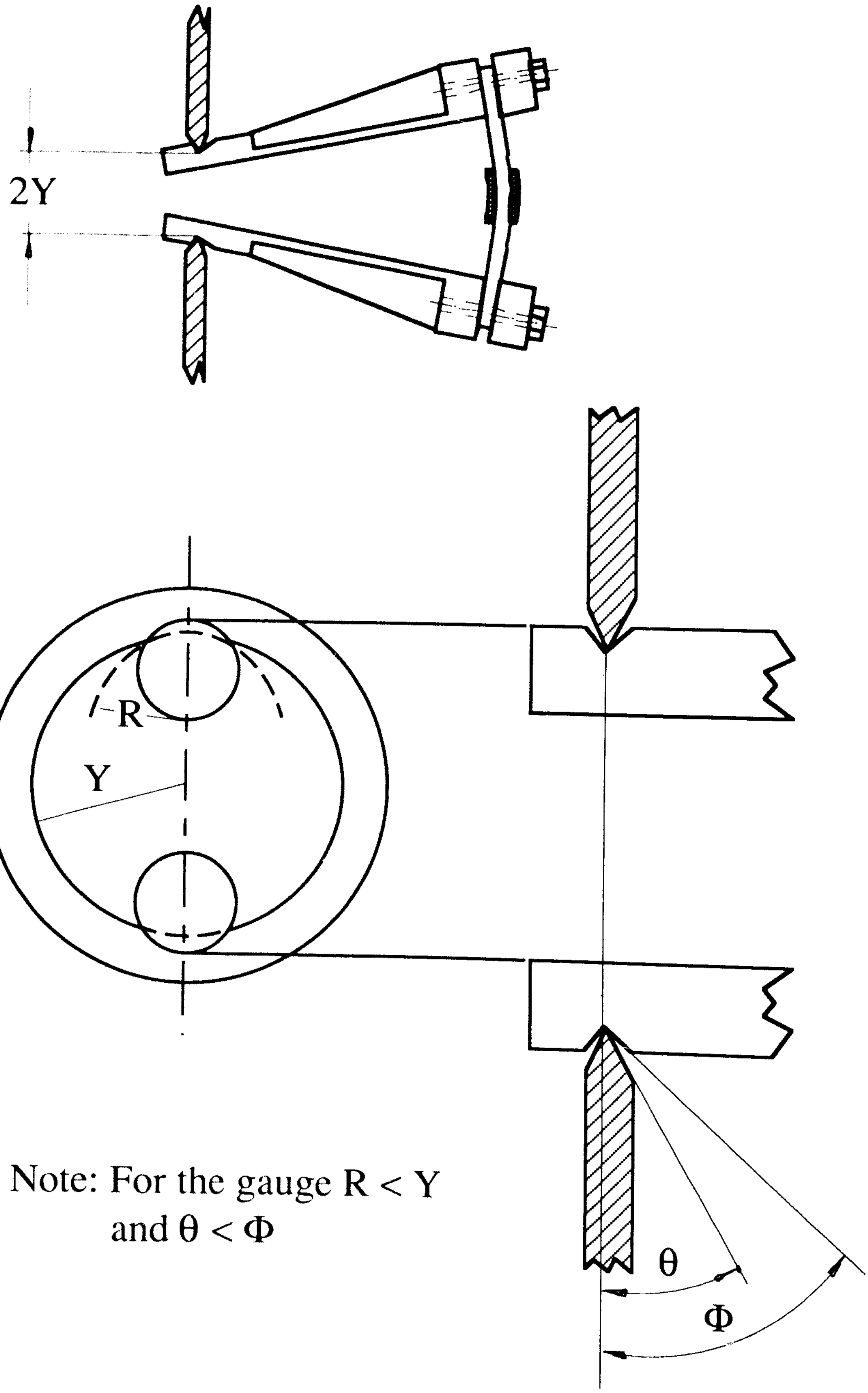

Figure A3.1: CMOD gauge mounting with detail of probe design.

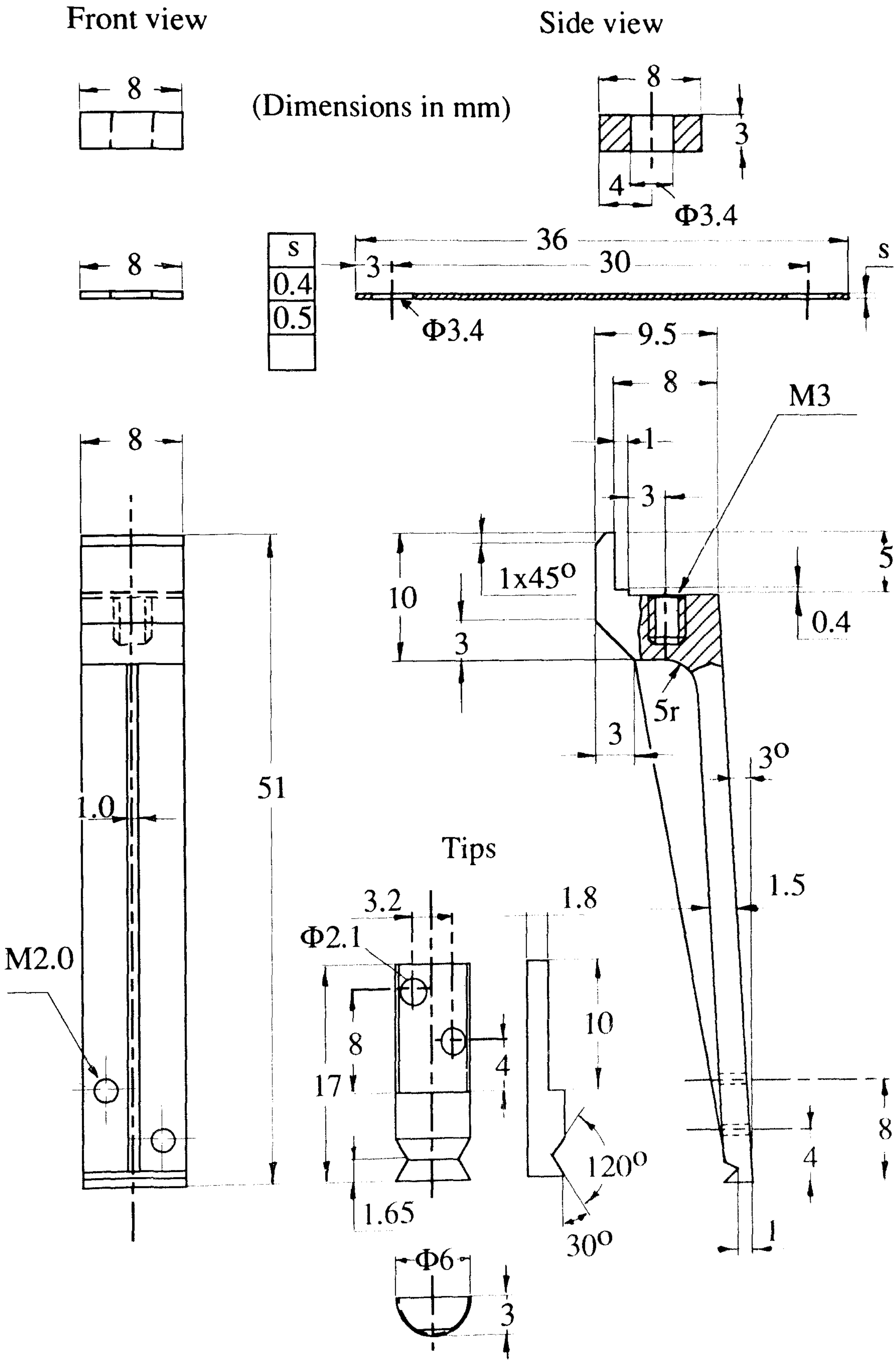

Figure A3.2: Detail drawings of CMOD gauge.

APPENDIX 4

Measurement of the Crack Tip Opening Displacement, δ_5

The basic arrangement [1] for measuring δ_5 is shown in Figure A4.1. The area around the expected fatigue crack propagation path should be polished. After fatigue pre-cracking, Vickers hardness indentations are placed ± 2.5 mm on either side of the crack tip to give a gauge length of 5 mm. A δ_5 clip gauge with needle tips is seated into the hardness indentations and attached to the specimen using the lever mechanism shown in Figure A4.2 for a CT specimen. Figure A2.1 shows a similar arrangement for an SENB specimen, whereas the instrumentation of a CCT specimen is illustrated in Figure A4.3.

Indentation points for weldments are shown schematically in Figure A4.4. For HAZ cracks a W-clip gauge arrangement can be used which measures the contributions from the base material and from the weld metal separately, Figure A4.5. This is of particular interest for interface cracks.

The design and test setup of a W clip gauge are shown in Figure A4.6.

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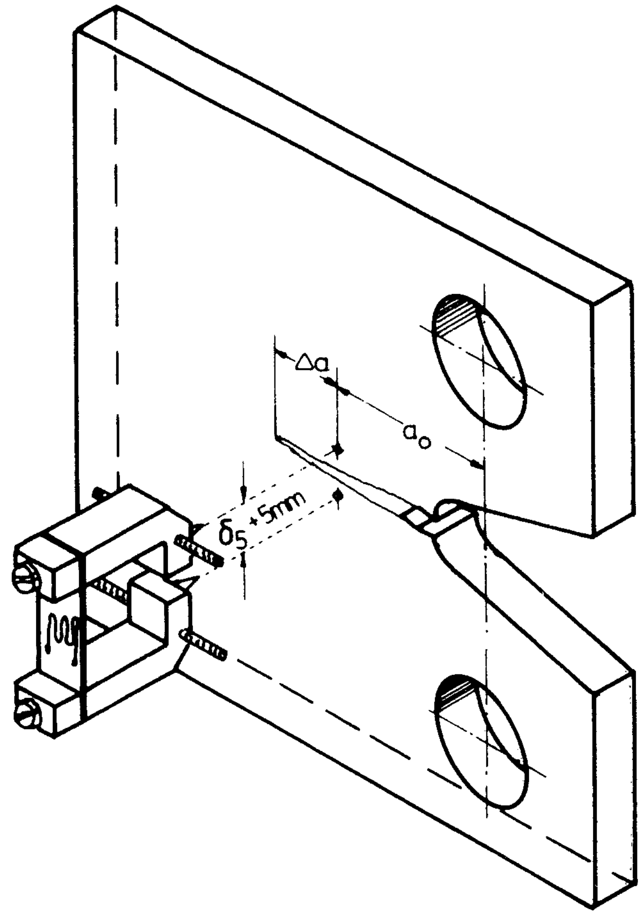
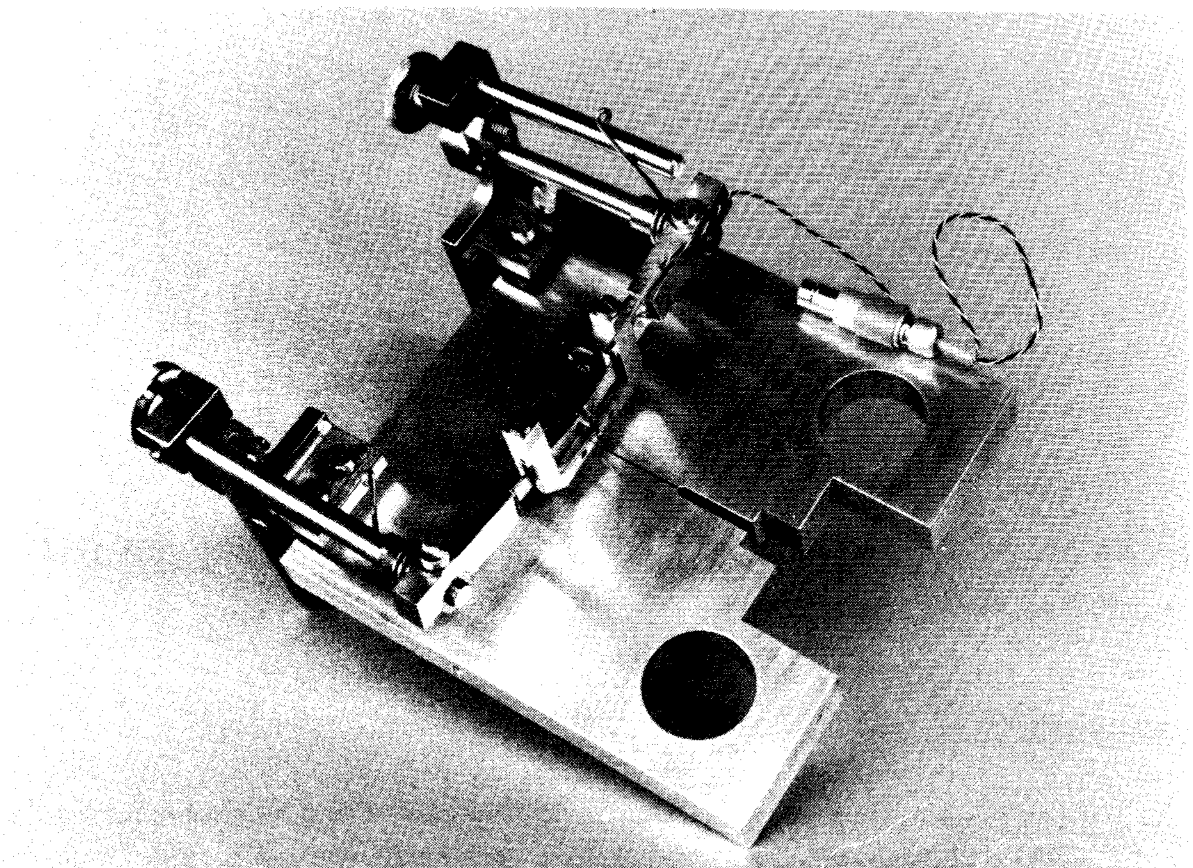
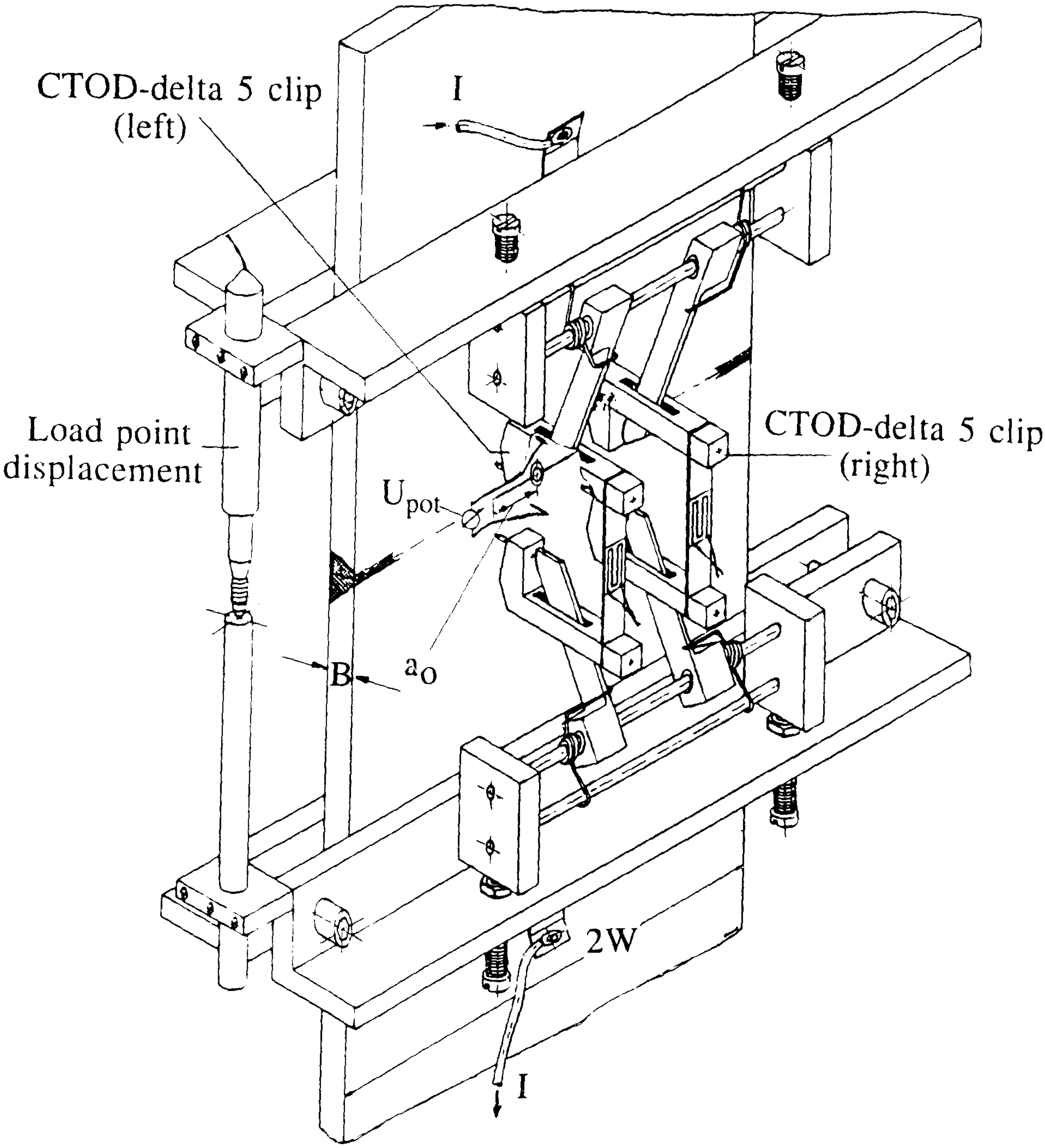


Figure A4.1:
Basic arrangement for measuring δ_5.

Figure A4.2:
Attachment of δ_5 clip gauge to CT specimen
▼





Instrumentation of tensile panel
for welded joints testing

Figure A4.3: Centre cracked tensile specimen showing instrumentation for δ_5 and load line displacement.

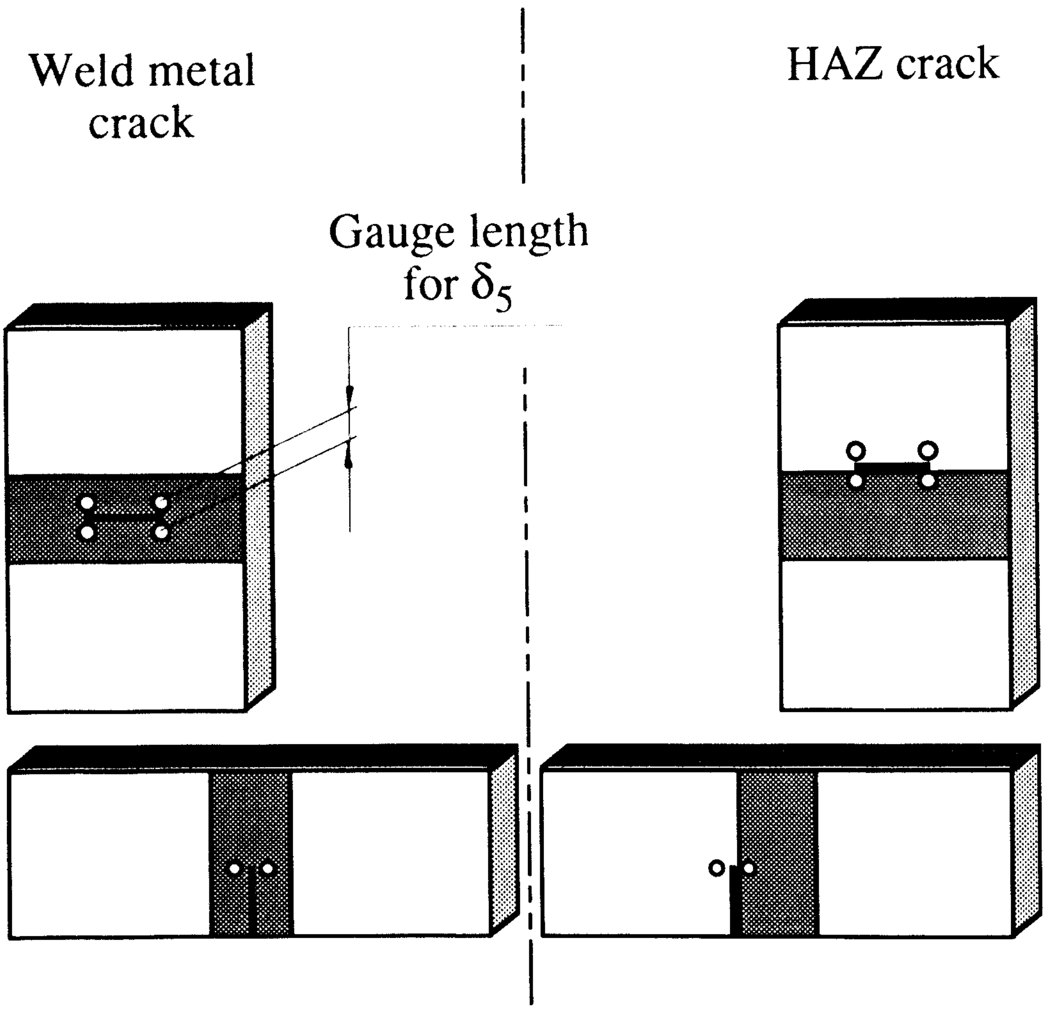


Figure A4.4: δ_5 gauge point configurations for weldments.

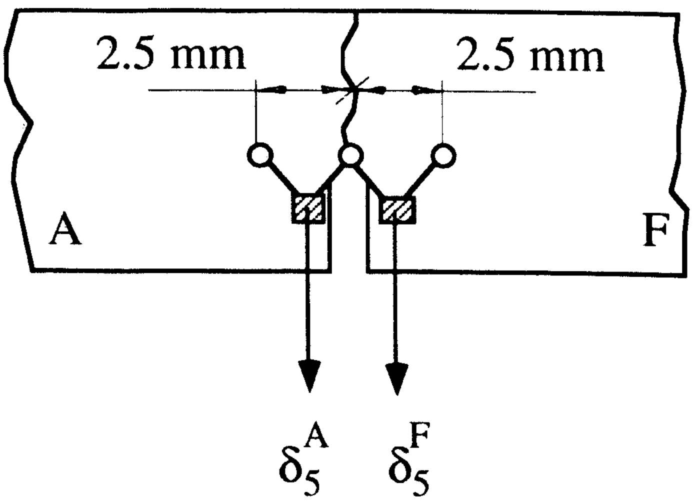


Figure A4.5:
W-clip gauge for interface cracks, schematical.

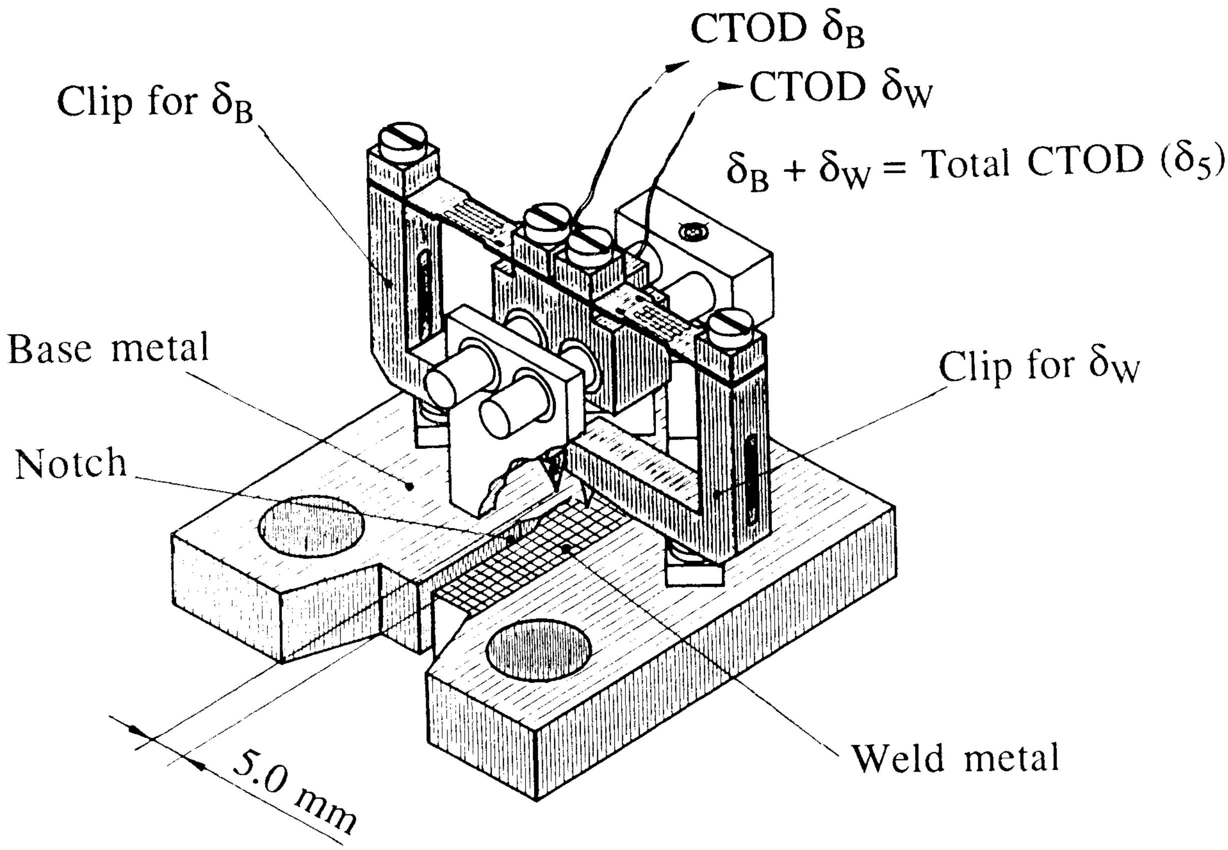


Figure A4.6: W-clip gauge for interface cracks, actual design.

APPENDIX 5

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 unloading compliance technique is not recommanded for centre cracked tensile specimens.

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 muliple specimen method gives only an average of the crack growth restistance behaviour and of the initiation parameters. The single specimen method gives individual results which can provide information on material inhomogenity.

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, Figure 5.1. The other should be terminated midway between the valid crack growth range, Δa_{max}, Figure A5.1. 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 in invalid and the single specimen technique may require improvement.

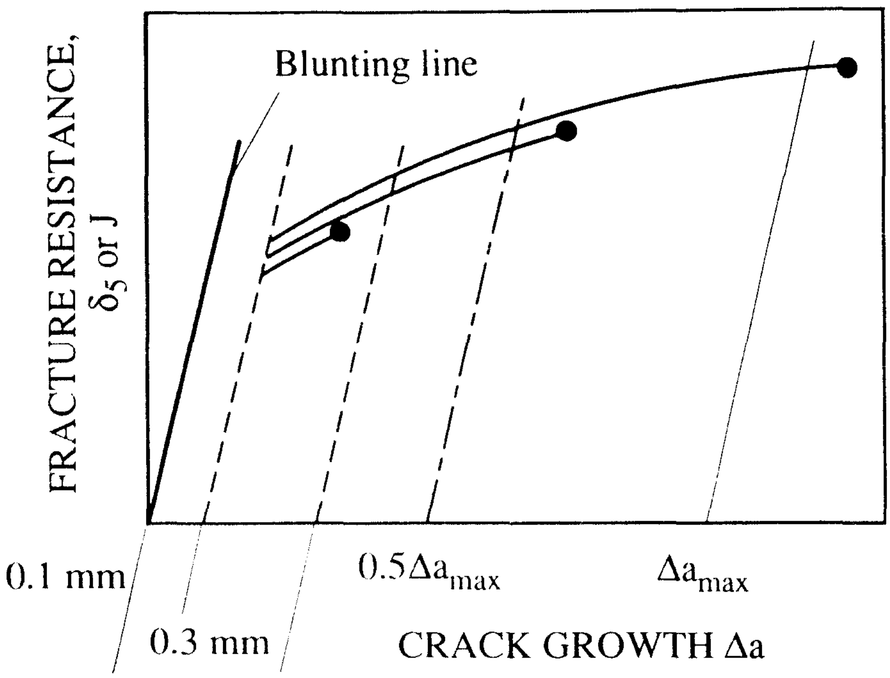


Figure A5.1: Single specimen crack growth termination requirement.

In order to characterise the fracture behaviour of a material, all single specimen data must also satisfy the data spacing requirements, Section 7.4, and the appropriate validity limits, Sections 7.6 and 7.7.

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

A5.1 Unloading Compliance Technique for CT and SENB Specimens

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 includes 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 8.5 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

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

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. For CCT specimens no recommendation concerning the unloading compliance technique is available.

A5.1.1 Test Requirements

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

A5.1.1.1 Specimens

Prepare sidegrooved specimens to the specification given in Section 2 of the procedure with an initial crack length ao in the range $0.45 \geq a_o/W \geq 0.65$.

A5.1.1.2 Test Fixtures

For compact specimen testing, the clevis must have a flat bottomed hole, Figure 11. 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.

A5.1.1.3 Compliance Measurement

Unloading compliance is determined from either mouth opening or load point displacements, Section 3.4. 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 and be located at the mouth of the crack as for crack opening displacement.
Errors may occur in the compliance measurements as a result of transducer 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.

A5.1.1.4 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 force resolution ΔF should be better than

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

For the duration of a test, stability of the digitised force 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 force and displacement signals to attain a satisfactory level for digitisation.

A5.1.1.5 Autographic Signal Resolution

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

A5.1.2 Procedure

A5.1.2.1 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 force must not exceed the final fatigue force.

A5.1.2.2 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 force relaxation caused by time dependent plasticity effects is observed to cease.

A5.1.2.3 Initial Crack Length Measurement

At least three unloading compliance measurements should be made at a force less than the maximum allowable final fatigue force 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 force used to measure the three initial unloadings.

Non-linear parts of the force displacement record that may occur at low forces from crack closure effects should be excluded from the compliance measurement.

A5.1.2.4 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 7.4. It is recommended that the unloading range should be as small as practicable but not exceed 30 percent of the current force value. To improve the accuracy at lower forces it is permissible to exceed this limit. However, in such cases non-linear parts of the force-displacement record that may occur at low forces from crack closure effects should be excluded from the compliance measurement.

At each unloading evaluate the crack length a and δ_5 or J, as appropriate, using the formulae given in Sections, A.5.1.5, A5.1.3 and A5.1.4 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 force. In the case of computerised test systems, the compliance is generally determined by performing a regression analysis of the recorded data.

A5.1.2.5 Termination of Test

After the final unloading reduce the force to zero ensuring no further increase in displacement. Mark the extent of ductile crack growth as described in Section 4.3.2 of the procedure.

Break open the specimen at or below room temperature to reveal the fracture surfaces. Measure the initial crack length a_0 and the total crack growth using the procedure described in Section 4.2.

A5.1.3 Crack Tip Opening Displacement, δ_5

The crack tip opening displacement, δ_5, is obtained explicitly in this Procedure.

A5.1.4 Fracture Resistance J

A5.1.4.1 Calculate $J_{o,k}$ for compact and single edge notch bend specimens 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 $\eta = 2 + 0.522\,(1 - a_o/W)$ for compact specimens

$= 2$ for single edge notch bend specimens and U_k is the area under the force displacement record up to the line of constant displacement at the k th data point.

A5.1.4.2 Fracture Resistance J Allowing for Crack Growth

The J equations used in Section A5.1.4.1 do not allow for crack growth during a test. The errors in J are usually negligible for crack growth less than 0.1 ($W-a_o$). If crack growth is analysed beyond this value, then all data points should be corrected for crack growth. A suitable approximation for compact and single edge notch bend specimens, is given in Section 7.2.1.3.

A5.1.5 Crack Length Calculation

A5.1.5.1 Compact Specimens

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

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

where

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

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

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 A5.1.2.3.

The effective modulus E_M fits the above equation to the crack length a_o measured in Section A5.1.2.5. 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.

A5.1.5.2 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

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

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 6.

r = radius of rotation given by $\frac{W+a}{2}$ where a is the current crack length

D = one half of the initial distance between the displacement measurement points.

θ = the angle of rotation given by

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

q = total measured load line displacement.

A5.1.5.3 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

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

$$+ 51.51564\mu^4 - 113.031\mu^5$$

where

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

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

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

$$E_M = \frac{6S}{B_{eff} W C_o}\left(\frac{a_o}{W}\right)[0.76 - 2.28\left(\frac{a_o}{W}\right) + 3.87\left(\frac{a_o}{W}\right)^2$$

$$-2.04\left(\frac{a_o}{W}\right)^3 + \frac{0.66}{(1 - a_o/W)^2}]$$

C_0 is the average compliance determined from the unloadings performed in the elastic regime, Section A5.1.2.3.

The effective modulus E_M fits the above equation to the crack length a_0 measured in Section A5.1.2.5. 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.

A5.1.5.4. 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

$$a/W = 0.07204 + 1.25147 \times 10^{-2}\mu - 1.10295 \times 10^{-4}\mu^2$$

$$+ 5.28088 \times 10^{-7}\mu^3 - 1.26564 \times 10^{-9}\mu^4 + 1.18958 \times 10^{-12}\mu^5$$

where

$$\mu = E_M B_{eff} C$$

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

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

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

$$+ 2(1-\upsilon^2)\left(\frac{a_o}{W}\right)\left(\frac{S}{W}\right)^2\left[4.21\left(\frac{a_o}{W}\right) - 8.89\left(\frac{a_o}{W}\right)^2 + 36.9\right.$$

$$\left(\frac{a_o}{W}\right)^3 - 83.6\left(\frac{a_o}{W}\right)^4 + 174.3\left(\frac{a_o}{W}\right)^5 - 284.6\left(\frac{a_o}{W}\right)^6$$

$$\left.\left. + 387.6\left(\frac{a_o}{W}\right)^7 - 322.8\left(\frac{a_o}{W}\right)^8 + 149.8\left(\frac{a_o}{W}\right)^9\right]\right]$$

C_0 is the average compliance determined from the unloadings performed in the elastic regime, Section A5.1.2.3.

The effective modulus E_M fits the above equation to the crack length, a, measured in Section A5.1.2.5. 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 Youngs Modulus by more than 10 percent then the test is not valid.

A5.1.5.5 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].

A5.1.6 Crack Growth Fracture Resistance

Ideal crack growth fracture resistance behaviour is characterised by monotonically increasing crack growth, Figure A5.2. 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.

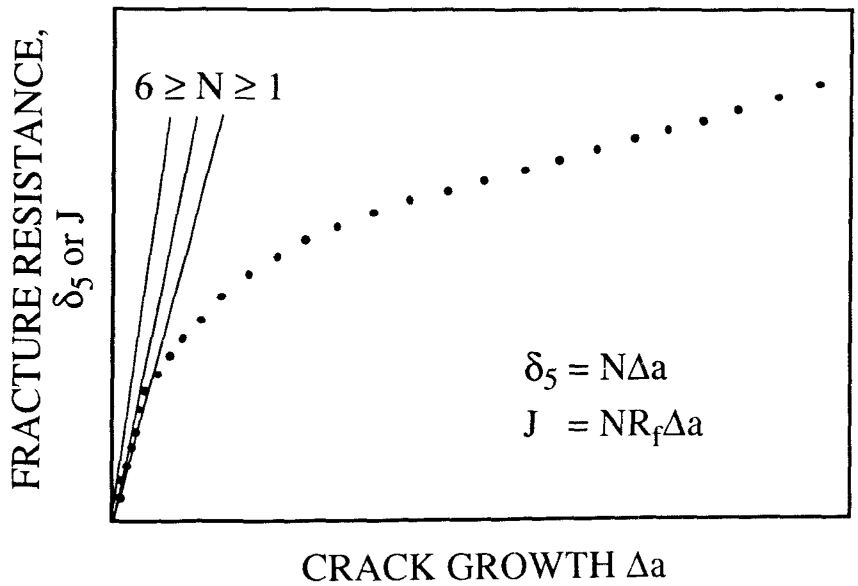


Figure A5.2:
Ideal behaviour of crack growth fracture resistance curve.

A5.1.6.1 Construction of Resistance Curves

Plot graphs of either δ_5 or J against the predicted crack length.

A5.1.6.2 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 elasticunloading compliance measured in Section A5.1.2.2.

(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

$$\delta_5 = N\Delta a \quad \text{or} \quad J = NR_f\Delta a$$

where $1 \geq N \geq 6$.

Alternative methods of defining a_i can be used provided details of the method are reported and justified in Section 8.3 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.

A5.1.6.3 Estimated Crack Growth

Calculate the estimated crack growth Δa_k at the kth unloading from

$$\Delta a_k = a_k - a_i.$$

A5.1.6.4 Crack Growth Resistance Curves

Construct plots of δ_5 or J against estimated crack growth Δa_k.

A5.1.6.5 At least 5 data points should remain within 0.2mm of a_i in order to adequately describe the initial portion of the crack growth fracture resistance curve.

A5.2 Potential Drop Techniques

A5.2.1 A.C. Potential Drop Method

(i) A typical A.C. potential drop test system is shown in Figure A5.3. 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 A5.4. This minimum is taken as the point of crack initiation.

(ii) Load the test specimen as described in Section 4 of the procedure and obtain test records of both force and potential against either load-point or mouth opening displacement. The general form of the test records is illustrated in Figure A5.4.

(iii) On completion of the test mark the extent of ductile crack growth as described in Section 4.3.2 before breaking the specimen open.

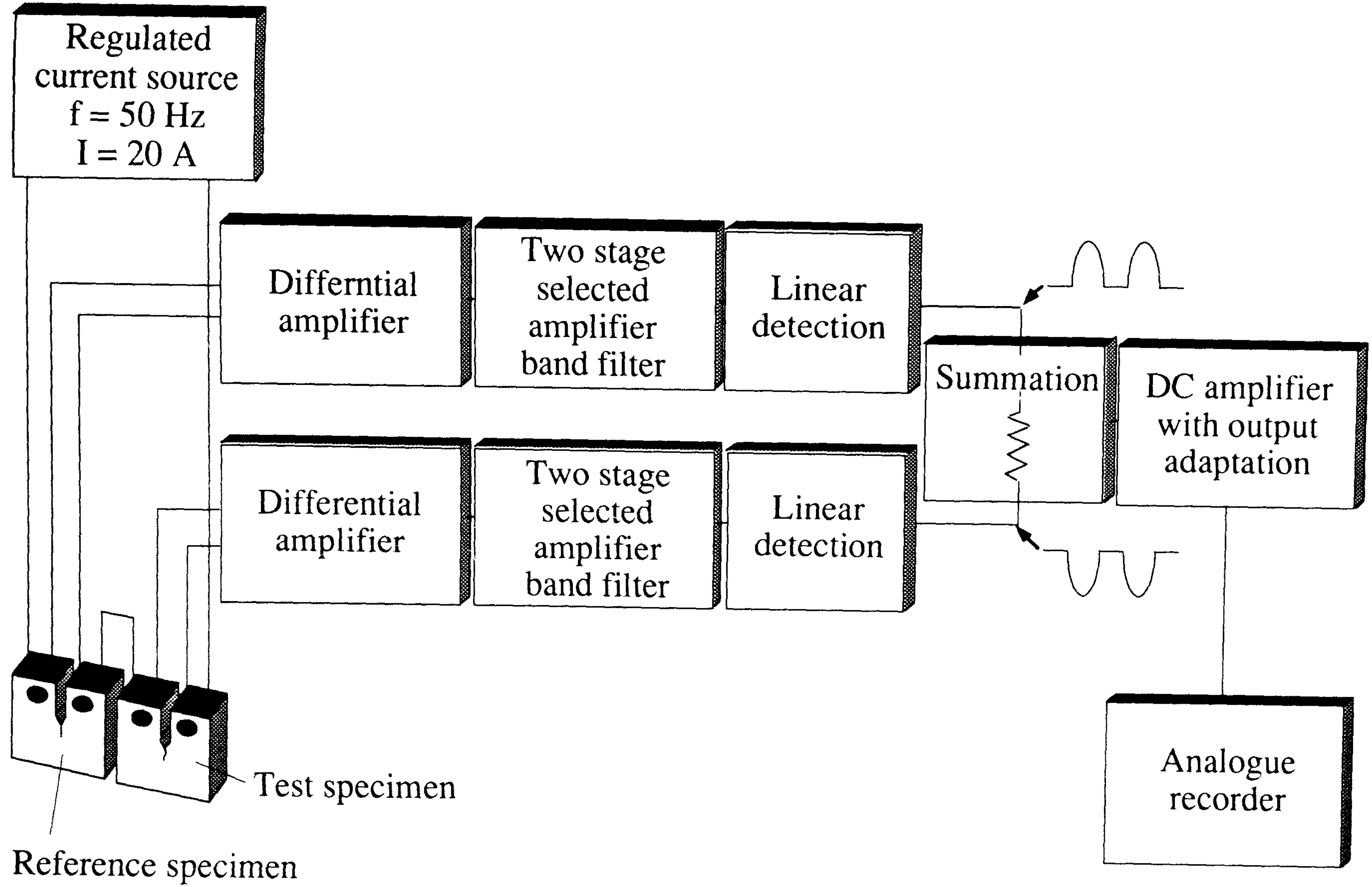


Figure A5.3: Typical AC potential drop test system.

(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 J_i or δ_i at the point marked with F_i in Figure A5.4, according to the procedures described in Sections 3.3.1 or 3.3.2.

(vi) Determine Δa_B according to Appendix 7 for J_i or δ_i. The thus determined Δa_B is an estimate of the critical stretch zone width, Δa_{szw}.

(vii) Alternatively, determine the critical stretch zone width, Δa_{szw}, in a scanning electron microscope.

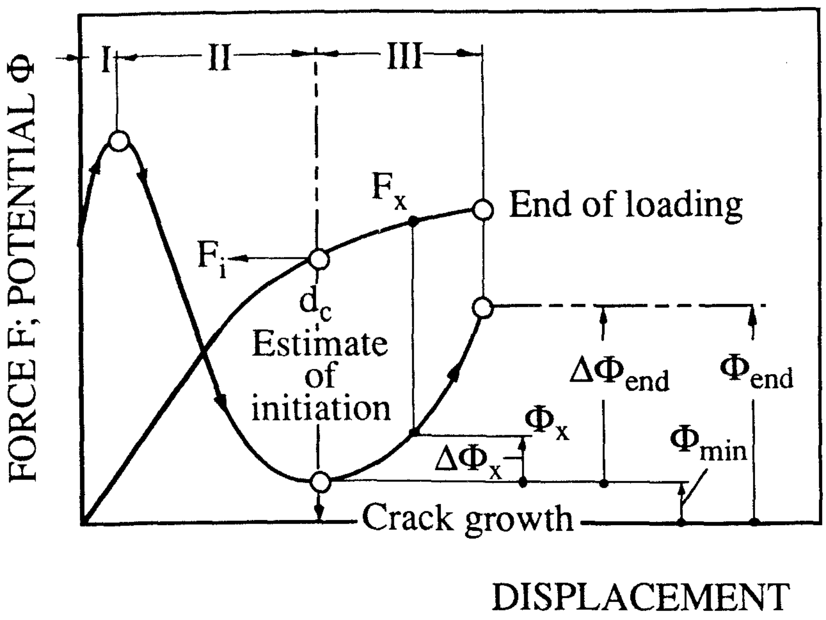


Figure A5.4:
Typical AC potential drop test record.

A5.2.1.1 Interpretation of Test Records

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

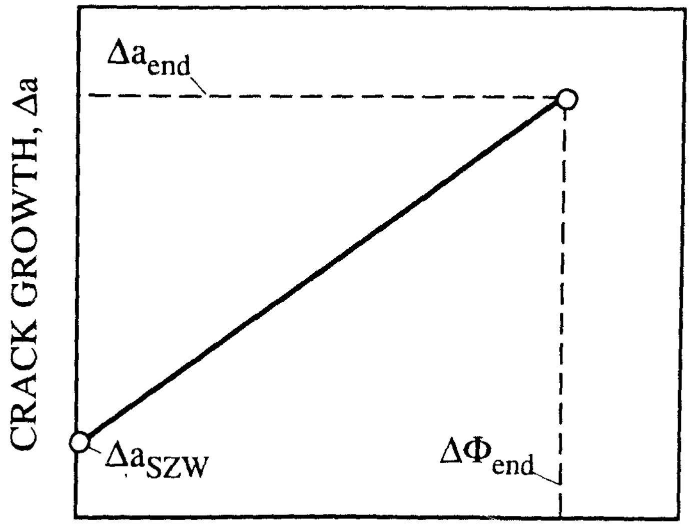
(ii) Measure the potential difference $\Delta\varphi_{end}$ between φ_{min} and the potential at the end of the test φ_{end}

(iii) Construct a graph of total crack growth against potential difference as shown in Figure A5.5.

(iv) Plot the points Δa_{szw}, $\Delta\varphi = O$ and $\Delta a, \Delta\varphi_{end}$ and draw a straight line between them, Figure A5.5. This represents the calibration line for the specimen.

(v) To determine the amount of total crack growth corresponding to the point F_x on the force-displacement record measure the potential difference between φ_{min} and φ_x as indicated in Figure 5.4. The amount of total crack growth corresponding to $\Delta\varphi_x$ is estimated from the calibrated line similar to that shown in Figure A5.5.

Figure A5.5:
Plot of crack growth against potential difference.



A5.2.2 DC Potential Drop Methods

Two DC potential drop methods are described in this section.

A5.2.2.1 Method 1

(i) The preferred DC potential drop test system [11-14] is shown in Figure A5.6.

(ii) Load the specimen as described in Section 4 of the Procedure and obtain records of force against displacement and potential. The general form of the load-potential test record is illustrated in Figure A5.7.

(iii) On completion of the test mark the extent of stable crack growth as described in Section 4.3.2 before breaking the specimen open.

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

A5.2.2.1.1 Interpretation of Test Records

(i) Construct a straight line through the steeply rising part of the force potential record as shown in Figure A5.7.

(ii) For any force of interest measure φ_0 and Δ_φ as shown in Figure A5.7 and evaluate

$\varphi = \varphi_0 + \Delta\varphi$.

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

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

where y is defined in Figure A5.6.

(iv) The corresponding crack growth Δa is given by

$\Delta a = a\text{-}a_o.$

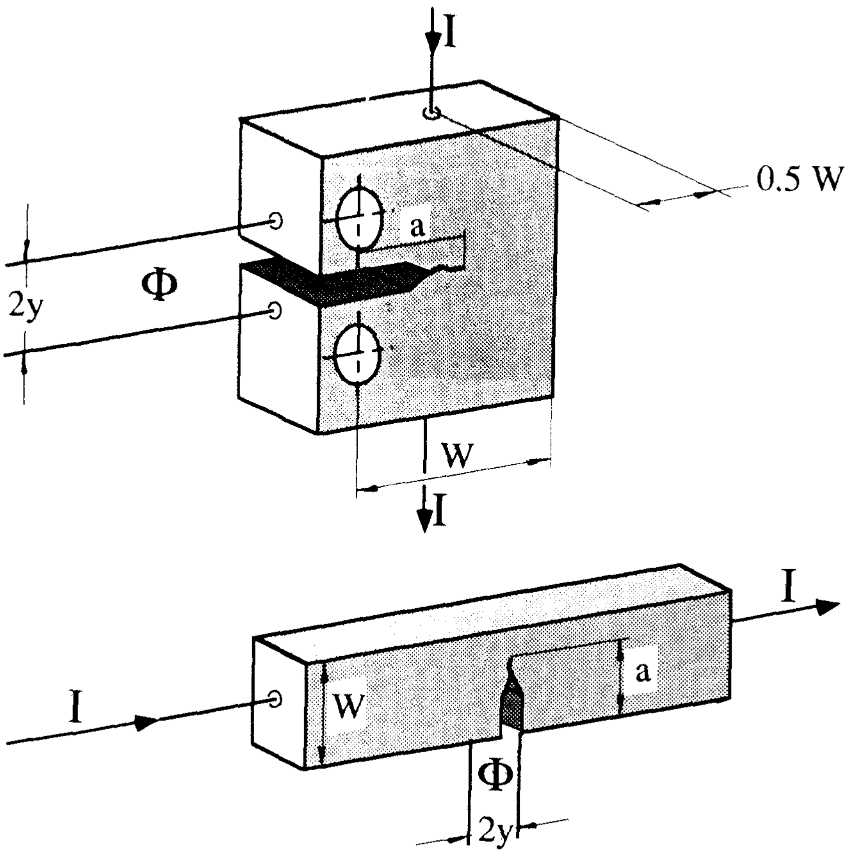


Figure A5.6:
Preferred DC potential drop test system.

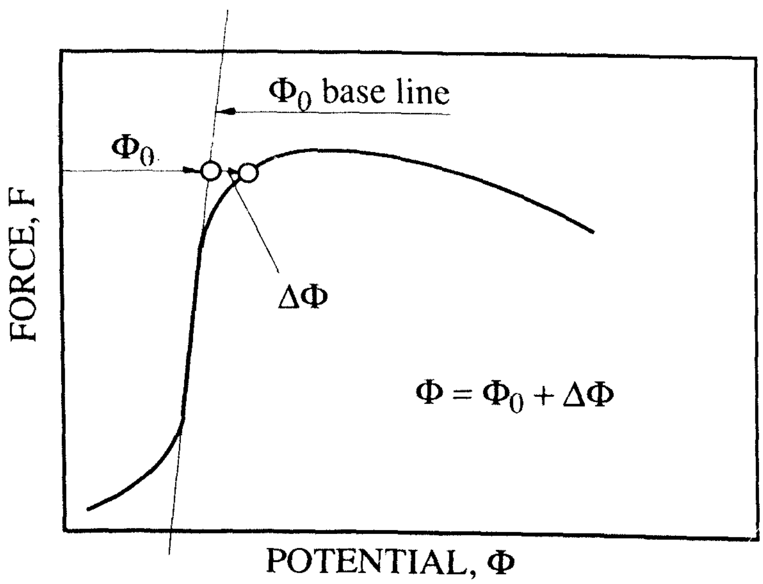


Figure A5.7:
Typical DC potential drop test record for system shown in Figure A5.7.

A5.2.2.2 Method 2

(i) An alternative DC potential drop system [15] for Method 2 is shown in Figure A5.8.

(ii) Load the test specimen as described in Section 4 of the procedure and obtain test records of both force and potential against either load-point or mouth opening displacement. The general form of the test records is illustrated in Figure A5.9.

(iii) On completion of the test mark the extent of ductile crack growth as described in Section 4.3.2 before breaking the specimen open.

(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 6 of the procedure.

A5.2.2.2.1 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 ($\Delta\varphi_{end}$) 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 A5.5.

(iv) Plot the points Δa_{szw}, $\Delta\varphi = O$ and Δa, $\Delta\varphi_{end}$ and draw a straight line between them, Figure A5.5. This straight line represents the calibration line for the specimen.

(v) To determine the amount of total crack growth corresponding to a point F_x on the force-displacement record measure the potential difference between φ_{min} and φ_x as indicated in Figure A5.9. The amount of total crack growth corresponding to $\Delta\varphi_x$ can be estimated from the calibrated line similar to that shown in Figure A5.5.

A5.2.3 Crack Growth Fracture Resistance Curves

A5.2.3.1 Crack Tip Opening Displacement δ_5

The crack tip opening displacement, δ_5, is obtained explicitly in this Procedure.

A5.2.3.2 Fracture Resistance J

Determine J for compact and single edge notch specimens at the force F_x using the equations given in Section A5.1.4.

For CCT specimens use the relationsship

$$J_{0,k} = \frac{K^2}{E} + \frac{U^*}{B(W - a_o)}$$

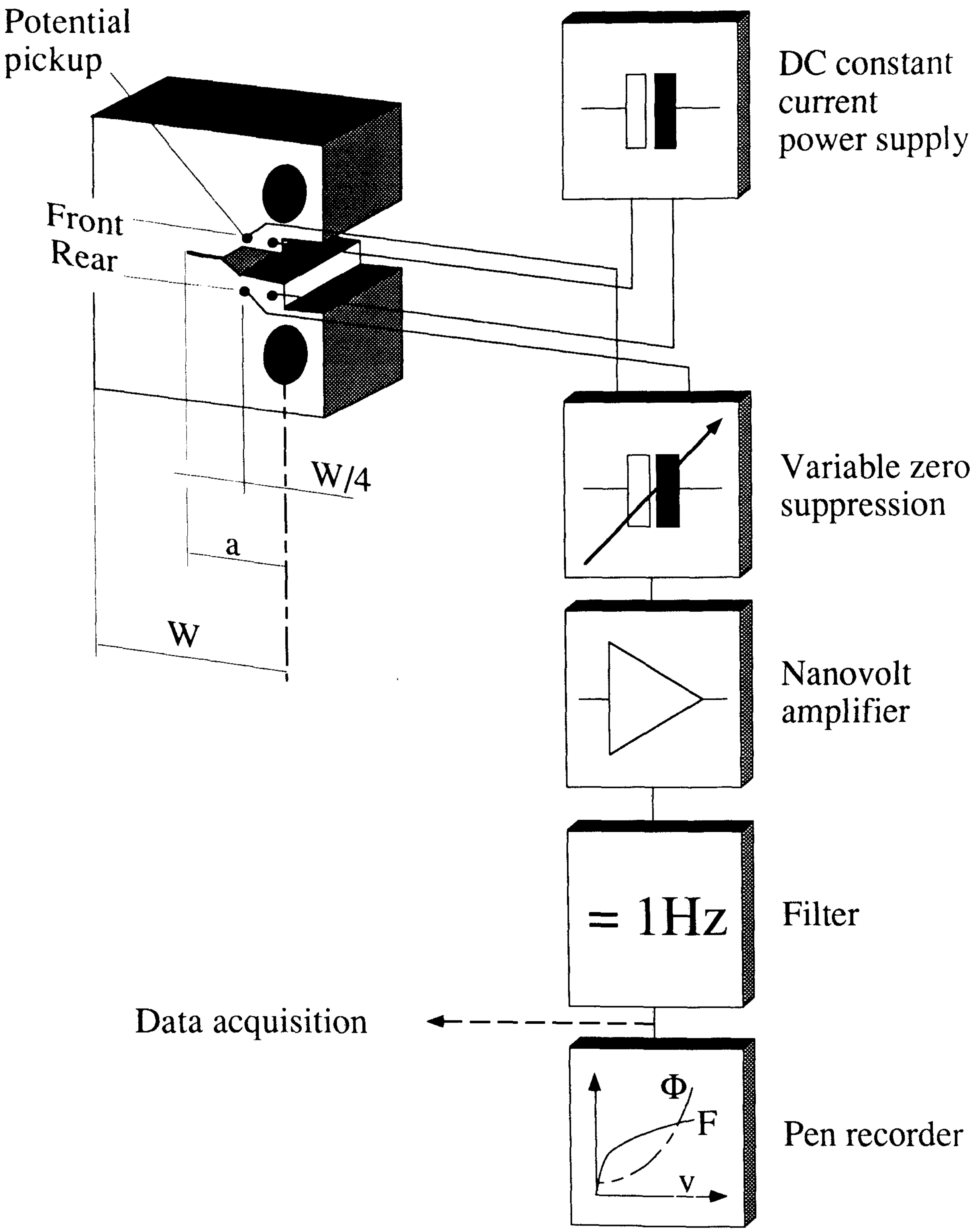


Figure A5.8: Alternative DC potential drop test system.

This equation does not allow for crack growth during a test. The errors in J are usually negligible for crack growth less than 0.1 ($W-a_0$). If crack growth is analysed beyond this value, then all data points should be corrected for crack growth. A suitable approximation is

$$J_j = J_{j-1} + \frac{2\Delta U^*}{B(b_{j-1}+b_j)} + \frac{2}{E(b_{j-1}+b_j)}\left[K_j^2 b_j - K_{j-1}^2 b_{j-1}\right]$$

where

j and j-1 indicate two consecutive points on the test record,
ΔU^* is defined in Figure 5.10,
b is the actual ligament length W-a,
K is the stress intensity factor.

A5.2.3.3 Construction of Resistance Curves

Plot graphs of either δ_5 or J against the predicted crack length.

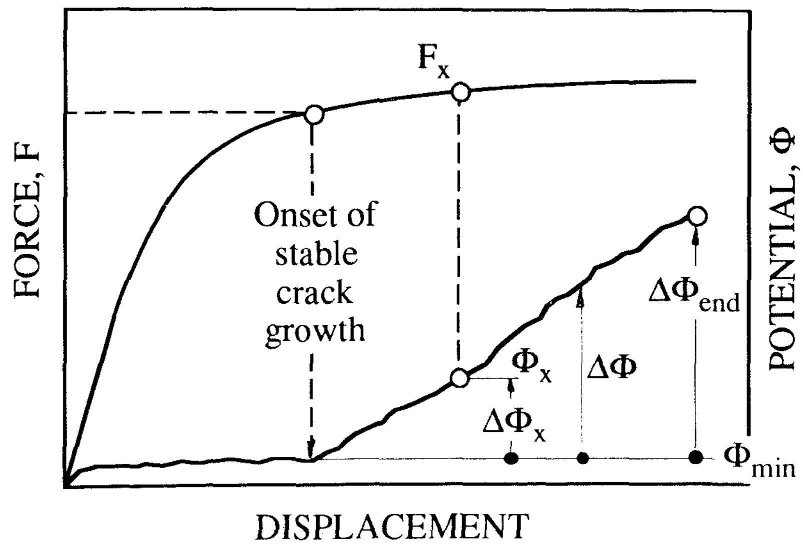


Figure A5.9:
Typical DC potential drop test record for system shown in Figure A5.8.

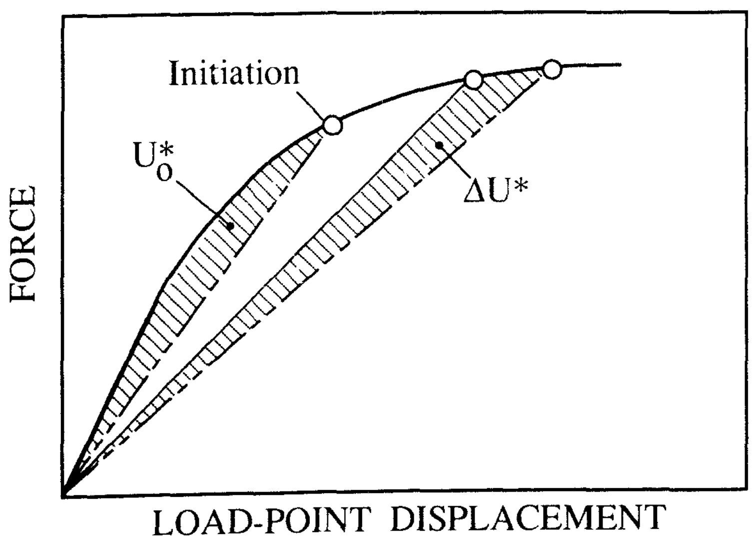


Figure A5.10:
Definition of ΔU^*. Note: If the force at any point of the diagram to be evaluated exceeds $1.8\,R_{p0.2}\,BW$, then evaluate U^* and ΔU^* from a force versus CMOD record.

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APPENDIX 6

δ_{5i} and J_i Determination

The determination of δ_{5i} and J_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 δ_{5i} and J_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, δ_{5i} and J_i cannot be determined.

A6.1 Critical Stretch Zone Width Measurement

A6.1.1 Measure the local critical stretch zone width SZW_L at the 9 positions shown in Figures 14 to 16 using calibrated photographs taken in a SEM. An example is shown in Figure A6.1.

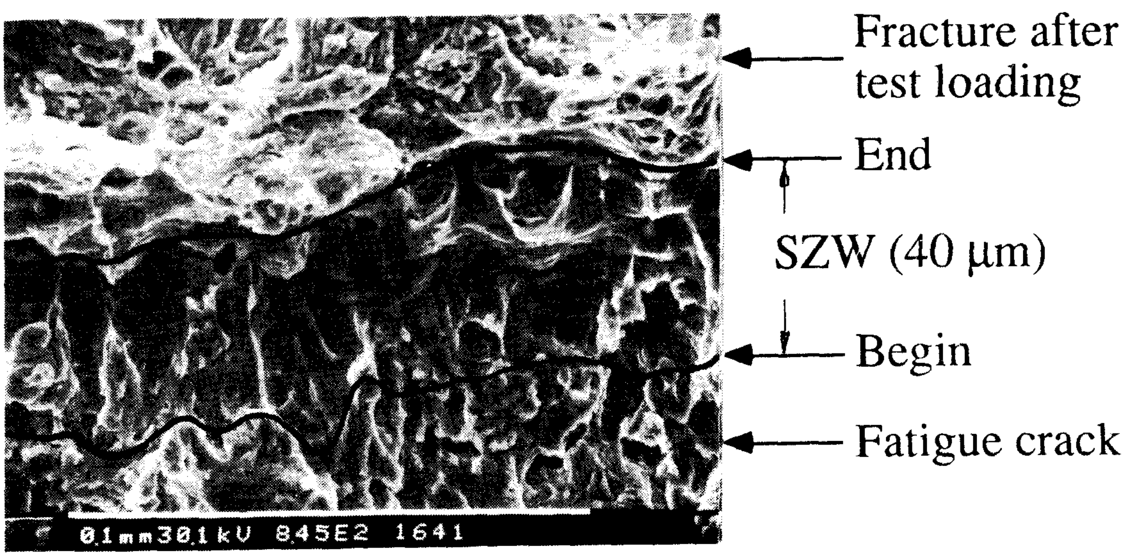


Figure A6.1: Typical stretch zone width.

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 A6.2. At least 5 measurements are required at each position giving the local stretch zone width

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

A6.1.2 Determine the critical stretch zone width of the specimen by averaging the nine local measurements

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

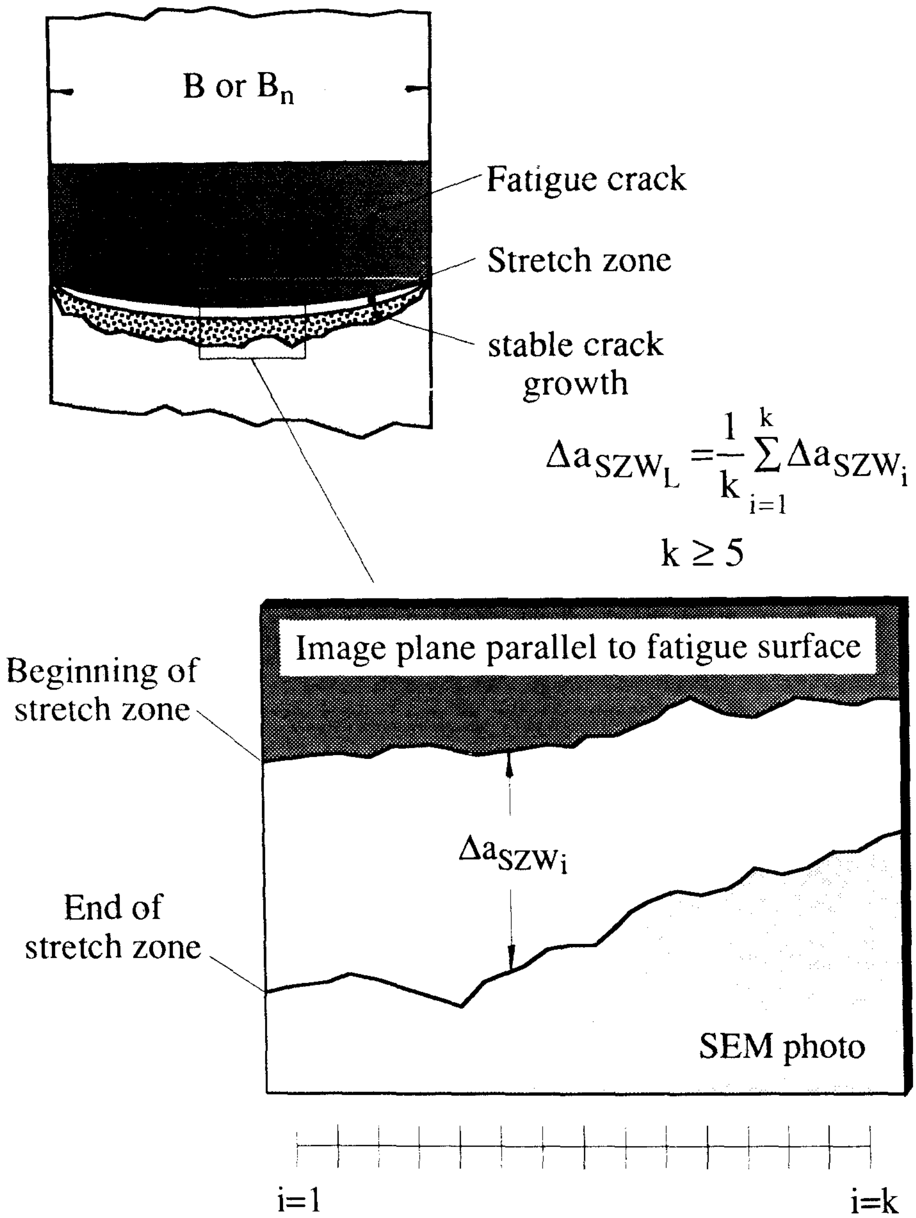


Figure A6.2: Determination of Δa_{szw}.

A6.1.3 For each specimen the crack growth Δa measured in Section 4.2 must be greater than Δa_{szw} + 0.2mm. 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 $\overline{\Delta a}_{szw}$.

$$\overline{\Delta a}_{szw} = \frac{1}{j}\,\frac{1}{k}\sum_{i=1}^{j} \Delta a_{SZW,i} \quad \text{providing } j \geq 3.$$

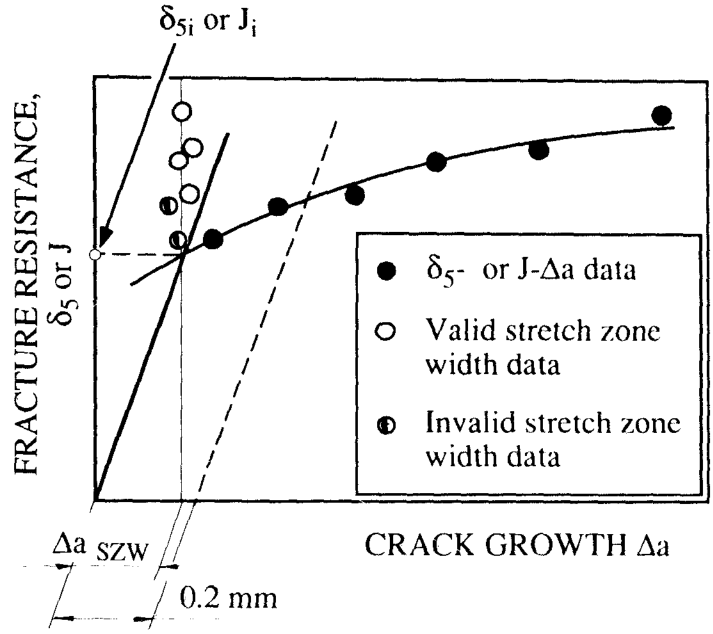
6.1.4 For the centre cracked tensile specimen, $\overline{\Delta a}_{szw}$ must be obtained from the average measurement ahead of both fatigue pre-cracks.

A6.2 δ_{5i}

A6.2.1 Construct a plot of the δ_5-Δa data obtained in Sections 4 and 7.1 and the critical stretch zone widths Δa_{szw} as shown in Figure A6.3.

Figure A6.3:

Determination of δ_{5i} and J_i.



A6.2.2 Construct a line parallel to the δ_5-axis through the mean of the stretch zone width data $\overline{\Delta a}_{szw}$ as shown in Figure A6.3. Evaluate and draw best fit curve through all the δ_5-Δa data which exceeds $\overline{\Delta a}_{szw}$ using the procedure given in Section 7.5.1. The intercept of the curve with the parallel line defines δ_{5i}. Construct a line through the intersection point and the origin. At least one δ_5-Δa point should be within 0.2 mm of this line.

A6.2.3 If δ_{5i} exceeds δ_{max} determined in Section 7.6, then δ_{5i} is invalid according to this Procedure.

A6.2.4 Evaluate the slope of the δ_5-Δa curve at the intersection point using the equation determined in Section A6.2.2. If the slope of the line constructed in Section A6.2.2

$$\left(\frac{d\delta_5}{da}\right)_L < 2\left(\frac{d\delta_5}{da}\right)_i,$$

then δ_{5i} is invalid according to this Procedure.

A6.3 J_i

A6.3.1 Construct a plot of the J-data obtained in Sections 4 and 7.2 and the critical stretch zone widths Δa_{szw} as shown in Figure A6.3.

A6.3.2 Construct a line parallel to the J-axis through the mean of the critical stretch zone width data $\overline{\Delta a}_{szw}$ as shown in Figure A6.3. Evaluate and draw the best fit curve through the J-Δa data which exceeds $\overline{\Delta a}_{szw}$ using the procedure given in

Section 7.5.1. 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 0.2mm of this line.

A6.3.3 If J_i exceeds J_{max} determined in Section 7.7, then J_i is invalid according to this procedure.

A6.3.4 Evaluate the slope of the J-Δa curve at the intersection point using the equation determined in Section A6.3.2. If the slope of the line constructed in Section A6.3.2.

$$\left(\frac{dJ}{da}\right)_L < 2\left(\frac{dJ}{da}\right)_i,$$

then J_i is invalid according to this procedure.

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APPENDIX 7

Determination of the 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.

$$\frac{\varepsilon}{\varepsilon_0} = \left(\frac{\sigma}{\sigma_0}\right)^{1/n} \quad \text{for} \quad \sigma \geq \sigma_0$$

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.

A7.1 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 stress R_m. The longitudinal dimension of the tensile specimen must be normal to the crack plane of the specimens and be in the same material condition.

A7.2 Determine the strain hardening exponent n from

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

where

$$\varepsilon_{p0.2} = \frac{R_{p0.2}}{E} + 0.002$$

A graphical solution for n is given in Figure A7.1.

A7.3 Determine the reference stress σ_0 from

$$\sigma_0 = R_{p0.2} 10^t$$

where

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

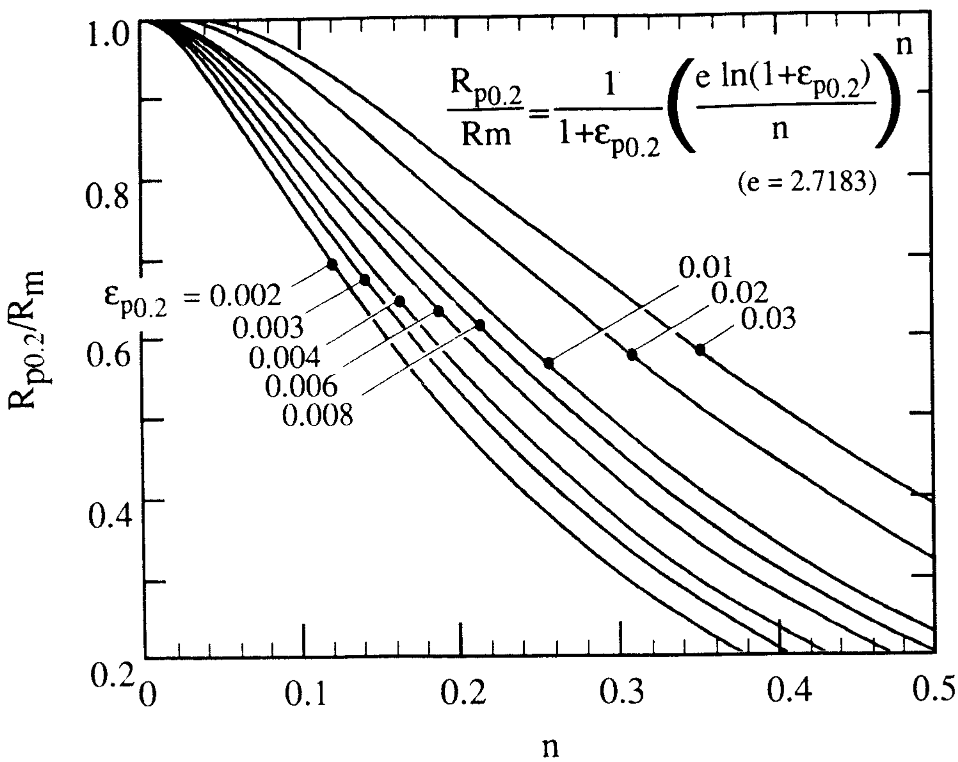

Figure A7.1: Determination of strain hardening exponent, n.

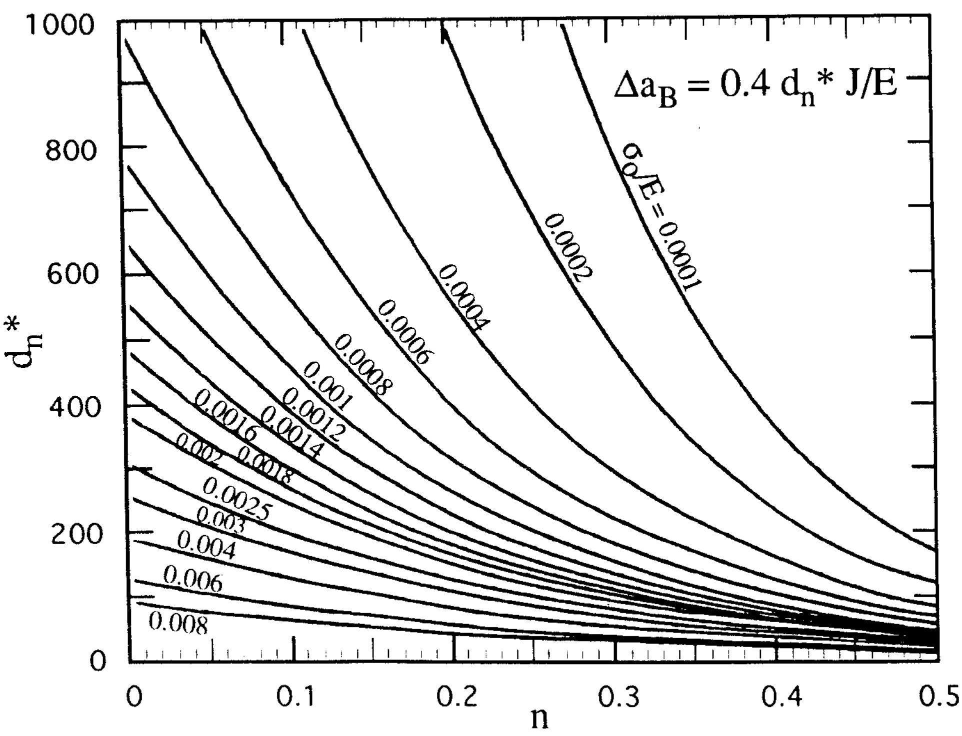

Figure A7.2: Determination of d_n^*.

A7.4 δ_5 blunting line

d_n^* is given graphically in Figure A7.2 for ν of 0.3. Alternatively, d_n^* can be determined using the equation

$$d_n^* = \varepsilon_0^{n-1} \cdot D_n$$

where

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

n is the strain hardening exponent, and the coefficients of the polynomial are

$$\begin{aligned} A_o &= 0.787 \\ A_1 &= 1.554 \\ A_2 &= -2.45 \\ A_3 &= 16.952 \\ A_4 &= -38.206 \\ A_5 &= 33.13 \end{aligned}$$

The slope of the blunting line is given by

$$\Delta a_B = 0.8\, d_n^* \left(\frac{R_{p0.2}}{E}\right) \delta_5$$

A suitable approximation is given by

$$\Delta a_B = \frac{\delta_5}{1.87(R_m / R_{p0.2}}$$

A7.5 J blunting line

Evaluate d_n^* as described in Section A7.4. The slope of the blunting line is given by

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

A suitable approximation is given by

$$\Delta a_B = \frac{J}{3.75\, R_m}$$

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APPENDIX 8

Offset Power Law Fit to Crack Growth Fracture Resistance Data

A8.1 The equation fitted to the crack extension data (y_i, Δa_i) is of the general form

$$y = A + C\Delta a^D$$

where y is either J or δ_5, Δa is the crack extension, A, C and D are constants.

A8.2 The substituion of $x = \Delta a^D$ in the equation enables A and C to be evaluated using linear regression available in statistical analysis packes or hand calculatros. The value of D is then chosen so as to maximise the correlation coefficient. An approach for doing this is given below.

A8.3 Take values of D from 0 to 1 in steps of 0.01. For each value of D calculate $x_i = \Delta a_i^D$ and the correlation coefficient r from

$$r = \frac{S_{xy}}{\sqrt{S_{xx}S_{yy}}}$$

where

$$S_{xx} = \sum x_i^2 - \frac{(\sum x_i)^2}{N}$$

$$S_{yy} = \sum y_i^2 - \frac{(\sum y_i)^2}{N}$$

$$S_{xy} = \sum x_i y_i - \frac{\sum x_i \sum y_i}{N}$$

for the N data points.

A8.4 Select the value of D which maximises r. Evaluate the corresponding A and C from

$$C = \frac{S_{xy}}{S_{xx}} \text{ and } A = \bar{y} - C\bar{x}$$

where

$$\bar{x} = \frac{\sum x_i}{N} \text{ and } \bar{y} = \frac{\sum y_i}{N}$$

REFERENCES

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APPENDIX 9

Testing of Weldments

In preparation

APPENDIX 10

Statistical Analysis of Toughness Data in the Ductile to Brittle Transition Regime

This appendix gives guidance on the statistical treatment of toughness data obtained by testing proportional CT and SENB specimens (W=2B) in the ductile to brittle transition regime. It is aimed at the determination of the cumulative failure probability P_f. The procedure outlined in this appendix was derived from the investigations in Ref.1 and 2. It covers the following subjects:

- Determination of the failure probability of laboratory specimens.
- Prediction of specimen size effects on the failure probability.
- Estimation of the temperature dependence of the failure probability using the master curve concept.

A10.1 Determination of the Failure Probability of Laboratory Specimen

This procedure allows to determine the failure probability, P_f, of deeply notched proportional CT or SENB specimens from an experimentally determined toughness data set.
It is based of the assumption that P_f is a Weibull distribution:

$$P_f = 1\text{-}\exp\text{-}((K\text{-}20)/(K_o\text{-}20))^4 \qquad (\mathrm{MPa}\sqrt{\mathrm{m}})$$

This distribution has one free quantity, K_o, to be determined from a set of toughness values.
This Weibull distribution does not explicitly account for constraint effects and stable crack extension. Therefore, the limits of its application are also defined in this procedure.

A10.1.1 Data Qualification for Determining K_o

The toughness data set to be used for determining K_o must fulfil the various requirements outlined in this Section:

A10.1.1.1

All toughness values must be obtained from replicate tests conducted under identical test temperature, identical loading rate using identical proportional SENB or proportional CT specimens.

A10.1.1.2

The total number of tests, N, of a data set contains all the replicate tests. This includes tests terminated by cleavage instability plus the tests which were unloaded before unstable fracture occurred. Therefore the total number of tests, N, is:

$$N = N_{unstable} + N_{unloaded}.$$

All specimens which were unloaded at a toughness value less than any of the toughness values related to cleavage instability are considered as non-test. These tests must be ignored and do not contribute to the number of N, Figure A.10.1.
At least 50 % of the N tests must reveal cleavage instability:

$$N_{unstable} / N > 0.5.$$

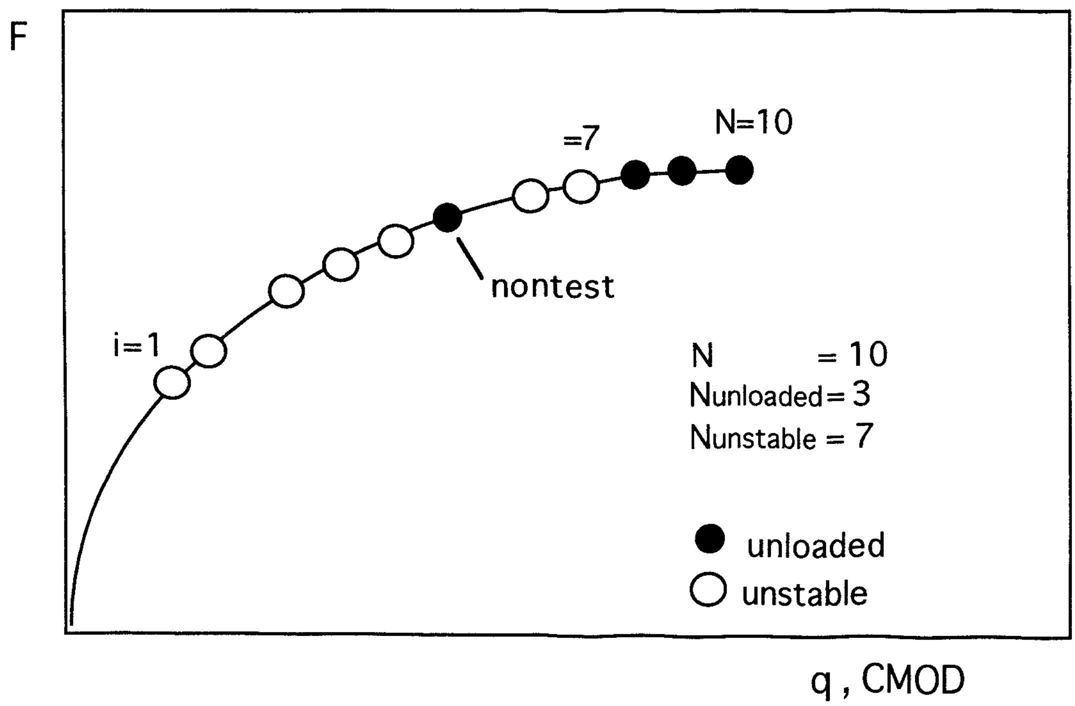


Figure A10.1: Test record and data qualification in the transition regime.

A10.1.1.3

All toughness data which are beyond the limits

$$\Delta a_{max} = 0.05(W - a_0)$$

$$K_{max} = \sqrt{(W - a_0)R_e E / 50}$$

are considered as invalid and must not be used for the determination of K_0 as outlined Section A10.1.2. These invalid data do only contribute to the total number of tests, N, Figure A10.2.

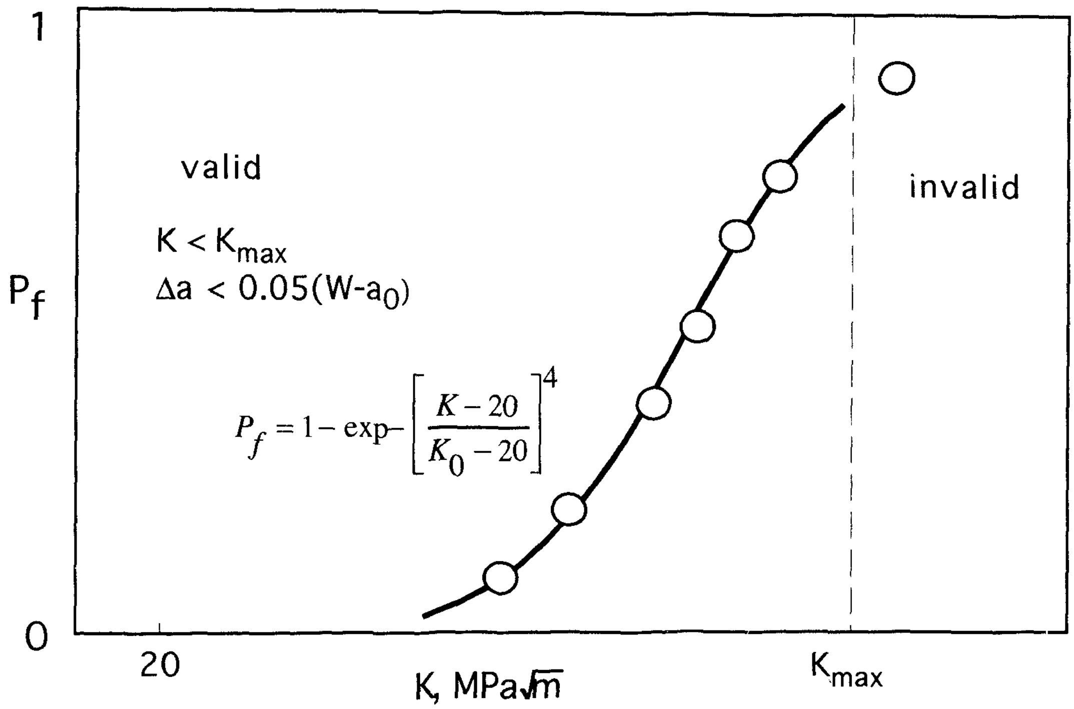


Figure A10.2: Cumulative failure probability P_f of instable cleavage fracture modelled using a Weibull distribution.

A10.1.2 Determination of K_0

To determine a K_0 value at least 6 valid toughness values related to cleavage instability must remain after the data qualification outlined in A10.1.1.

Note:

To increase the number of valid data points the following measures can be taken:

- Using larger specimens;
- Lowering the test temperature;
- Increasing the number of tests.

The N toughness values of the data set are ranked and subsequently the toughness values related to cleavage instability are assigned with a failure probability ,P_{fi}, calculated as follows:

$$P_{fi} = (i - 0.3) / (N+0.4)$$

$$1 \leq i \leq N_{unstable}$$

The data pairs ($K_{ci};P_{fi}$) are plotted in a Weibull diagram.
The valid data points are then fitted using a straight line with a constant slope of 4.
K_0 is the abscissa value of the ordinate lnln(1/(1-P_f)=0 of the straight line fit:

$$K_o = (K\text{-}20)_{\ln\ln(1/(1-Pf)=0} + 20 \quad (\mathrm{MPa}\sqrt{m})$$

A schematic of the determination procedure is presented in Figure A10.3.

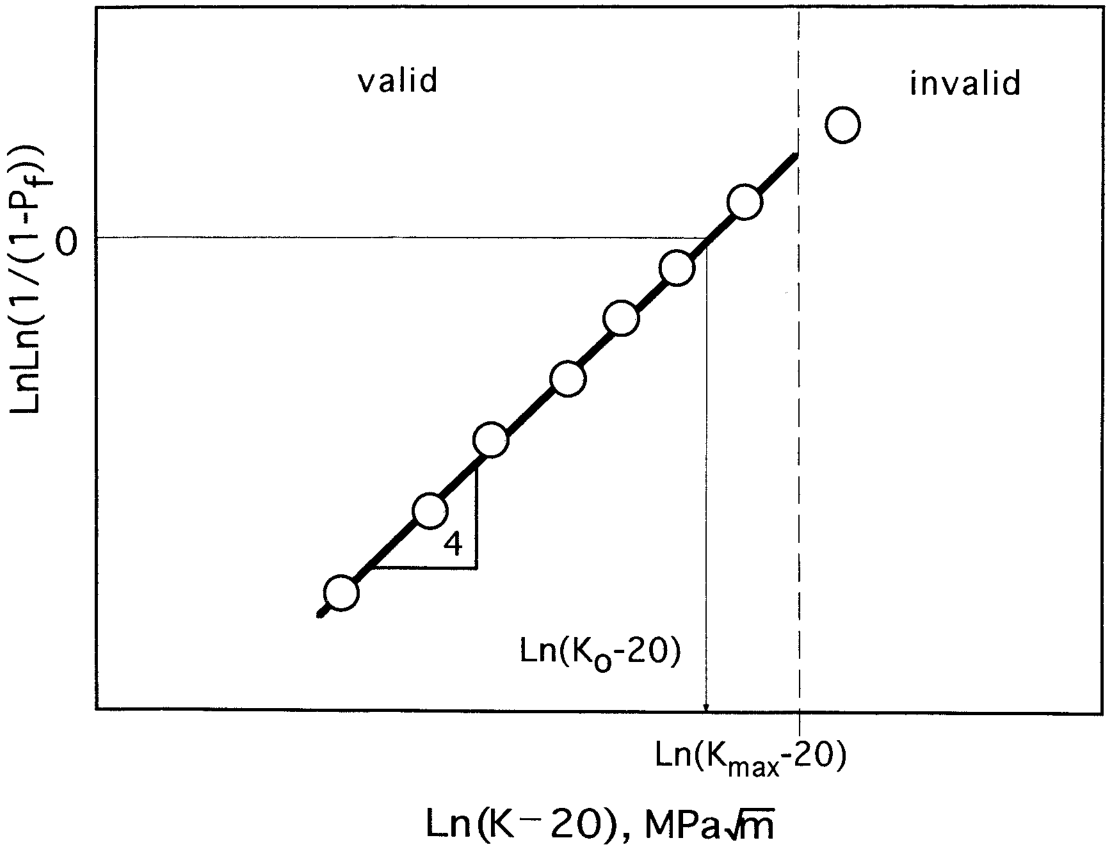


Figure A10.3: Determination of K_o using a straight line fit in a Weibull plot.

A10.2 Prediction of Size Effects

In the transition regime the P_f Weibull distribution depends on the size of the specimen. Within the lower and upper toughness borders outlined in Section A.10.2.1 a change of the size of proportional specimens influences only the K_0-value of the P_f Weibull distribution. This effect can be predicted as follows:

$$K_{oB2} = 20 + (K_{oB1} - 20) \ (B_1/B_2)^{0.25} \quad (\mathrm{MPa}\sqrt{m})$$

B_1 is the thickness of the specimen on which the prediction is based, B_2 is the specimen thickness for which the size effect is predicted.

Therefore, the prediction is performed by determining K_{oB1} from a measured tough-

ness data set as outlined below in Section A10.2.1 and by the above equation to calculate K_{oB2} which represents the K_o value of the P_f Weibull distribution to be predicted.
A schematic of the prediction is shown in Figure A10.4.

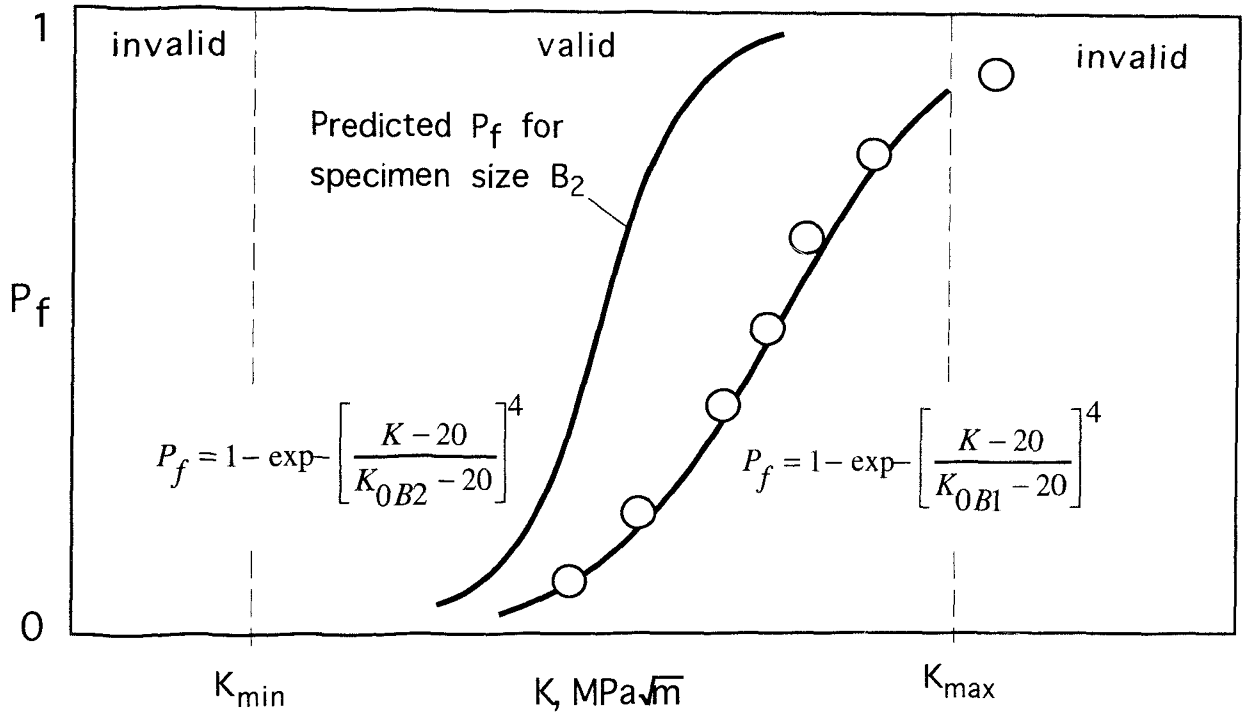


Figure A10.4: Prediction of specimen size effects on the P_f Weibull distribution of proportional specimens.

A10.2.1 Data Qualification for Determining K_{oB1}

The K_{oB1} value can be determined from a toughness data set which has to fulfill several requirements as outlined below:

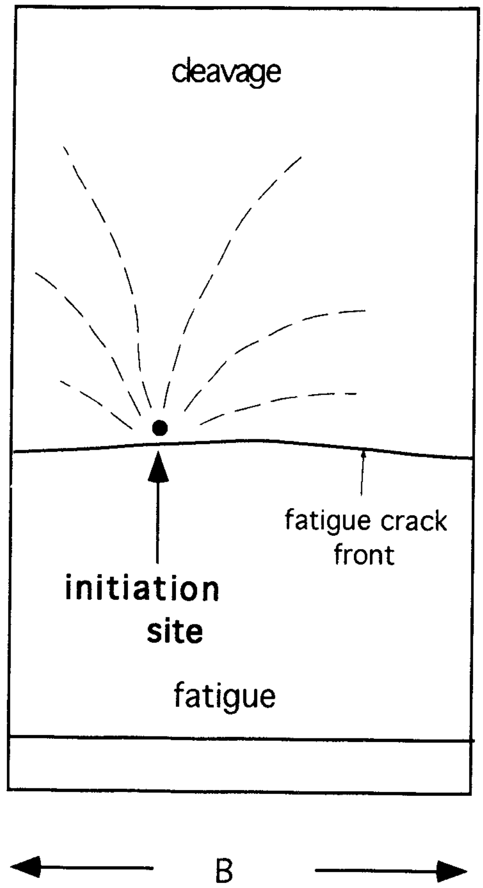
A10.2.1.1

The toughness values must be produced by replicate tests conducted under identical test temperatures and identical loading rates using identical proportional SENB or CT specimens.

A10.2.1.2

The prediction is restricted to a weakest link fracture mechanism. This is the case if at least 80% of all the fracture surfaces produced by cleavage instability reveal macroscopically a „single cleavage initiation side“ located at the fatigue crack front, Figure A10.5.

Figure A10.5:
A cleavage initiation site indicates a weakest link fracture mechanism.



A10.2.1.3

The total number of tests, N, contains all the replicate tests. This includes tests terminated by cleavage instability plus tests which were unloaded before unstable fracture occurred. Therefore, the total number of tests, N, is:

$$N = N_{unstable} + N_{unloaded}$$

All specimens which were unloaded at a toughness value less than any of the toughness values related to cleavage instability are considered as non-tests. These tests must be ignored and do not contribute to the number of N, see Figure A10.1. At least 50 % of the tests of a data set must reveal cleavage instability:

$$N_{unstable} / N > 0.5$$

A10.2.1.4

All toughness data which are above

$$\Delta a_{max} = (W - a_0)0.05$$

$$K_{max} = \sqrt{(W - a_0)R_e E / 50}$$

and below

$$K_{min} = \sqrt{r6\pi R_e^2}$$

$$r = 0.5 \text{ mm}$$

are considered to be invalid and must not be used for the determination of K_{oB1} as outlined Section A10.2.2. These data do only contribute to the total number of tests, N.

A10.2.2 Determination of K_{oB1}

In order to determine a K_{oB1} value at least 6 toughness values related to cleavage instability must remain after the data qualification outlined in A10.2.1.

The N toughness values of the data set are ranked and subsequently the toughness values related to cleavage instability are assigned with a failure probability, P_{fi}, calculated as follows:

$$P_{fi} = (i - 0.3) / (N+0.4)$$

$$1 \leq i \leq N_{unstable}$$

The data pairs (K_{ci};P_{fi}) are plotted in a Weibull diagram.
The valid data points are then fitted using a straight line with a constant slope of 4. K_{0B1} is the abscissa-value of the ordinate lnln(1/(1-P_f)=0 of the straight line fit, Fig. A10.6:

$$K_{oB1} = (K\text{-}20)_{\ln\ln(1/(1-Pf) = 0} + 20 \qquad (\text{MPa}\sqrt{\text{m}})$$

A10.2.3 Limits on the Predicted P_f Weibull Distribution

A predicted P_f Weibull distribution is limited by the lower and upper toughness borders shown in Section A10.2.1.4 determined using the thickness B_2 of the specimens to be predicted. Outside these borders the predicted P_f-Weibull distribution function may give unreliable results.

A10.3 Estimation of the Temperature Dependence of the Failure Probability Using the Master Curve Concept

For pressure vessel steels it has been shown that the temperature dependence of the fracture toughness of proportional 25 mm thick CT and SENB specimens in the transition regime can be modelled using the "master curve":

$$K_{med} = 30 + 70 \exp(0.019 (t - t_o))$$

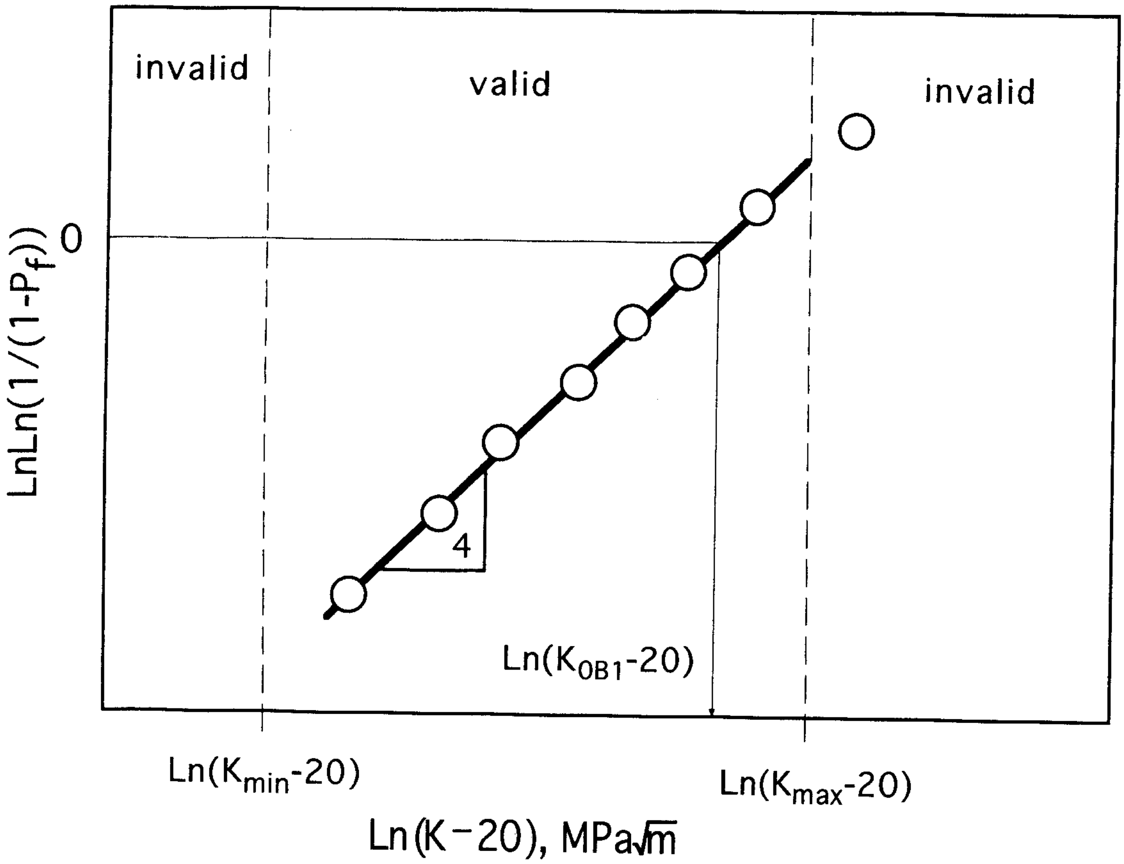


Figure A10.6: Determination of K_{0B1} using a straight line fit in a Weibull plot.

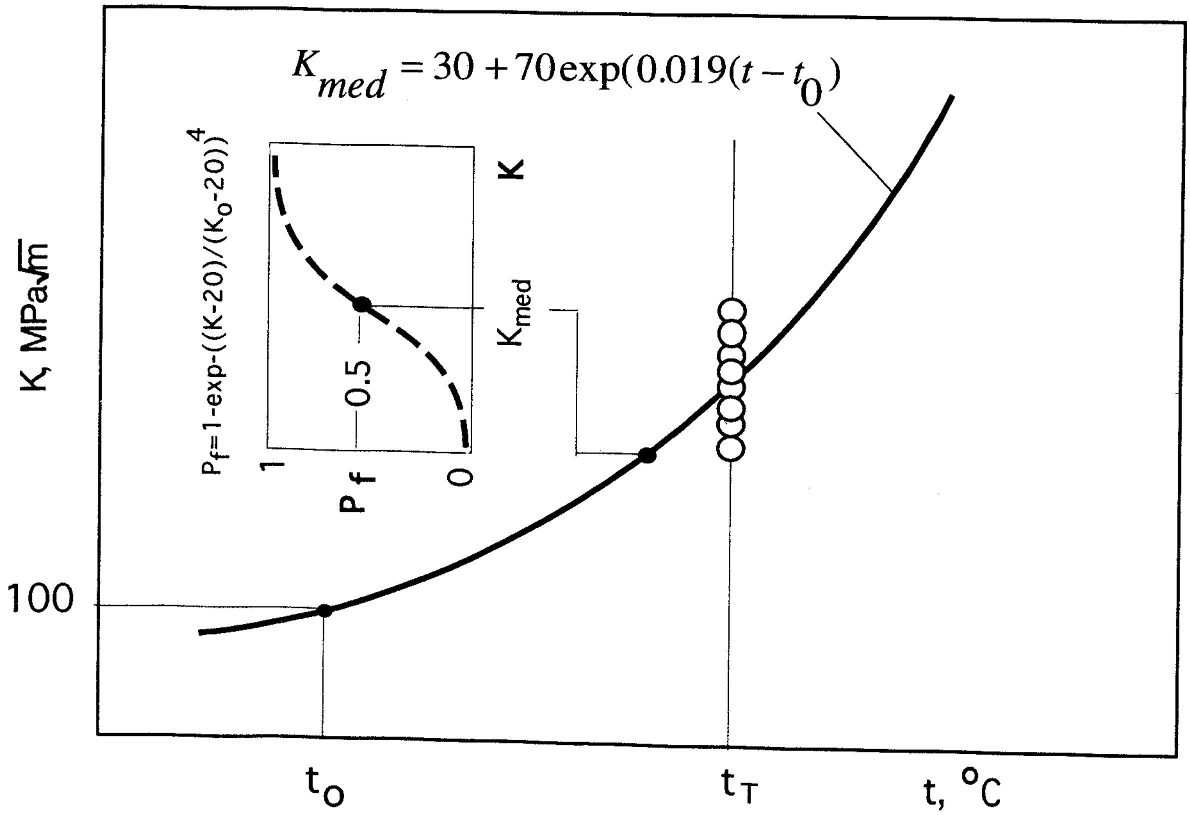


Figure A10.7: Master curve and P_f Weibull distribution obtained from a toughness data set measured at the temperature t_T.

K_{med} is the medium value of the fracture toughness scatter. The reference temperature t_0 is the temperature at which K_{med} is 100 ($MPa\sqrt{m}$). In order to apply this curve, the reference temperature t_o must be determined from the medium value K_{med} of a fracture toughness data set measured at the temperature t_T in the transition regime, Figure A10.7:

$$t_o = t_T - (0.019)^{-1} \ln((K_{med}-30)/70)$$

A10.3.1 Data Qualification for Determining K_{med}

In order to determine a K_{med} value the same data qualification as outlined in Section A10.1.1 must be applied to the toughness data set.

A10.3.1.1 Determination of K_{med}

At least 6 valid toughness data related to cleavage instability must remain after the data qualification procedure.
The N toughness values of the data set are ranked and subsequently the toughness values related to cleavage instability are assigned with a failure probability ,P_{fi}, calculated as follows:

$$P_{fi} = (i - 0.3) / (N+0.4)$$
$$1 \le i \le N_{unstable}$$

The data pairs (K_{ci};P_{fi}) are then arranged in a Weibull plot.
The valid data points are fitted using a straight line with a constant slope of 4. K_{med} is the abscissa value of the ordinate lnln(1/(1-Pf)= -0.36 of the straight line fit, Fig. A10.8

$$K_{med} = (K-20)_{\ln\ln(1/(1-Pf) = -0.36} + 20 \qquad (MPa\sqrt{m})$$

A10.3.2 Determination of the Temperature Dependence of the P_f Weibull Distribution Based on the Master Curve

The temperature dependence of the P_f Weibull distribution in Section A10.1 results from the temperature dependence of the K_o value. This is determined from the temperature dependence of the K_{med} value predicted by the master curve given in Section A10.3 which can be converted into K_o as follows:

$$K_o = (K_{med}-20)/((\ln 2)^{0.25}) + 20 \qquad (MPa\sqrt{m})$$

At all temperatures the P_f Weibull distribution is limited by the upper toughness border as defined in Section A10.1.1.3. Beyond this limit the P_f-Weibull distribution may not yield realistic results.

Note:

Although the master curve determination outlined in Section A10.3 is based on toughness values obtained from proportional 25 mm thick specimens, also toughness data sets obtained from other specimen thicknesses can be used. In that case the procedure outlined in Section A10.2 must be applied to the toughness data set first in order to predict the toughness of the 25 mm thick specimen. The master curve can then be derived from the predicted fracture toughness by following the procedure of Section A10.3.

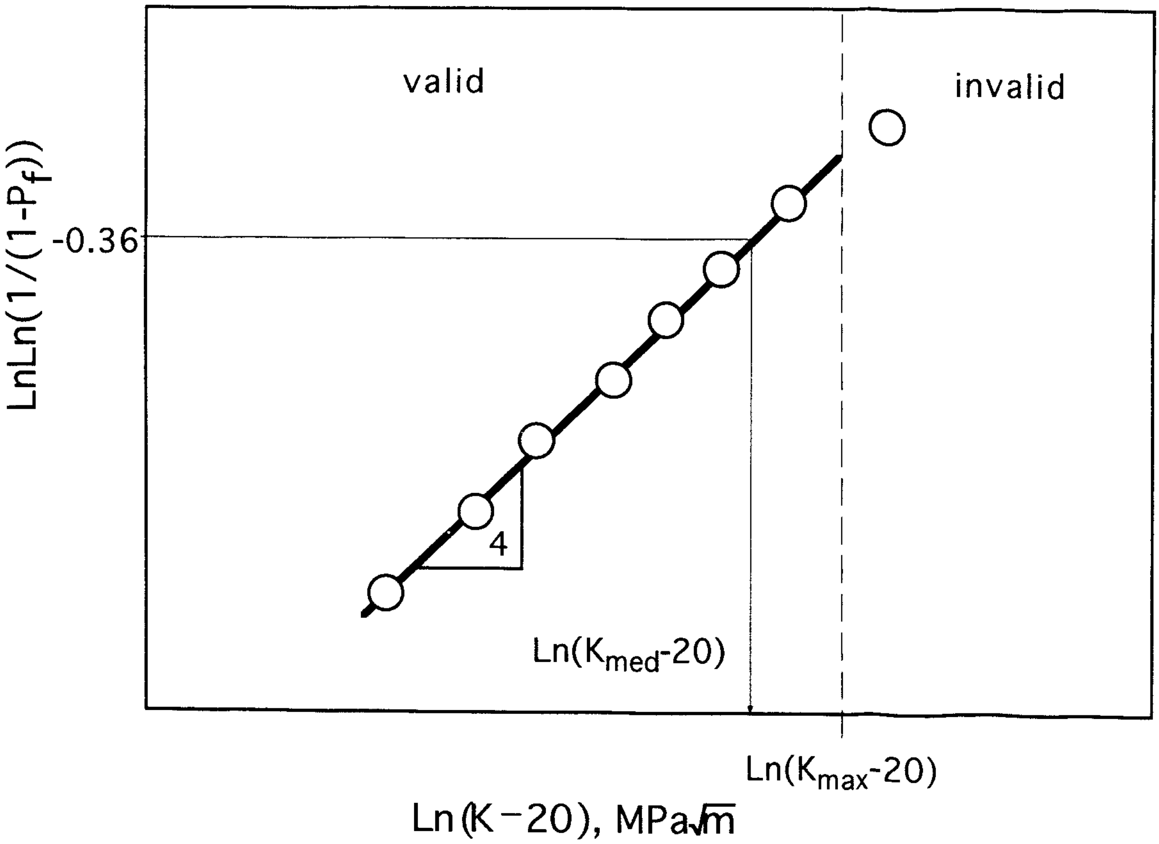


Figure A10.8: Determination of K_{med} using a straight line fit in a Weibull plot.

A10.4 General Remark

In this procedure the P_f Weibull distribution is based on the toughness values obtained from proportional, deeply notched CT or SENB specimens. Due to the square sized ligament, these types of specimens promote plane strain fracture. Therefore the P_f Weibull distribution determined in this procedure represents the cumulative failure probability of a "through-crack under plane strain condition" related to a particular crack front length.

There are numerous experimental results which show that the "plane strain P_f Weibull distribution" is a conservative estimate of the failure probability for a non-plane strain case realised by tension loading (e.g. centre crack tension specimen) and realised by CT and SENB specimens which have an elongated ligament, i.e. (W-a)>B.

It is not clear yet whether the master curve represents the correct temperature dependence for all kinds of ferritic steels. Good results have been found for pressure vessel steels. Less experience is available for other steels. Therefore, if the master curve is applied to other types of steels care should be taken. This can be done by comparing the reference temperatures determined from several independent data sets measured at different temperatures in the transition regime.The master curve is applicable if all data sets yield very similar reference temperatures.

Note:
The procedure in this appendix is based on the stress intensity factor K. If the J-Integral is used for characterising the fracture behaviour, the J-values must be converted into K values before the above procedure can be applied:

$$K = \sqrt{JE/(1-\nu)}\,.$$

REFERENCES

[1] J. Heerens, U. Zerbst and K.-H. Schwalbe, Strategy for Characterising Fracture Toughness in the Ductile to Brittle Transition Regime, Fatigue and Fracture of Engineering Mat. and Structures, Vol. 16, No.11, pp. 1213–1230 (1993).

[2] D. E. McCabe, U. Zerbst and J.Heerens, Development of Test Practice Requirements for a Standard Test Method on Fracture Toughness Testing in the Transition Regime, GKSS-Report, GKSS 93/E/81, (1994)

APPENDIX 11

K-Based Fracture Resistance Curves For Centre Cracked Tensile Panels

High strength materials such as aerospace materials are frequently tested in the form of CCT specimens fabricated from thin sheets. In these cases the crack growth resistance curve can often be expressed as the variation in the plasticity adjusted stress intensity factor, K_{eff}, with crack growth, Δa.

A11.1 The option described in this Appendix can be used if

$$F_j \leq 1.8\, R_{p0.2}\, (W\text{-}a)B$$

where F_j is either the force at termination of the test when using the muliple specimen method or the last point to be avaluated in a single specimen test.

A11.2 The specimens should satisfy the requirement

$$(W\text{-}a_0)/B \geq 4$$

A11.3 Calculate the fracture resistance

$$K_{eff} = \frac{F}{B\sqrt{W}} f(a_{eff} / W)$$

where

$$a_{eff} = a + \frac{K^2}{2\pi R_{p0.2}^2}$$

F = applied force

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

and f(a/W) is the stress intensity function given in Appendix 1.

A11.4 Determine Δa_{max} from either the crack growth associated with

$$F = 1.8\, R_{p0.2}\, (W\text{-}a)B$$

or $\Delta a_{max} = 0.5\, (W\text{-}a_0)$, whichever is the smaller.

A11.4 The plot of ΔK_{eff} versus Δa represents the crack growth resistance curve for a given thickness, B, provided the data spacing requirements of Section 7.4 are met.

A11.5 The crack growth resistance curve is either represented by the curve fit of Section 7.5.1 or as the series of data points.

REFERENCES

[1] Schwalbe, K.-H., and Setz, W., R-curve and fracture toughness of thin sheet materials, Journal of Testing and Evaluation, Vol. 9, 1981, pp. 182–194.

[2] Schwalbe, K.-H., and Hellmann, D., Correlation of stable crack growth with the J-integal and the crack tip opening displacement, effects of geometry, size, and material. GKSS 84/E/37, GKSS-Forschungszentrum Geesthacht, Geesthacht (1984).

APPENDIX 12

Testing Specimens With Shallow Cracks

The initial crack length ratio $0.45 \leq a_0/W \leq 0.65$ required for compact and single edge notched bend specimens ensures high constraint and hence lower bound fracture resistance. However, in many structural applications the cracks are shallow, i.e. the crack length ratio is substantially smaller than 0.45. This leads to a loss of constraint and hence to increased fracture resistance which can be beneficial if the crack length ratio of the test specimen models the structural situation.

Tests of this kind can be carried out using this Procedure considering the following suggestions:

– Only single edge notched bend specimens should be used because compact specimens containing shallow cracks tend to fail at the pin holes or at the machined steps.

– The J formulas in this Procedure may become invalid for cracks with $a_0/W < 0.45$. It is therefore recommended to determine the fracture resistance in terms of δ_5 unless it can be demonstrated that either the J determination used in this Procedure or alternative experimental J determination methods are appropriate.

– The validity criteria outlined in this Procedure should not be applied to the test results.

– The test results should be reported together with the a_0/W value used in the test.