THE DEVELOPMENT OF A EUROPEAN GROUP ON FRACTURE PROCEDURE TO MEASURE ELASTIC-PLASTIC FRACTURE PARAMETERS

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ABSTRACT

Recent progress in elastic-plastic fracture mechanics and experience with existing test standards has prompted the European Group on Fracture (EGF) to form a Working Party aimed at writing an elastic-plastic fracture mechanics testing Procedure which is based on European experience and European views. The present status of the Working Party Procedure is described together with a brief description of existing methods.

INTRODUCTION

It is now recognised that most structures contain crack like flaws when they enter service. These flaws may well propagate and grow to a size such that the integrity of the structure becomes seriously impaired. When a structure is operating in the fully ductile upper shelf regime the material parameters which are usually used to assess structural integrity are resistance to crack initiation and resistance to crack growth. These parameters together describe the upper shelf crack growth fracture resistance behaviour and their determination is an important requirement of any structural integrity assessment.

The measurement of ductile crack growth fracture resistance has attracted a great deal of attention in recent years.

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An appreciable part of this work has been aimed at standardising methods for determining both crack initiation toughness and resistance to crack growth.
In this paper, the present state of discussion in the Working Party on Fracture Mechanics Testing Standards in Task Group I: Elastic-Plastic Fracture Mechanics of the European Group on Fracture (EGF) is described against the background of existing methods.

EXISTING TESTING STANDARDS AND PROCEDURES

Historically, the first testing Standard to incorporate a method for measuring upper shelf crack initiation toughness was BS 5762 (1). The initiation value, δ_i 1), of the crack tip opening displacement (CTOD) is determined as shown in Figure 1: The amount Δa_{DT} of ductile tearing (stable crack growth without the stretch zone) is determined as the average of individual measurements at seven evenly spaced locations along the crack front and plotted versus the CTOD determined via

$$\delta = \frac{K^2(1-\nu^2)}{2\,\sigma_Y E} + \frac{0.4(W-a_o)v_p}{0.4W+0.6a_o+z} \qquad (1)$$

Back extrapolation to $\Delta a_{DT} = 0$ yields δ_i.
Following the issue of BS 5762, the ASTM Standard E 813-81 (2) was released. In this method, J_{Ic} is supposed to determine the toughness at or near the onset of crack initiation following crack tip blunting from an originally sharp fatigue pre-crack. In Figure 2 the principle of this method is outlined: J-Δa data (Δa means total crack growth including blunting) within a given validity range (within the dashed "exclusion lines") are fitted by a best fit straight line. The intercept of this line with the blunting line given by

$$J = 2\,\sigma_F \Delta a_B \qquad (2)$$

defines J_{Ic} providing additional validity requirements are met. The actual crack growth, Δa, is measured on the fracture surface at at least nine evenly spaced locations along the crack front.

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1) In this paper a nomenclature was chosen which is consistent throughout the whole text. Therefore, the symbols used are not in all cases identical with those used in the various Standards and Procedures.

There are several drawbacks to this approach (Heerens et al. (3), Schwalbe et.al. (4)):

- Straight line fits to non-linear experimental data often result in straight lines with differing slopes and hence different J_{Ic} values.
- J_{Ic} can depend on the data point distribution.
- J_{Ic} is not on the actual R-curve, Figure 2. It is by an undefined amount larger than the "true" initiation value, J_i.
- The blunting line equation is unrealistic as can be seen in Figure 3 where stretch zone width measurements are compared with Eq(2) and with

$$\Delta a_B = 0.4 d_n \frac{J}{\sigma_o} \qquad (3)$$

an expression which accounts for the strain hardening properties of the material (Heerens et.al.(3)). In this equation, σ_o is the yield stress obtained by a power law fit to the stress-strain data; d_n depends on the strain hardening properties of the material. Figure 3 shows clearly that Eq(3) represents a more appropriate blunting line than Eq(2).

It should be noted that in recent amendments to E 813-81, a power law equation is now fitted through the valid data. J_{Ic} is defined at the intercept of the power law curve with a line offset 0.2mm and parallel to the blunting line given by Eq(2), Figure 4.

In the Japanese J_{Ic} Standard JSME S 001-1981 (quoted by Kobayashi et.al.(5)), J_{Ic} is defined as J_i at the onset of ductile tearing and can be determined in three different ways:

- The stretch zone width technique requires the experimental determination of the stretch zone width, SZW, on at least two specimens. The data points are then fitted by a straight line going through the origin. Three or more specimens are pulled apart and the critical stretch zone width, SZW_c, is measured on the fracture surface . Figure 5 shows how J_i is determined from the data points. The SZW measurements have to be made at three or more evenly spaced locations in the range 3/8 B to 5/8 B (Figure 5) and are then averaged.

- With the R-curve technique, at least four data points are determined in the range specified in Figure 6. Crack growth, Δa, is measured as SZW at three or more evenly spaced locations in the range 3/8 B to 5/8 B. A straight line is fitted to the data points and its intersection with the blunting line, which is determined as outlined above, is defined as the initiation point. An interesting detail is given by the condition that the slope of the R-curve data shall be equal to or less than one half of the slope of the blunting line.

- Three experimental techniques, based on the electrical potential, ultrasonic, and the acoustic emission are specified for the single specimen technique. The first specimen (specimen A) of a total of three specimens is loaded to a load-line displacement, $\Delta_o(A)$, at which a single specimen technique indicates the onset of ductile tearing, Figure 7. Two additional specimens (B and C) are then loaded within the limits shown in Figure 7. It is to be ascertained by one of the single specimen techniques specified that specimen B does exhibit initiation whereas specimen C remains in the blunting phase. The initiation values, J_i, of the material under consideration is the average of $J_i(A)$ and J_i (B).

- It is worth noting that the Japanese method does not recommend the unloading compliance technique because of insufficient accuracy for small values of crack extension, whereas ASTM E813 specifies this technique although other techniques are also permitted.

Since the actual blunting behaviour (expressed by SZW) is in most cases at variance with the prediction by Eq(2) coincidence of initiation values determined after JSME and ASTM cannot be expected.
For more details of the Japanese method see reference (5).

Although the authors are not aware of details, it should be mentioned that China has also published a J_{Ic} standard, see Guo et.al.(6).

A method for measuring ductile crack growth fracture resistance was first described by Albrecht et al. (7). This method is now being formulated into an ASTM Standard. It does not include a procedure for determining crack initiation toughness but does give specimen size dependent limits to the data.

Neale et al. (8) developed a procedure for describing the ductile crack growth fracture resistance of a material in terms of parameters suitable for structural integrity assessments. The value of the fracture resistance at 0.2mm crack growth, $J_{0.2}$, as shown in Figure 8 is used as an engineering approximation toughness. J_g is the maximum value of the fracture resistance that can be validly measured from a test specimen and dJ/da is the slope of the crack growth resistance curve at J_g.

ASTM are drafting a CTOD Test Method which follows the general philosophy and most of the details of BS 5762. However, there are two alterations which are worth mentioning:

- The ASTM draft method offers two alternative procedures to determine the initiation value: from a graph of δ versus Δa_{DT} (Figure 9a) δ_i can be obtained by extrapolation to $\Delta a_{DT} = 0$, as was outlined in Figure 1. However, the condition that at least one data point shall be in the range $\Delta a_{DT} < 0.15$mm has been dropped. This condition seems useful to ensure that measurements are close enough to initiation.

- Alternatively, δ can be plotted versus total crack growth, Δa (Figure 9b), and initiation is obtained by the intersection of the straight line fitted to the δ-Δa data with the blunting line

$$\delta = 2\Delta a_B \tag{4}$$

If this blunting line formulation is correct, both alternatives should yield equal δ_i values. Stretch zone studies (Schwalbe et al.(9)) revealed that Eq(4), which is the equivalent to Eq(2), exhibits a similar discrepancy as Eq(1), Figure 10. Therefore, the counterpart of Eq(2), i.e.

$$\Delta a_B = 0.4 d_n \frac{G_{eff}}{\sigma_Y} \quad \text{for } F \leqq 0.9 F_Y \tag{5}$$

(with F_Y: yield load of the specimen) is proposed, see Figure 10. The plasticity corrected strain energy release rate, G_{eff}, has to be determined in the quasi linear elastic regime ($F \leqq F_Y$); Eq(5) can then be linearly extrapolated into the net section yielding regime. The reason for taking G_{eff} instead of J is to make the procedure independent of the determination of the J-integral. For more details see reference (9).

Only The Welding Institute Procedure (Gordon(10)) combines both J and crack tip opening displacement in one document. The methods used to interpret the data have already been described in BS 5762 (1), ASTM E 813-81(2) and Neale et al. (8). The value of crack tip opening displacement at 0.2mm crack growth is introduced as an engineering approximation to the initiation toughness.

EGF DRAFT PROCEDURE

Recent progress in elastic-plastic fracture mechanics testing (see for example the symposium proceedings (11, 12)) has seen a proliferation of test standards and procedures. Among these, Task Group I: Elastic-Plastic Fracture Mechanics of the European Group on Fracture (EGF) has set up the Working Party on Fracture Mechanics Testing Standards.

The driving forces behind the EGF efforts are:
- Updating test methods.
- To reach a consensus view within Europe.
- Unification of fracture mechanics testing standards to cover as many aspects as possible, e.g. J-integral and CTOD, initiation and crack growth by one method instead of having a number of independent standards.

EGF cannot issue Standards. Consequently, documents endorsed by EGF can only be regarded as expert's views which may influence national or international Standards.

Objective and Applicability. It is intended that a unified fracture mechanics test standard should be the objective of the Working Party. As a first step, the Working Party is drafting a Procedure covering resistance against initiation and crack growth, both in terms of J and CTOD. The method will initially concentrate on the upper shelf or ductile tearing regime and the transition region in the future.
Although most of the experience with elastic-plastic fracture mechanics has been gained on austenitic and ferritic steels, the method should be applicable to other materials.

Format. The text of the procedure contains the steps necessary to evaluate the desired fracture parameter including all the requirements for conducting the test and deriving valid data. Descriptions of experimental techniques such as the unloading compliance method and the electrical potential method are in Appendices.

The method will be supplemented by background information in order to explain decisions made in the Procedure.

Single Versus Mutiple Specimen Method. The multiple specimen method is the reference method. Single specimen methods utilising indirect techniques for determining crack growth (like the unloading compliance or the electric potential drop techniques) are permitted if sufficient accuracy is demonstrated. "Sufficient accuracy" means ±15% in crack growth, Δa, or ±0.1mm, whichever is greater. Each single specimen test shall be terminated such that the final crack extension can be made visible by any appropriate method. This way each test provides an accuracy check. At least one test should be terminated close to the expected initiation point in order to achieve sufficient accuracy in the early stages of crack growth. The single specimen method provides more information on scatter or systematic variations of material properties.

Specimens. Only single edge notched bend (SENB) and compact (CT) specimens are permitted in the Procedure. The measurement of load point displacement in SENB specimens can be difficult. The use of a reference bar is the preferred technique. However, other suitable techniques are allowed, providing all forms of extraneous displacements are accounted for.
The preferred geometry of the CT specimen is similar to that in ASTM E399, with an additional cut-out for conveniently measuring the load line displacement.
The preferred thickness is one half of the specimen width. However, it may vary independently of the width. The thickness should be as large as practicable, and ideally be as thick as the structural component. If the specimen is thinner than the component, then sidegrooving is mandatory. Sidegrooving has the advantage of improving the accuracy of the crack length measurement techniques.

Minimum Number of Specimens, Data Point Distribution, and Data Fit.

For the single specimen method, a minimum of three specimens should be tested. Four specimens may suffice for the multiple specimen method. However, the preferred number of specimens is six, with at least four specimens satisfying the condition $\Delta a \leq 0.06(W-a_o)$, with a_o being the starting crack length.

The data points of the R-curve shall be evenly distributed between $\Delta a = 0$ and the final limit as specified by Eqs(10-15).

J and CTOD Estimation Formulae. The tests are instrumented such that either the J-integral or the CTOD can be derived from the experimental data.

The J-integral is evaluated from

$$J_o = \frac{\eta U}{B(W-a_o)} \tag{6}$$

where

$$\eta = 2 \qquad \text{for SENB specimens,} \tag{7}$$

$$\eta = 2+0.522 \left(1 - \frac{a_o}{W}\right) \quad \text{for CT specimens,} \tag{8}$$

and U is the area under the load - load line displacement record. For non-sidegrooved specimens, B is the specimen thickness, in case of side-grooved specimens, B is replaced by B_n, the net section thickness. In principle, J should be corrected for crack growth using the equation

$$J = J_o\left[1 - \frac{0.75\eta-1)\Delta a}{W-a_o}\right] \tag{9}$$

However, experience shows that for amounts of crack growth not exceeding the validity limit in Eq(14) the error by using the uncorrected values according to Eq(6) is negligible.

The CTOD is determined by Eq(1).

Validity Requirements. The validity limits are expressed in terms of the maximum J or CTOD, respectively, and Δa values which can be measured for a given test specimen size. These values are the smaller of:

$$J_{max} = (W-a_o)\,\frac{\sigma_F}{25} \tag{10}$$

and

$$J_{max} = B\,\frac{\sigma_F}{25} \tag{11}$$

with σ_F being the average of the proof stress, $\sigma_{0.2}$, and the tensile strength, σ_u.

Similarly, the maximum valid δ value is given by the smaller of

$$\delta_{max} = \frac{W-a_o}{50} \tag{12}$$

and

$$\delta_{max} = \frac{B}{50} \tag{13}$$

The maximum amount of crack growth which is supposed to be J controlled is given by

$$\Delta a_{max} = 0.06(W-a_o) \qquad (14)$$

whereas

$$\Delta a_{max} = 0.1(W-a_o) \qquad (15)$$

determines the maximum amount of crack growth which is supposed to be δ controlled. However, there is much less evidence supporting Eq(15) than Eq(14).
Due to uncertainties with these limits, other limits may be used if adequate evidence justifying their use is available.
The valid data are fitted by the equation

$$J \text{ or } \delta = A(\Delta a + D)^C \qquad (16)$$

which has the advantage of modelling both linear and power law behaviour. The curve fit should not include Δa data less than 0.2mm, Figure 11.

Derivation of Fracture Parameters. Methods are described for interpreting valid crack growth fracture resistance data in terms of parameters suitable for material characterisation and structural integrity assessments related to crack initiation:

(1) J or δ at crack initiation, J_i or δ_i.

If a stretch zone is clearly visible on the fracture surfaces at

the end of the fatigue pre-crack, J or δ at crack initiation are defined at the intersection of the line parallel to the J or δ axis representing the mean of the stretch zone width data with the best fit curve through the J-Δa or δ-Δa data (Eq(16)), Figure 12. The straight line through the intersection point and the origin describes the blunting behaviour of the material. At least one data point should be within 0.2mm to the blunting line.

Alternatively, if the stretch zone cannot be physically measured, the slope of the blunting line can be determined using Eq(3) or Eq(5). J_i or δ_i are then defined at the intersection of Eq(16) with the blunting line.

J_i or δ_i are valid fracture parameters only if the slope of Eq(16) at J_i or δ_i is less than or equal to one half of the slope of the blunting line.

(2) J or δ at 0.2mm of ductile tearing, $J_{0.2/BL}$ or $\delta_{0.2/BL}$.

J or δ at 0.2mm of ductile tearing, $J_{0.2/BL}$ or $\delta_{0.2/BL}$, are defined at the intersection of the J-Δa or δ-Δa curve with a straight line offset to the blunting line at 0.2mm of ductile tearing, Figure 13. The blunting line is determined using Eq(3) or Eq(5). At least one data point is required within 0.4mm to the blunting line. $J_{0.2/BL}$ or $\delta_{0.2/BL}$ are valid fracture parameters only if the slope of Eq(16) at $J_{0.2/BL}$ or $\delta_{0.2/BL}$ is less than or equal to one half of the slope of the blunting line.

(3) J or δ at 0.2mm of total crack growth, $J_{0.2}$ or $\delta_{0.2}$.

J or δ at 0.2mm of total crack growth including crack tip blunting are defined at the intersection of the J-Δa or δ-Δa curve with the line of constant total crack growth of 0.2mm, Figure 14.

The methods described above refer to the multiple specimen method. Due to uncertainties in measuring small amounts of crack growth the single specimen method is not permitted for determining J_i or δ_i.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the work and support of their colleagues G. Angelino, M. Bethmont, J.G. Blauel, M.G. Dawes, J.R. Gordon, G. Prantl, B. Voss, and M. de. Vries in the development and writing of the EGF Procedure.

SYMBOLS USED

a_o	fatigue pre-crack length
Δa	total crack growth
Δa_B	crack growth due to crack tip blunting
Δa_{DT}	crack growth due to ductile tearing
Δa_{max}	maximum amount of total crack growth which can be validly determined in a given specimen
B	specimen thickness
B_n	net thickness of sidegrooved specimen
E	Young's modulus
F	applied load
F_Y	yield load
G_{eff}	plasticity corrected strain energy release rate
J	J-integral
J_i	J at crack initiation
J_{Ic}	fracture toughness determined in ASTM E813-81
J_{max}	maximum valid J value which can be determined for a given specimen
$J_{0.2}$	J at 0.2mm of total crack growth
$J_{0.2/BL}$	J at 0.2mm of ductile tearing
K	linear elastic stress intensity factor
V_p	plastic portion of crack mouth opening displacement
W	specimen width
z	distance of knife edge from specimen front face
δ	crack tip opening displacement
δ_i	δ at crack initiation
δ_{max}	maximum valid δ value which can be determined for a given specimen
$\delta_{0.2}$	δ at 0.2mm of total crack growth
$\delta_{0.2/BL}$	δ at 0.2mm of ductile tearing
ν	Poisson's ratio
σ_F	flow stress, average of yield strength and ultimate tensile strength
σ_Y	yield strength
σ_o	yield strength obtained by a power law fit to stress-strain data.

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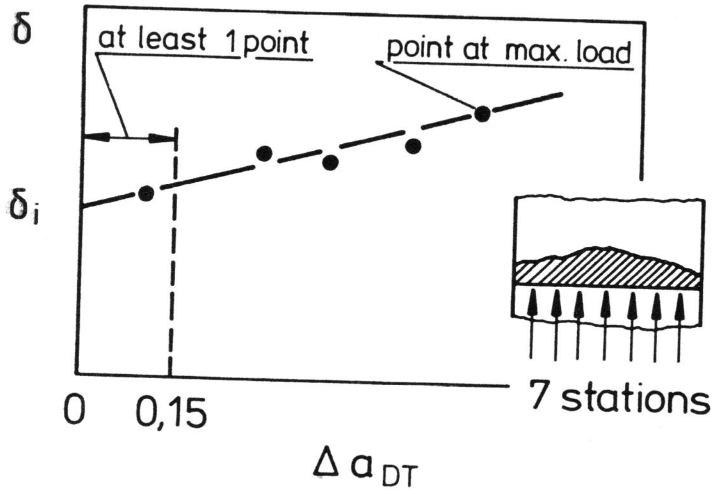

Figure 1: Determination of δ_i according to BS 5762:1979

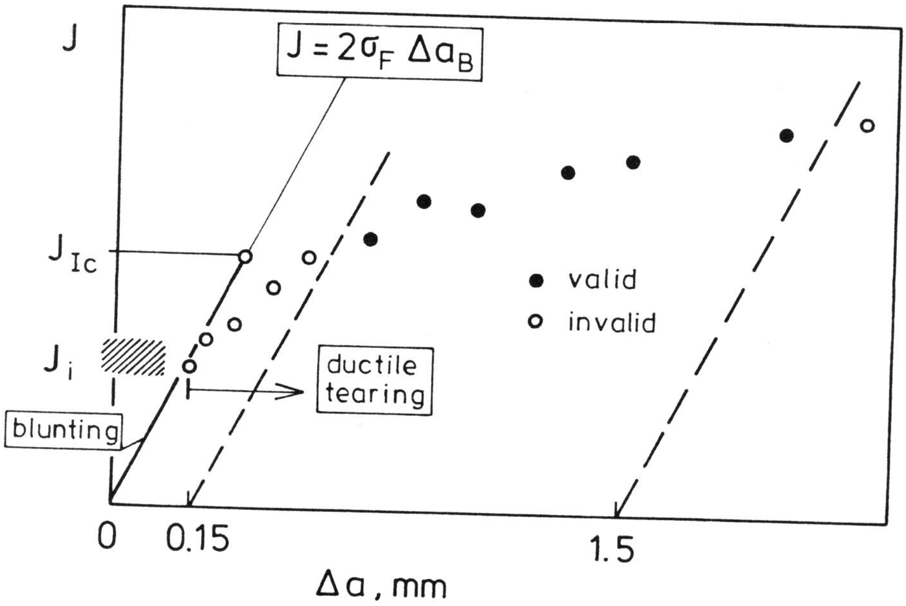

Figure 2: Determination of J_{Ic} according to ASTM E813-81

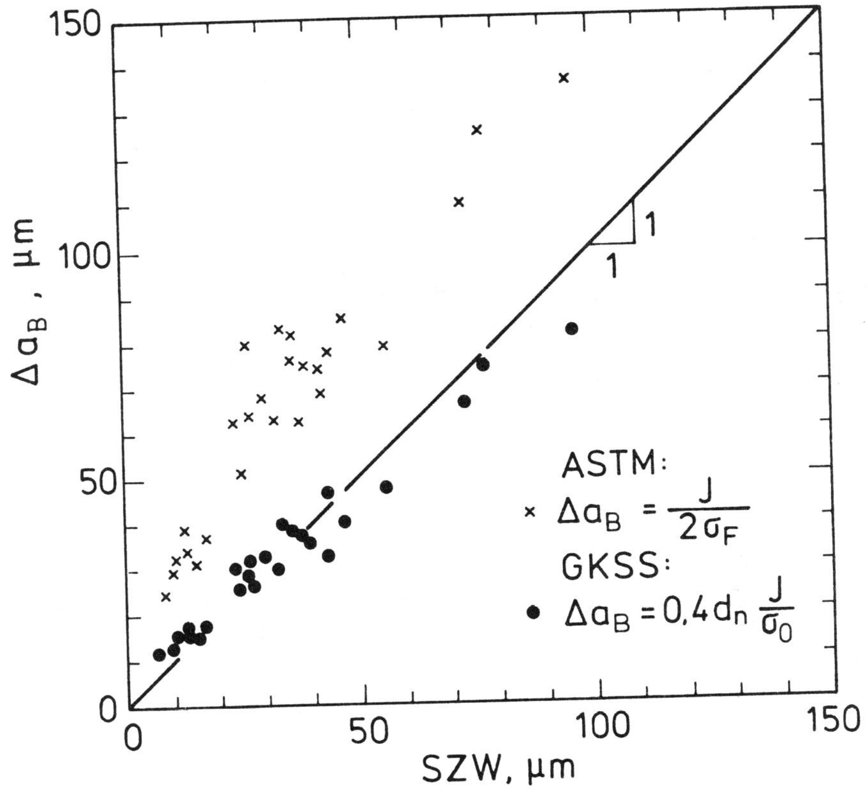

Figure 3: Measured and predicted stretch zone width, Heerens et al. (3)

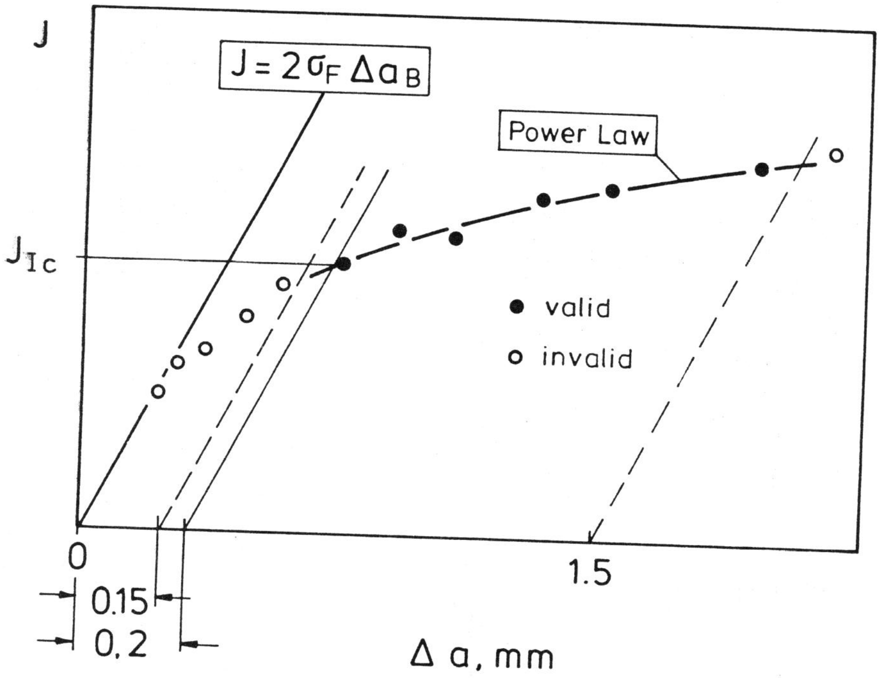

Figure 4: Modified determination of J_{Ic} according to new draft of ASTM E813

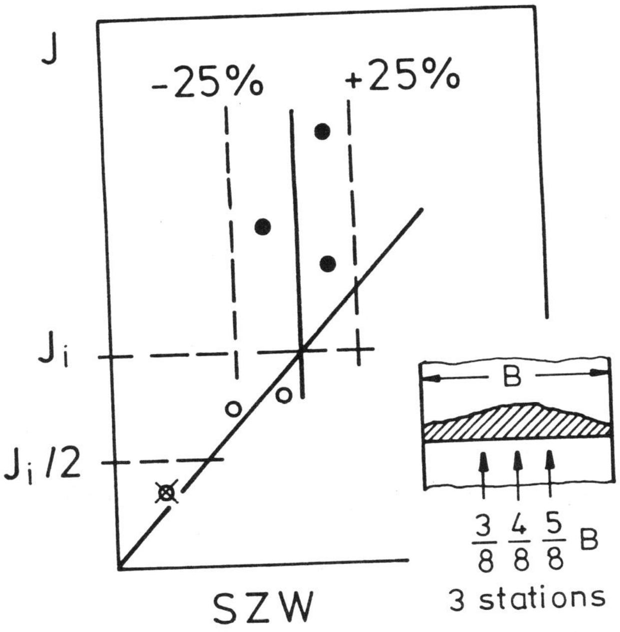

Figure 5: Determination of J_i according to JSME S001-1981, using the stretch zone width technique

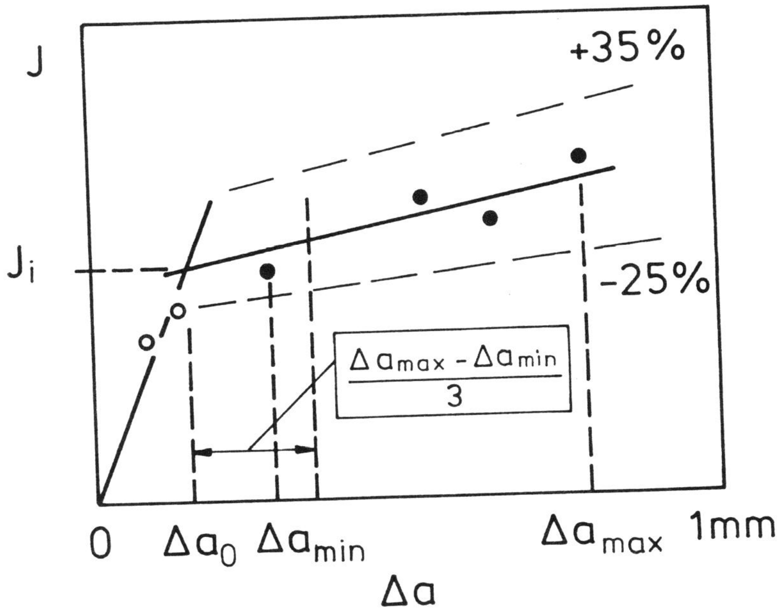

Figure 6: R-curve method of JSME S001-1981 for determining J_i

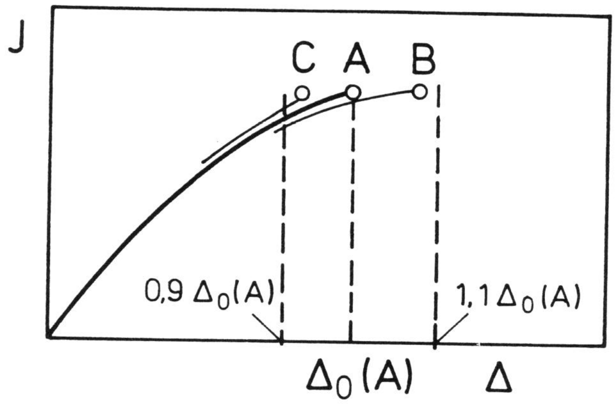

Figure 7: Single specimen method of JSME S001-1981 for determining J_i

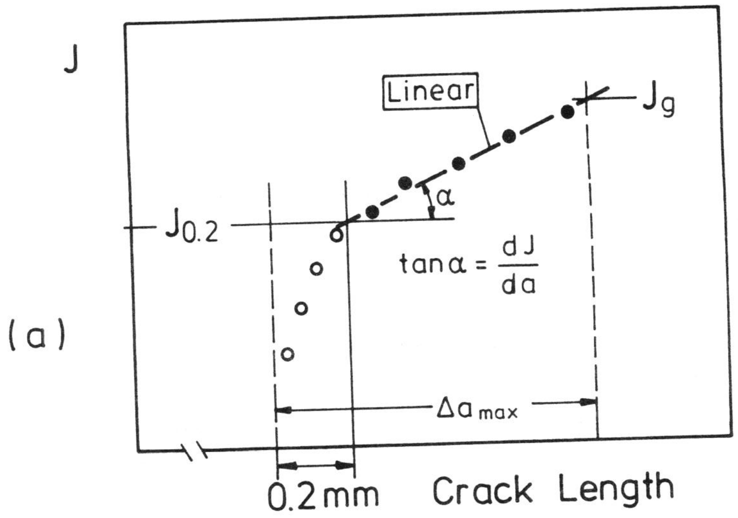

Figure 8a: Representation of the J- Δa data by a linear relationship for Δa_{max} less than 2mm and determination of $J_{0.2}$, CEGB Procedure, Neale et al.(8)

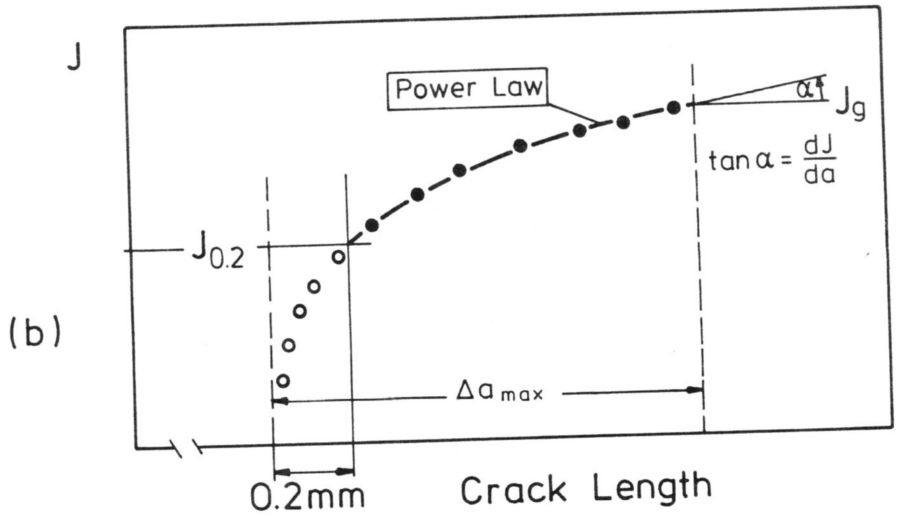

Figure 8b: Representation of the J- Δa data by a power law for Δa_{max} exceeding 2mm, and determination of $J_{0.2}$, CEGB Procedure, Neale et al.(8)

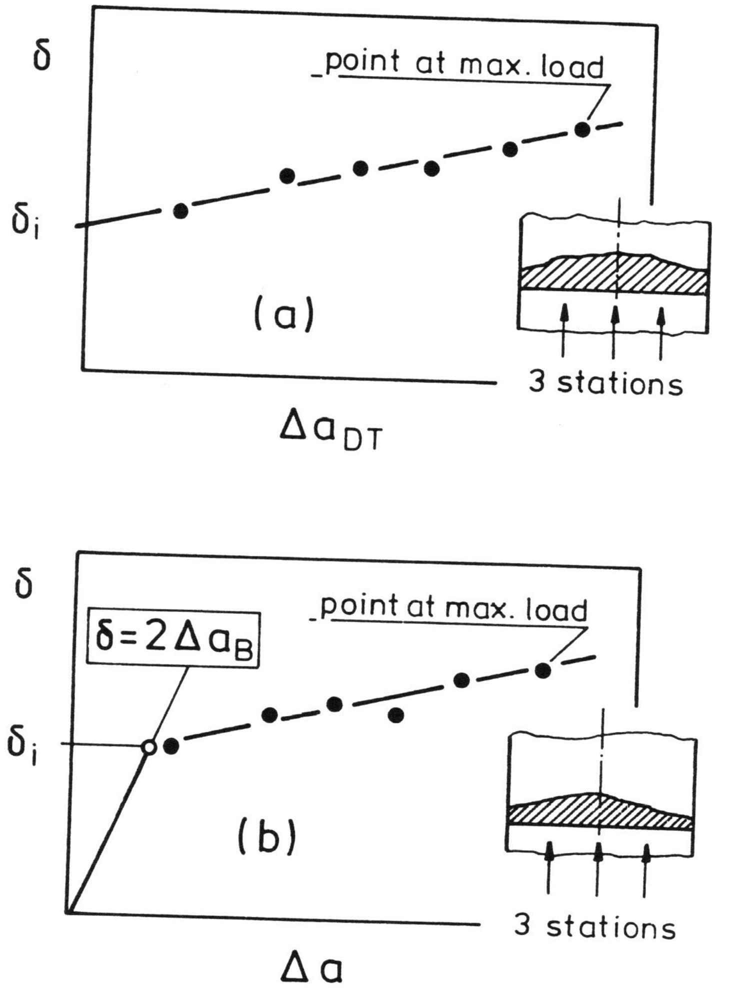

Figure 9: Determination of δ_i in the ASTM draft CTOD method
a) from δ versus amount of ductile tearing
b) from δ versus total crack extension, using blunting line construction

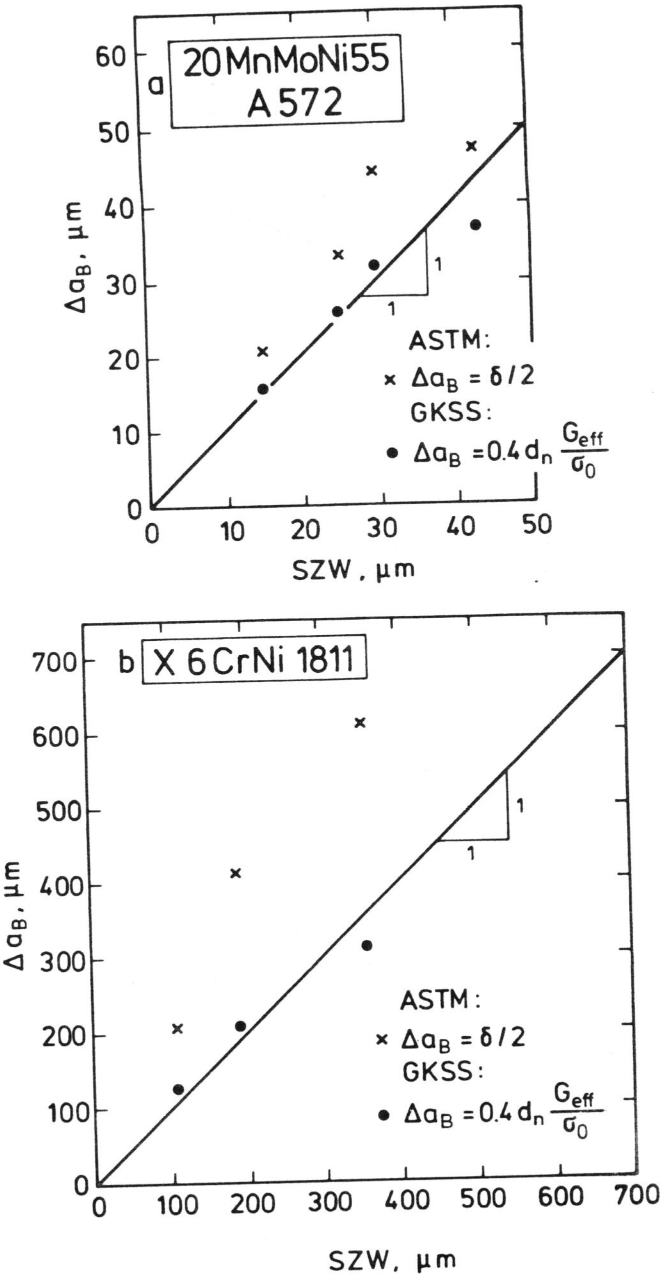

Figure 10: Measured and predicted stretch zone width, Schwalbe et al.(9)

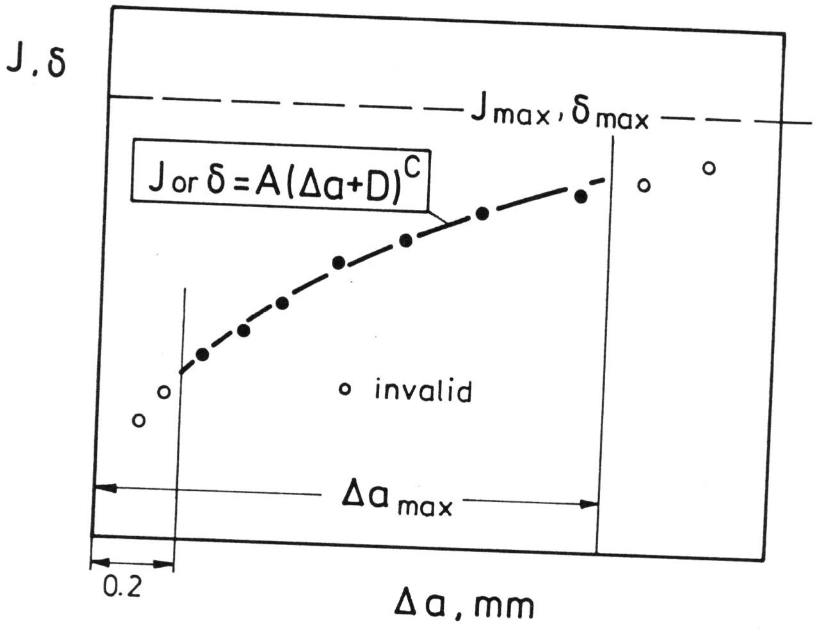

Figure 11: EGF draft Procedure: determination of crack growth resistance curve

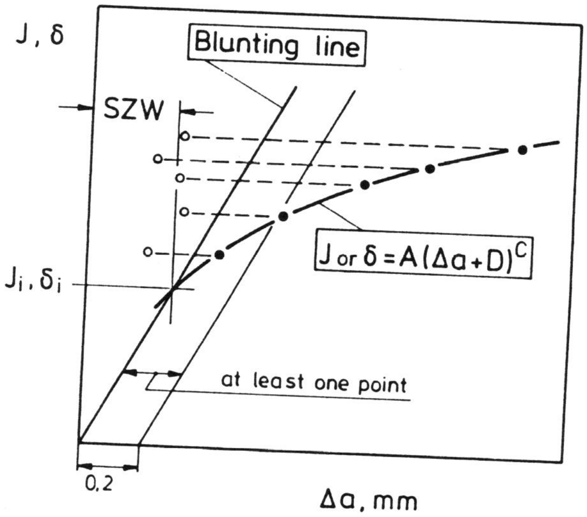

Figure 12: EGF draft Procedure: determination of J_i or δ_i using R-curve technique

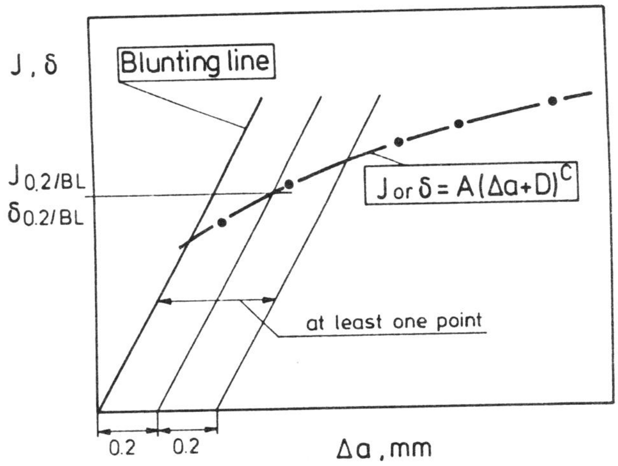

Figure 13: EGF draft Procedure: determination of $J_{0.2/BL}$ or $\delta_{0.2/BL}$ defined at 0.2mm of ductile tearing

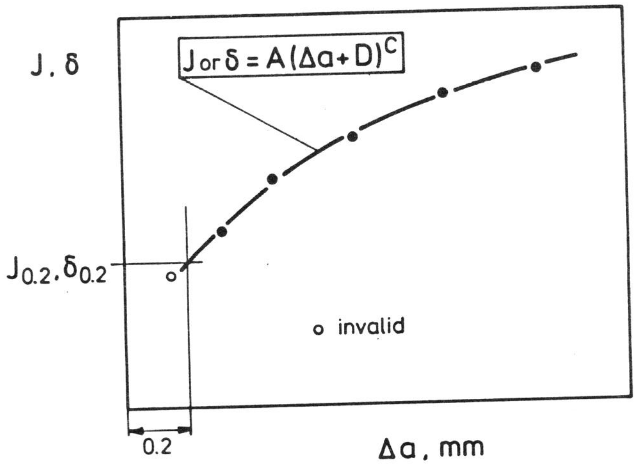

Figure 14: EGF draft Procedure: determination of $J_{0.2}$ or $\delta_{0.2}$ defined at 0.2mm of total crack growth