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Metallic materials — Method of test for the determination of resistance to stable crack extension using specimens of low constraint

Matériaux métalliques — Méthode d'essai pour la détermination de la résistance à la propagation stable de fissures au moyen d'éprouvettes à faible taux de triaxialité des contraintes

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 22889 was prepared by Technical Committee ISO/TC 164, *Mechanical testing of metals*, Subcommittee SC 4, *Toughness testing — Fracture (F), Pendulum (P), Tear (T)*.

Introduction

ISO 12135 uses compact and bend specimens to determine specific (point) values of fracture toughness at the onset of either stable or unstable crack extension, and to quantify resistance to stable crack extension. These specimen types have near-square remaining ligaments to provide conditions of high constraint. If certain size requirements are met, then the values of the quantities K_{Ic}, $\delta_{0,2\mathrm{BL}}$ and $J_{0,2\mathrm{BL}}$ determined from these specimens are considered size insensitive, and regarded as lower-bound fracture toughness values. Although not explicitly stated, size insensitivity holds also for the crack extension resistance curve (R-curve).

In engineering practice, however, there are cases which are not covered by the method of test in ISO 12135, for example where

- the component thickness is much less than that required for size-insensitive properties as determined using ISO 12135,
- the thickness of the available material does not enable fabrication of specimens meeting the criteria for size insensitivity, and
- the loading conditions in the structural component are characterized by tension rather than bending.

In these cases, constraint in the structural component may be lower than that of the specimens specified by ISO 12135, thus leading to higher resistance to crack extension and higher load-carrying capability in the structural component than would have been forecast based on the test in ISO 12135.

INTERNATIONAL STANDARD **ISO 22889:2007(E)**

Metallic materials — Method of test for the determination of resistance to stable crack extension using specimens of low constraint

1 Scope

This International Standard specifies methods for determining the resistance to stable crack extension in terms of crack opening displacement, δ_5, and critical crack tip opening angle, ψ_c, for homogeneous metallic materials by the quasistatic loading of cracked specimens that exhibit low constraint to plastic deformation. Compact and middle-cracked tension specimens are notched, precracked by fatigue, and tested under slowly increasing displacement.

This International Standard describes methods covering tests on specimens not satisfying requirements for size-insensitive fracture properties; namely, compact specimens and middle-cracked tension specimens in relatively thin gauges.

Methods are given for determining the crack extension resistance curve (R-curve). Point values of fracture toughness for compact specimens are determined according to ISO 12135. Methods for determining point values of fracture toughness for the middle-cracked tension specimen are given in Annex D.

Crack extension resistance is determined using either the multiple-specimen or single-specimen method. The multiple-specimen method requires that each of several nominally identical specimens be loaded to a specified level of displacement. The extent of ductile crack extension is marked and the specimens are then broken open to allow measurement of crack extension. Single-specimen methods based on either unloading compliance or potential drop techniques can be used to measure crack extension, provided they meet specified accuracy requirements. Recommendations for single-specimen techniques are described in ISO 12135. Using either technique, the objective is to determine a sufficient number of data points to adequately describe the crack extension resistance behaviour of a material.

The measurement of δ_5 is relatively simple and well established. The δ_5 results are expressed in terms of a resistance curve, which has been shown to be unique within specified limits of crack extension. Beyond those limits, δ_5 R-curves for compact specimens show a strong specimen dependency on specimen width, whereas the δ_5 R-curves for middle-cracked tension specimens show a weak dependency.

CTOA is more difficult to determine experimentally. The critical CTOA is expressed in terms of a constant value achieved after a certain amount of crack extension. The CTOA concept has been shown to apply to very large amounts of crack extension and can be applied beyond the current limits of δ_5 applications.

Both measures of crack extension resistance are suitable for structural assessment. The δ_5 concept is well established and can be applied to structural integrity problems by means of simple crack driving force formulae from existing assessment procedures.

The CTOA concept is generally more accurate. Its structural application requires numerical methods, i.e. finite element analysis.

Investigations have shown a very close relation between the concept of constant CTOA and a unique R-curve for both compact and middle-cracked tension specimens up to maximum load. Further study is required to establish analytical or numerical relationships between the δ_5 R-curve and the critical CTOA values.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 3785, *Metallic materials — Designation of test specimen axes in relation to product texture*

ISO 7500-1, *Metallic materials — Verification of static uniaxial testing machines — Part 1: Tension/compression testing machines — Verification and calibration of the force-measuring system*

ISO 9513, *Metallic materials — Calibration of extensometers used in uniaxial testing*

ISO 12135:2002, *Metallic materials — Unified method of test for the determination of quasistatic fracture toughness*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1
crack opening displacement
COD
δ_5
relative displacement of the crack surfaces normal to the original (undeformed) crack plane at the tip of the fatigue precrack, as measured on the specimen's side surface over an initial gauge length of 5 mm

3.2
crack tip opening angle
CTOA
ψ
relative angle of the crack surfaces measured (or calculated) at 1 mm from the current crack tip

3.3
stable crack extension
Δa
crack extension that, in displacement control, occurs only when the applied displacement is increased

3.4
crack extension resistance curve
R-curve
variation in δ_5 with stable crack extension Δa

3.5
critical crack tip opening angle
ψ_c
steady-state value of crack tip opening angle ψ at 1 mm from the current crack tip

NOTE This value is insensitive to the in-plane dimensions specified in this method; however, it may be thickness dependent.

4 Symbols

For the purposes of this International Standard, the following symbols and units apply. For all parameters, the temperature is assumed to be the test temperature unless otherwise noted.

Symbol	Unit	Designation
a	mm	crack length
a_f	mm	final crack length ($a_0 + \Delta a_\mathrm{f}$)
a_m	mm	length of machined crack starter notch
a_0	mm	initial crack length
Δa	mm	stable crack extension
Δa_min	mm	crack extension beyond which ψ_c is nearly constant
Δa_max	mm	crack extension limit for δ_5 or ψ_c controlled crack extension
Δa_f	mm	final stable crack extension
B	mm	specimen thickness
E	MPa	Young’s modulus of elasticity
F	kN	applied force
F_f	kN	maximum fatigue precracking force
$R_\mathrm{p0,2}$	MPa	0,2 % offset yield strength perpendicular to crack plane at the test temperature
R_m	MPa	tensile strength perpendicular to crack plane at the test temperature
α	degrees	crack path deviation
W	mm	width of compact specimen, half width of middle-cracked tension specimen
$W - a$	mm	uncracked ligament length
$W - a_0$	mm	initial uncracked ligament length
$W - a_\mathrm{f}$	mm	final uncracked ligament length
ψ	degrees	crack tip opening angle (CTOA)
ψ_c	degrees	critical crack tip opening angle (critical CTOA)
ν		Poisson’s ratio
δ_5	mm	crack opening displacement over a 5 mm gauge length at tip of fatigue precrack

NOTE This is not a complete list of parameters. Only the main parameters are given here; other parameters are referred to and defined in the text.

5 General requirements

5.1 Introduction

The resistance to stable crack extension of metallic materials can be characterized in terms of either specific (single point) values (see Annex D) or a continuous curve relating fracture resistance to crack extension over a limited range of crack extension (see Clause 6). Any one of the fatigue-cracked test specimen configurations specified in this method may be used to measure or calculate any of these fracture resistance parameters. Tests are performed by applying slowly increasing displacement to the test specimen and measuring the resulting force and corresponding crack opening displacement and angle. The measured forces, displacements and angles are then used in conjunction with certain pre-test and post-test specimen measurements to determine the material's resistance to crack extension. Details of test specimens and general information relevant to the determination of all fracture parameters are given in this method. A flow-chart illustrating the way this International Standard can be used is presented in Figure 1.

Fracture resistance symbols identified for use in this International Standard method of test are given in Table 1:

Table 1 — Fracture resistance symbols

Parameter	Size-insensitive quantities	Size-sensitive quantities (specific to thickness B tested)	Qualifying limits
δ_5, point value of fracture toughness	See Annex D	Not applicable	
δ_5 R-curve	Not applicable	a_0, $(W - a_0) \geqslant 4B$	$\Delta a < \Delta a_{\text{max}} = 0{,}25(W - a_0)$ for compact specimens; $\Delta a < \Delta a_{\text{max}} = W - a_0 - 4B$ for middle-cracked tensile specimens
ψ_c	Not applicable	a_0, $(W - a_0) \geqslant 4B$	$\Delta a > \Delta a_{\text{min}} = 50/(5 + B)$ $\Delta a < \Delta a_{\text{max}} = W - a_0 - 4B$ (see Figure 11)
NOTE The qualifying limit for ψ_c, $\Delta a > \Delta a_{\text{min}} = 50/(5 + B)$ was established using surface measurements of crack extension for aluminium alloys and steels in sheet thicknesses ranging from 1 mm to 25 mm.			

5.2 Test specimens

5.2.1 Specimen configuration and size

Specimen dimensions and tolerances shall conform to those shown in Figures 2 and 3.

The choice of specimen design shall take into consideration the likely outcome of the test (see Figure 1), which fracture resistance value (δ_5 or ψ) is to be determined, the crack plane orientation of interest, and the amount and condition of test material available.

NOTE Both specimen configurations (Figures 2 and 3) are suitable for determination of δ_5 and ψ_c values.

For both specimen configurations, the conditions $[a_0, (W - a_0)] \geqslant 4B$ shall be satisfied.

5.2.2 Specimen preparation

5.2.2.1 Material condition

Specimens shall be machined from stock in the final heat-treated and mechanically worked conditions.

In exceptional circumstances where material cannot be machined in the final condition, final heat treatment may be carried out after machining, provided that the required dimensions and tolerances for the specimen, its shape, and its surface finish are met. Where dimensions of the machined specimen are substantially different from the pre-machined stock, a size effect on the heat-treated microstructure and mechanical properties shall be taken into account in the service application.

5.2.2.2 Crack plane orientation

Orientation of the crack plane shall be decided before machining, identified in accordance with ISO 3785, and recorded in accordance with Table A.1.

NOTE Crack extension resistance depends on the orientation and direction of crack extension in relation to the principal directions of mechanical working, grain flow and other forms of anisotropy.

5.2.2.3 Machining

The specimen notch profile shall not exceed the envelope shown in Figure 4. The root radius of a milled notch shall be not greater than 0,10 mm. Sawn, disk ground, or spark-eroded notches shall not have a width greater than 0,15 mm.

5.2.2.4 Fatigue precracking

5.2.2.4.1 General

Fatigue precracking shall be performed with the material in the final heat-treated, mechanically worked or environmentally conditioned state. Intermediate treatments between fatigue precracking and testing are acceptable only when such treatments are necessary to simulate the conditions of a specific structural application; such departure from recommended practice shall be (explicitly) reported.

Maximum fatigue precracking force during any stage of the fatigue precracking process shall be accurate to ±2,5 %.

Measured values of specimen thickness, B, and width, W, determined in accordance with 5.3.1, shall be recorded and used to determine the maximum fatigue precracking force F_{f} in accordance with 5.2.2.4.3 and 5.2.2.4.4.

The ratio of minimum-to-maximum force in the fatigue cycle shall be in the range 0 to 0,1 except that, in order to expedite crack initiation, one or more cycles of –1,0 may be applied first.

5.2.2.4.2 Equipment and fixtures

Fixtures for fatigue precracking shall be carefully aligned and arranged so that loading is uniform through the specimen thickness B and symmetrical about the plane of the prospective crack.

5.2.2.4.3 Compact specimens

For compact specimens, the maximum fatigue precracking force during the final 1,3 mm or 50 % of precrack extension, whichever is less, shall be the lowest value of

$$F_\mathrm{f} = \xi E \left[\frac{B\sqrt{W}}{g_1(a_0/W)} \right] \tag{1}$$

where $\xi = 1{,}6 \times 10^{-4}\,\mathrm{m}^{0{,}5}$, and

$$g_1(a_0/W) = \left[1 - \frac{a_0}{W}\right]^{-1{,}5} \left[2 + \frac{a_0}{W}\right] \left[0{,}886 + 4{,}64\frac{a_0}{W} - 13{,}32\left(\frac{a_0}{W}\right)^2 + 14{,}72\left(\frac{a_0}{W}\right)^3 - 5{,}6\left(\frac{a_0}{W}\right)^4\right] \tag{2}$$

5.2.2.4.4 Middle-cracked tension specimens

For middle-cracked tension specimens, the maximum fatigue precracking force during the final 1,3 mm or 50 % of precrack extension, whichever is less, shall be the lowest value of

$$F_\mathrm{f} = \xi E B 2W \left[\pi a \sec \frac{\pi a}{2W} \right]^{-0{,}5} \tag{3}$$

where $\xi = 1{,}6 \times 10^{-4}\,\mathrm{m}^{0{,}5}$

5.3 Pre-test requirements

5.3.1 Pre-test measurements

The dimensions of specimens shall conform to those shown in Figures 2 and 3. Measurement of the thickness B and width W shall be within 0,02 mm or to ±0,2 %, whichever is the larger.

Specimen thickness B shall be measured, before testing, at a minimum of three equally spaced positions along the intended crack extension path. The average of these measurements shall be taken as the thickness B.

Specimen width W of the middle-cracked tension specimen shall be measured at a minimum of three equally spaced positions within ±0,1 W of the crack plane. The average of these measurements shall be taken as the width W.

The compact specimen width W shall be measured with reference to the loading-hole centreline. Customarily, the loading-hole centreline is established first, and then the dimension W is measured to the specimen edge ahead of the crack tip in the plane of the crack. This measurement shall be made at a minimum of three equally spaced positions across the specimen thickness. The dimension 1,25 W (between the specimen edges ahead and behind the crack tip) shall be measured in addition, at the same equally spaced positions across the thickness in a plane as close as possible to the plane of the crack.

5.3.2 Crack front shape and length requirements

A fatigue crack shall be developed from the root of the machined notch of the specimen as follows:

- for compact specimens (see Figure 2), the ratio a_0/W shall be in the range 0,45 to 0,65;
- for middle-cracked tension specimens, the ratio a_0/W shall be in the range 0,25 to 0,50.

The minimum fatigue crack extension shall be the larger of 1,3 mm or 2,5 % of the specimen width W. The notch plus fatigue crack shall be within the limiting envelope shown in Figure 4.

5.4 Test apparatus

5.4.1 Calibration

Calibration of all measuring apparatus shall be traceable either directly or indirectly via a hierarchical chain to an accredited calibration laboratory.

5.4.2 Force application

The combined force sensing and recording device shall conform to ISO 7500-1.

The test machine shall operate at a constant displacement rate.

A force measuring system of nominal capacity exceeding 1,2 F_L shall be used, where

— for compact specimens

$$F_L = \frac{B(W - a_0)^2}{(2W + a_0)} R_m \tag{4}$$

— or for middle-cracked tension specimens

$$F_L = 2B(W - a_0)R_m \tag{5}$$

5.4.3 Displacement measurement

The displacement gauge used for the determination of δ_5 shall have an electrical output that accurately represents the displacement between two precisely located gauge positions 5 mm apart, spanning the crack at the fatigue crack tip. The design of the displacement gauge (or transducer where appropriate) and specimen shall allow free rotation of the points of contact between the gauge and specimen.

NOTE 1 Guidance for determining δ_5 is given in Annex B.

NOTE 2 The crack mouth opening displacement is not needed for the δ_5 and ψ_c determinations, but a force crack mouth opening displacement record may be suitable for evaluating the methods from finite element analyses and other fracture analysis methods. Examples of proven displacement gauge designs are given in References [1] and [2] (see Bibliography), and similar gauges are commercially available.

Gauges for crack mouth opening displacement measurement shall be calibrated in accordance with ISO 9513, as interpreted in relation with this International Standard, and shall be at least of Class 1. Calibration shall be performed at least each week when the gauges are in use.

NOTE Calibration may be carried out more frequently depending on use and agreement between contractual parties.

Verification of the displacement gauge shall be performed at the test temperature ±5 °C. The response of the gauge shall be true to ±0,003 mm for displacements up to 0,3 mm and to ±1 % of the actual reading thereafter.

5.4.4 Test fixtures

Compact specimens shall be loaded using a clevis and pin arrangement designed to minimize friction. The arrangement shall ensure load train alignment as the specimen is loaded under tension. Clevises for R-curve measurements shall have flat-bottomed holes (see Figure 5) so that the loading pins are free to roll throughout the test. Round-bottomed holes (see Figure 6) shall not be allowed for single-specimen (unloading compliance) tests. Fixture-bearing surfaces shall have a hardness greater than 40 HRC (400 HV) or a yield strength of at least 1 000 MPa. Middle-cracked tension specimens shall be loaded using hydraulically clamped or bolted grips designed to carry the applied load by friction. Bolt bearing should be avoided in order to minimize non-uniform loading. The arrangement shall ensure alignment of the specimen with minimal in-plane and out-of-plane bending. All specimens shall be tested with anti-buckling guide plates, as shown in Figure 7. The anti-buckling guide plates shall cover a large portion of the specimen. Support only along the crack plane has been shown to be insufficient to prevent buckling between the grip lines and the crack plane for thin-sheet materials. Flat plates are sufficient for small middle-cracked tension specimens ($W < 600$ mm); but flat plates and I-beams, as illustrated in Figure 7a), are required for middle-cracked tension specimens with widths larger than about 600 mm. A suitable design for compact specimens is shown in Figure 7b).

5.5 Test requirements

It is recommended that anti-buckling plates be attached to both sides of the tension specimen covering the expected path of the crack for a distance four times the initial total crack length perpendicular to the crack. Frictional forces between the specimen and anti-buckling plates shall be minimized by the use of an inert lubricant such as Teflon® applied to the mating surfaces. An access hole is required in one of the plates for mounting the δ_5 gauge on the specimen or, if the potential method is used, for the attachment of cables.

5.5.1 Compact specimen testing

5.5.1.1 Specimen and fixture alignment

The loading clevises shall be aligned to within 0,25 mm, and the specimen shall be centred on the loading pins within 0,75 mm with respect to the clevis opening.

5.5.1.2 Crack opening displacement δ_5

A method of measuring the crack opening displacement δ_5 is described in Annex B.

5.5.1.3 Crack tip opening angle ψ

The crack tip opening angle ψ may be measured or calculated as described in Annex C.

5.5.2 Middle-cracked tension specimen testing

5.5.2.1 Specimen and fixture alignment

The fixture shall 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 assured at all loads. Otherwise, pinloading via detachable grips is recommended.

5.5.2.2 Crack opening displacement δ_5

A method of measuring the crack opening displacement δ_5 is given in Annex B.

5.5.2.3 Crack tip opening angle ψ

The crack tip opening angle ψ may be measured or calculated as described in Annex C.

5.5.3 Specimen test temperature

Specimen test temperature shall be controlled and recorded to an accuracy of ±2 °C. For this purpose, a thermocouple or platinum resistance thermometer shall be placed in contact with the surface of the specimen in a region not further than 5 mm from the fatigue crack tip. When substantial amounts of crack extension are anticipated, additional sensors (thermocouples or thermometers) shall be placed in proximity to the anticipated crack path so that the specified specimen temperature can be assured for the material being tested. Tests shall be made *in situ* in suitable low- or high- temperature media. Before testing in a liquid medium, the specimen shall be retained in the liquid for at least 30 s/mm of thickness B after the specimen surface has reached the test temperature. When using a gaseous medium, a soaking time of at least 60 s/mm of thickness shall be employed. Minimum soaking time at the test temperature shall be 15 min. The temperature of the test specimen shall remain within ±2 °C of the nominal test temperature throughout the test and shall be recorded as required in Clause 7.

5.5.4 Recording

The force and corresponding displacement outputs shall be recorded.

NOTE Corresponding displacements are either crack opening displacement δ_5 (for determining the δ_5 R-curve) or the crack mouth opening displacement CMOD (not required here, but useful for supplementary evaluations).

5.5.5 Testing rates

Tests shall be conducted under crack mouth opening, load-line, or crosshead-displacement control. The load-line displacement rate shall be such that, within the linear elastic region, the stress intensification rate is within the range 0,2 $\text{MPa}\cdot\text{m}^{0,5}\cdot\text{s}^{-1}$ to 3 $\text{MPa}\cdot\text{m}^{0,5}\cdot\text{s}^{-1}$. For each series of tests, all specimens shall be loaded at the same nominal rate.

5.5.6 Test analyses

Analyses for point determinations of fracture toughness for compact specimens are given in Annex D, and for δ_5 resistance-curve determinations in Clause 6 (see Figure 1).

5.6 Post-test crack measurements

The specimen shall be broken open after testing and its fracture surface examined to determine the original crack length a_0, and the final stable crack extension Δa_f.

For some tests, it may be necessary to mark the extent of stable crack extension before breaking open the specimen. Marking of stable crack extension may be done by either heat tinting or post-test fatiguing. Care shall be taken to minimize post-test deformation of the specimen. Cooling ferritic steels to ensure brittle behaviour may be helpful.

5.6.1 Initial crack length a_0

5.6.1.1 Compact specimens

The initial crack length a_0 shall be measured from the centreline of the pinhole to the tip of the fatigue crack with an instrument accurate to ±0,1 % or ±0,025 mm, whichever is the greater. Measurements shall be made at five positions through the specimen thickness. The value of a_0 is obtained by first averaging the two surface measurements made at positions 0,01B inward from the surface (see Figure 8) and then averaging these values with those at the three equispaced inner measurement points:

$$a_0 = \frac{1}{4}\left[\left(\frac{a_{01}+a_{05}}{2}\right)+\sum_{j=2}^{j=4} a_{0j}\right] \tag{6}$$

5.6.1.2 Middle-cracked tension specimens

The initial crack length a_0 shall be measured as one-half of the total crack length to the tips of both fatigue cracks with an instrument accurate to ±0,1 % or 0,025 mm, whichever is the greater. Measurements are made using a 5-point average. The value of a_0 is obtained by first averaging the two surface measurements made at positions 0,01B inward from the surface (see Figure 9), averaging these values with those at the three equispaced inner measurement points, and then dividing the resulting value by 2:

$$a_0 = \frac{1}{8}\left[\left(\frac{2a_{01} + 2a_{05}}{2}\right) + \sum_{j=2}^{j=4} 2a_{0j}\right] \tag{7}$$

NOTE For both compact and middle-cracked tension specimens of thickness $B < 5$ mm, a 3-point average is sufficient. The value of a_0 is obtained by first averaging the two surface measurements $a_{0,1}$ and $a_{0,5}$, and then averaging that with the measurement made at mid-plane of the specimen, $a_{0,3}$:

$$a = 0{,}5\left[\left(a_{0,1} + a_{0,5}\right)/2 + a_{0,3}\right]$$

5.6.1.3 Requirements

The initial crack length a_0 shall satisfy the following.

a) The ratio a_0/W shall be within the range 0,45 to 0,65 for compact specimens, and within the range 0,25 to 0,50 for middle-cracked tension specimens.

b) If a five-point average for determining a_0 has been used, then the difference between any one of the central three points and the five-point average shall not exceed 0,1 a_0.

c) If a three-point average for determining a_0 has been used, then the difference between the central point and the three-point average shall not exceed 0,1 a_0.

d) No part of the fatigue precrack front shall be closer to the crack starter notch than 1,3 mm or 0,025W, whichever is the larger.

e) The fatigue precrack shall be within the envelope shown in Figure 4.

If the above requirements are not satisfied, the test result is not qualified according to this method of test.

5.6.2 Stable crack extension, Δa

The total final crack extension (including any crack tip blunting) Δa_f between the initial and final crack fronts shall be measured with an instrument accurate to ±0,025 mm using the averaging procedure of 5.6.1. For middle-cracked tension specimens, the crack extension Δa_f is given by the average of the crack extension values measured at both crack fronts. Any irregularities in crack extension, such as spikes and isolated ‘islands’ of crack extension, shall be reported in accordance with Clause 7.

NOTE 1 It may only be practical to estimate the length of irregular cracks by ignoring the spikes or subjectively averaging the crack extension region. Care should be exercised when the results derived from highly irregular crack fronts are used in analysis. It is useful to provide an additional sketch or photograph of such irregular cracks in reporting results. All individual pre-test and post-test measurements are to be recorded and used for calculations in accordance with Clause 6.

NOTE 2 For specimens with thickness $B < 5$ mm, a three-point average as in 5.6.1.2 is suggested.

5.6.3 Crack path

The crack plane may deviate during stable crack extension from the original fatigue precrack plane (which is a flat surface perpendicular to the applied force). Typically, the transition is to shear planes at the specimen surfaces. When such shear planes are sloped similarly with respect to the original fatigue precrack plane, then crack extension is said to be in a single-shear mode. When they are sloped differently, such as to resemble a roof in cross-section (the mating fracture surface then resembles a V-groove), crack extension occurs in a double-shear mode. Shear fracture surfaces are typically sloped 30° to 45°.

NOTE Depending on the material and specimen thickness, the fracture surface in the central part of the specimen thickness may still be perpendicular to the applied force. This is a mixed mode of crack extension.

5.6.3.1 Crack extension resistance

For fractures that deviate from planarity, the crack extension resistance of those exhibiting double shear is customarily higher than for those exhibiting single shear. Test results for such double-shear fractures are considered to be not qualified to characterize the material.

5.6.3.2 Crack path deviation

When the angle α between the original flat precrack plane and the plane of the deviated crack surface exceeds 10°, the test result is no longer considered qualified according to this method of test.

6 Determination of $\delta_5 - \Delta a$ resistance curve and CTOA

6.1 General

Fracture behaviour is characterized by this method in terms of the variation of either δ_5 (COD) or ψ (CTOA) with the crack extension Δa. It is important to note, however, that ψ versus Δa is not treated here as a crack extension resistance curve.

6.2 Test procedure

Load specimens and evaluate the resulting amount of crack extension in accordance with 5.5 and 5.6.

6.2.1 Multiple-specimen procedure

A series of nominally identical specimens shall be loaded to selected displacement levels and the corresponding amounts of crack extension determined. Each specimen tested provides one point on the $\delta_5 - \Delta a$ crack resistance curve (hereafter referred to generically as the R-curve).

NOTE Six or more favourably positioned points are required to generate an R-curve. Loading the first specimen to a point just past maximum load and measuring the resulting stable crack extension helps to determine the displacement levels needed to position data points favourably in additional tests.

6.2.2 Single-specimen procedure

The single-specimen procedure makes use of electric potential, elastic compliance or another technique to obtain multiple points on the resistance curve from the test of a single specimen. Single-specimen testing procedures are described in ISO 12135.

Using a direct method (e.g. elastic compliance), the estimated final crack extension Δa_f shall be within 15 % of the measured crack extension or 0,15 mm, whichever is the greater, for $\Delta a_f \leqslant 0{,}2(W - a_0)$, and within $0{,}03(W - a_0)$ for $\Delta a_f > 0{,}2(W - a_0)$. For techniques that require an *a priori* estimate of the initial crack length a_0 for subsequent determination of crack extension, such as the unloading-compliance technique, the estimated a_0 shall be within 2 % of the (post-test) measured a_0 value.

For indirect techniques (e.g. electrical potential), the first specimen tested shall be used to establish a correlation between experimental output and measured crack extension to beyond the Δa_{max} defined in 6.4. At least one additional test shall be conducted to estimate crack extension using the results from the first test. Agreement between the estimated and actual crack extension Δa shall be within 15 % or 0,15 mm, whichever is the greater; otherwise the procedure shall not be accepted.

6.2.3 Final crack front straightness

The final crack length shall be determined as the sum of the initial crack length and the final stable crack extension measured using the averaging methods of 5.6.1 and 5.6.2. If the five-point averaging method is used, none of the three interior final crack length measurements shall differ from the five-point average value by more than $0{,}1a_0$; if the three-point averaging method is used, the central final crack length measurement shall not differ from the three-point average by more than $0{,}1a_0$; otherwise the result is not qualified.

6.3 R-curve plot

The points of crack opening displacement, δ_5, versus stable crack extension, Δa, form the fracture resistance R-curve (see Figure 10). The data may be used in tabular form or as a plotted graph. An equation may be fitted to the graph for analysis, or the plot itself may be used for analysis.

6.3.1 Plot construction

Construct a plot of the crack opening displacement, δ_5, versus the stable crack extension, Δa, from the data obtained in 5.5.1.2, 5.5.2.2 and 5.6.2 (see Figure 10).

For each compact specimen tested, calculate Δa_{max} from

$$\Delta a_{\text{max}} = 0{,}25\left(W - a_0\right) \tag{8}$$

For each middle-cracked tension specimen tested, calculate Δa_{max} from

$$\Delta a_{\text{max}} = \left(W - a_0\right) - 4B \tag{9}$$

Plot δ_5 versus Δa as shown in Figure 10.

Tests terminating in unstable fracture shall be reported as such and, if the amount of stable crack extension to fracture can be measured on the fracture surface, include that datum point in the R-curve plot. Unstable fracture data points shall be clearly marked on the R-curve plot and appropriately noted in the test report (see Annex A).

NOTE The point of unstable failure can depend on the specimen size and geometry.

6.3.2 Data spacing and curve fitting

A minimum of six data points shall be used to define the R-curve.

When an equation is to be fitted to the R-curve, at least one data point shall reside within each of the four equal crack extension regions shown in Figure 10. The curve shall be best-fitted through the data points lying between the 0 and Δa_{max} exclusion lines (see Figure 10) using the power-law Equation (10):

$$\delta_5 = \alpha + \beta \Delta a^{\gamma} \tag{10}$$

where α and $\beta \geqslant 0$, and $0 \leqslant \gamma \leqslant 1$.

A method for evaluating the constants α, β and γ is given in ISO 12135:2002, Annex H. If α or β is less than zero from the linearized regression, then the result is unacceptable and the fitted equation is not representative of the R-curve. In such cases, additional tests or the use of a single-specimen test procedure are suggested.

The R-curve thus obtained characterizes the material for the thickness and specimen geometry tested, and is independent of the in-plane dimensions of either compact specimens or middle-cracked tension specimens.

6.4 Critical CTOA determination

A steady-state (average) value of ψ, ψ_c, is established after a minimum amount of crack extension.

Construct a plot of the crack tip opening angle (CTOA), ψ, versus the crack extension, Δa, from the data obtained in 5.5.1.3, 5.5.2.3 and 5.6.2 (see Figure 11).

For each specimen tested, calculate the maximum amount of crack extension, Δa_max, from

$$\Delta a_\mathrm{max} = \left(W - a_0\right) - 4B \tag{11}$$

The minimum amount of crack extension, Δa_min, is that value of Δa where ψ in Figure 11 attains a constant value. These two values of Δa serve as the upper and lower bounds for the crack extension over which the critical CTOA, ψ_c, is evaluated.

NOTE 1 Due to the developing nature of the CTOA method, the Δa limits are based on limited experience.

Four methods (optical microscope, digital image correlation, microtopography analysis and finite element analysis) may be used to determine the CTOA. Details are given in Annex C.

Measurements of CTOA may be made at any amount of crack extension, in particular between the crack extension limits. CTOA values measured outside the crack extension limits are for informational purposes only.

Plot ψ against Δa as shown in Figure 11. Determine ψ_c from the $\psi - \Delta a$ plot between the limiting crack extension limits, Δa_min and Δa_max.

NOTE 2 Crack tip opening angles measured on the surface of a specimen in the initial phase of crack extension are generally large due to crack tip blunting and crack tunnelling. But in the interior region, which is under high local constraint, the ψ values are generally lower than the surface values (see Figure 11).

For CTOA testing, evaluate the critical value of ψ_c as

$$\psi_\mathrm{c} = \sum_{i=1}^{N} \psi_i / N \tag{12}$$

where ψ_i are values satisfying the Δa_min and Δa_max requirements, and N is their total number.

7 Test report

7.1 General

The test report shall reference this International Standard, and shall comprise three parts (7.2 to 7.5). Details regarding material, specimen and test conditions, including test environment, shall be reported as in 7.2. Machining, fatigue precracking, crack front straightness and crack length data shall conform to 7.3. Derived fracture parameters shall be quantified in accordance with 7.4 and 7.5. See Annex A for examples of the format for test reports.

7.2 Specimen, material and test environment

The format given in A.1 is suggested for reporting the following.

7.2.1 Specimen description

a) Identification;

b) Type;

c) Nominal a_0/W;

d) Crack plane orientation;

e) Location within product form.

7.2.2 Specimen dimensions

a) Thickness, B (mm);

b) Width, W (mm);

c) Initial relative crack length, a_0/W.

7.2.3 Material description

a) Composition and standardized designation code;

b) Product form (plate, forging, casting, etc.) and condition;

c) Tensile mechanical properties at precracking temperature, referenced or measured;

d) Tensile mechanical properties at test temperature, referenced or measured.

7.2.4 Test environment

a) Temperature (°C);

b) Loading displacement rate (mm/min);

c) Type of displacement control.

7.2.5 Fatigue precracking conditions

a) F_f (kN);

b) Precracking temperature (°C).

7.3 Test data qualification

7.3.1 General

All data shall meet certain requirements in order to be qualified in accordance with this International Standard. Only qualified data shall be used to define fracture resistance in accordance with this International Standard. The data described in 7.3.2 shall be reported in the format of A.2.

7.3.2 Crack length measurements

Measurements shall be made at five evenly spaced locations across the specimen thickness, as shown in Figures 8 and 9. For specimen thicknesses $B < 5$ mm, measurements at three evenly spaced locations are sufficient (see Note in 5.6.1.2). The following values shall be reported:

a) initial machined notch length (a_m);

b) initial crack length to the fatigued notch tip (a_0).

7.3.2.1 Multiple-specimen tests

a) Fatigue precrack length ($a_0 - a_\mathrm{m}$);

b) Final crack length (a_f);

c) Average crack extension ($\Delta a = a_\mathrm{f} - a_0$).

7.3.2.2 Single-specimen tests

a) Crack length (a);

b) Crack extension ($\Delta a = a - a_0$).

7.3.3 Fracture surface appearance

a) A record of unusual features on the fracture surface;

b) A record of the occurrence of unstable crack extension, such as cleavage.

7.3.4 Resistance curves

Include all data for resistance curves from single-specimen tests as shown in A.3.

7.3.5 Checklist for data qualification

The data set shall be considered qualified if it conforms to the following criteria:

a) the specimen conforms to the dimensions and tolerances of 5.2.1;

b) the test apparatus conforms to the tolerance and alignment requirements of 5.4;

c) the test machine and displacement gauge(s) conform to the accuracies specified in ISO 7500-1 and ISO 9513, respectively;

d) the average initial crack length a_0 is within the range 0,45W to 0,65W for compact specimens, and 0,25W to 0,50W for middle-cracked tension specimens;

e) all parts of the fatigue precrack have extended at least 1,3 mm or 2,5 % of W, whichever is the greater, from the root of the machined notch;

f) the fatigue precrack is contained within the appropriate envelope (see Figure 4) on both surfaces of the specimen;

g) none of the three interior initial crack length measurements differs by more than 0,1a_0 from the five-point average final crack length, or none of the centre crack length measurements differs by more than 0,1a_0 from the three-point average final crack length;

h) for a single-specimen direct crack length measurement method of estimating crack extension, the final estimated crack length a_f is within 15 % of the five- or three-point average measured crack length, or 0,15 mm, whichever is the greater, up to a crack extension of 0,20($W - a_0$), and to within 0,03($W - a_0$) thereafter;

i) the estimated initial a_0/W from single-specimen tests is within 2 % of the measured initial a_0/W; for a single-specimen indirect crack length measurement wherein the first specimen tested defines the correlation between the experimental output and the measured crack extension and, in subsequent tests, the final crack extension is predicted using the correlation from the first test, the initial a_0/W is within 15 % of the five- or three-point average of the measured final crack extension or 0,15 mm, whichever is the greater;

j) the number and spacing of data points required by 6.3.2 are satisfied for $\delta_5 - \Delta a$ curve determination;

k) the number and spacing of data points required by 6.3.2 are satisfied for $\psi - \Delta a$ curve determination;

l) the crack path requirements of 5.6.3 are satisfied.

7.4 Qualification of the δ_5 R-Curve

The δ_5 R-curve in this International Standard is the power law regression fit to the data of 6.3.2. The regression fit qualifies as a δ_5 R-curve in accordance with this International Standard if the data are qualified according to 7.3.

7.5 Qualification of ψ_c

The critical CTOA ψ_c in this International Standard is a steady-state value fit to the data of 6.4. The portion of the data that is between the specified minimum and maximum amounts of crack extension is used to determine ψ_c in accordance with this International Standard if the data are qualified according to 7.3.

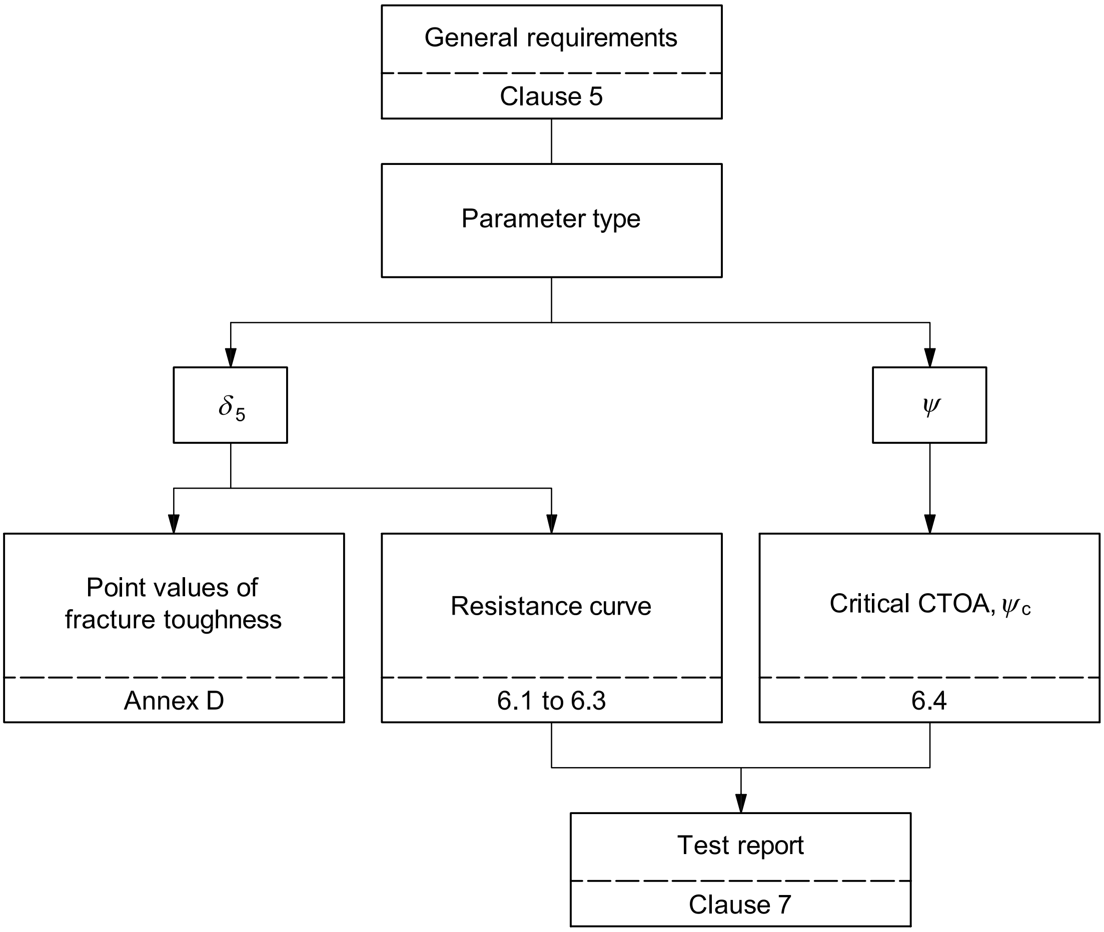
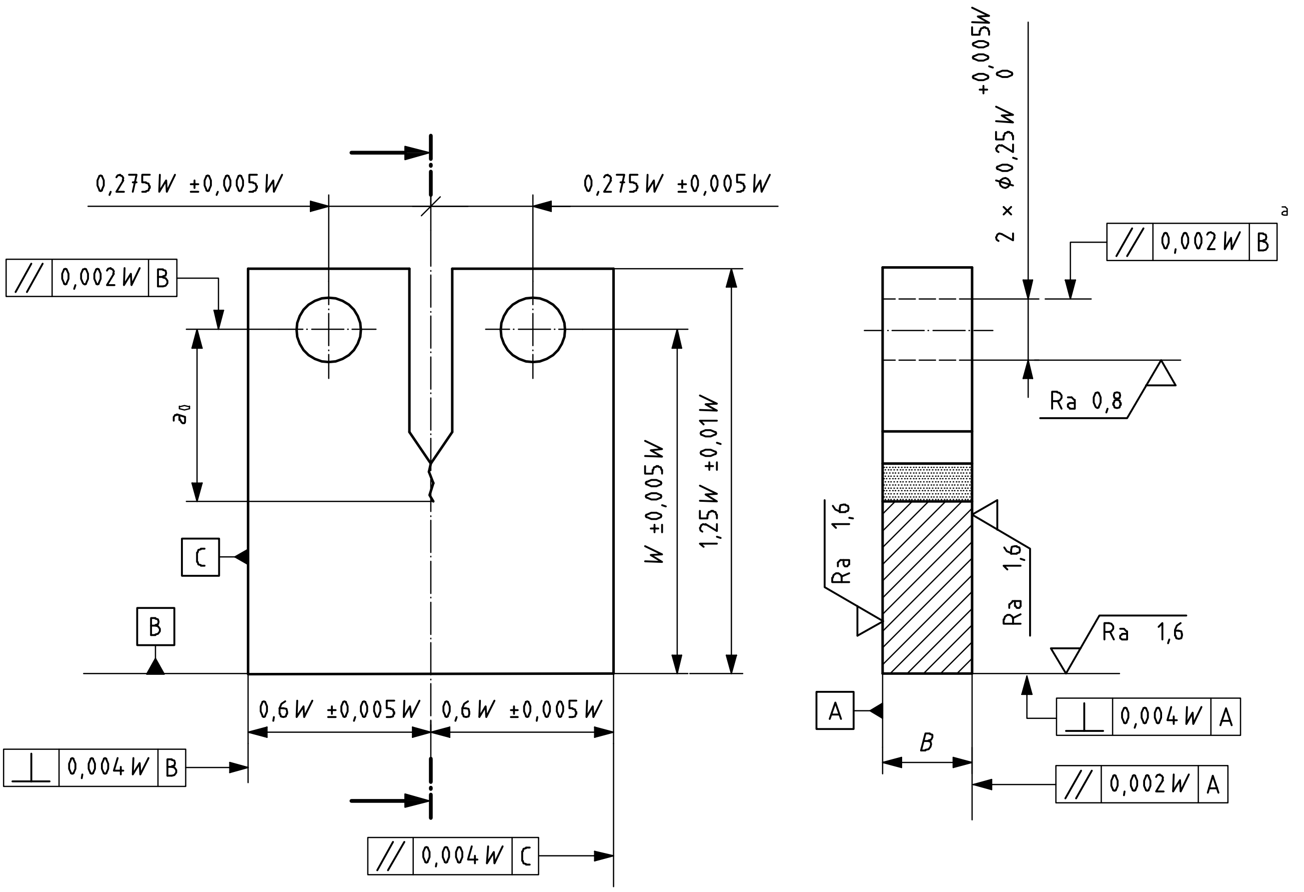


Figure 1 — Flowchart showing how to use this standard method of test

Dimensions in millmetres



The intersection of the crack starter notch tips with the two specimen surfaces shall be equidistant from the top and bottom edges of the specimen to within 0,005W.

NOTE 1 For starter notch and fatigue crack configurations, see Figure 4 and 5.2.2.4.

NOTE 2 $W \geqslant 8B \geqslant 150$ mm.

NOTE 3 $0{,}45 \leqslant a_0/W \leqslant 0{,}65$.

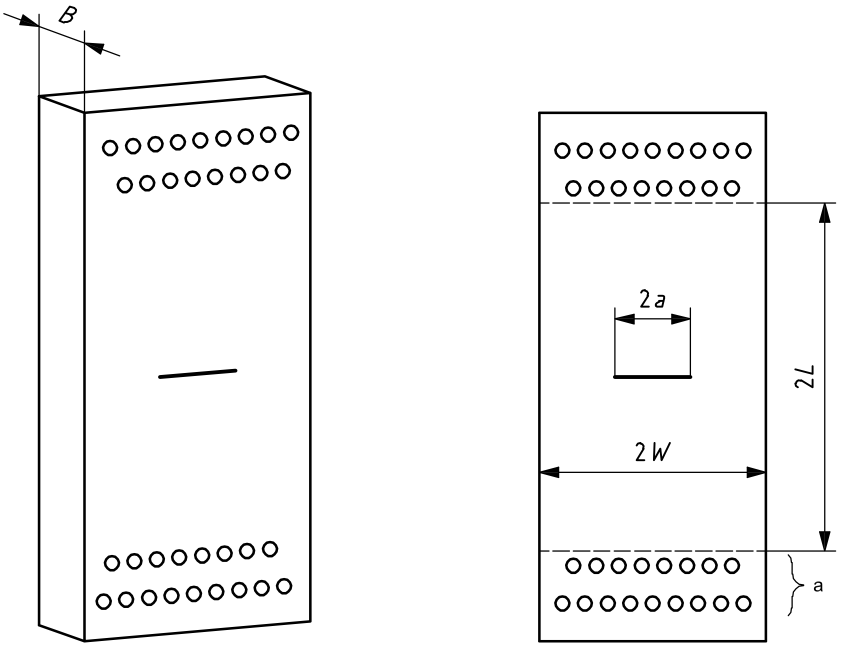
NOTE 4 An alternative pin-hole diameter, $\Phi = 0{,}188W\,^{+0{,}004W}_{-0}$.

Key

a Two holes.

Figure 2 — Proportional dimensions and tolerances for straight-notch compact specimen

Dimensions in millimetres



NOTE 1 For starter notch and fatigue crack configurations, see Figure 4 and 5.2.2.4.

NOTE 2 $W \geqslant 8B \geqslant 150$.

NOTE 3 $0{,}25 \leqslant a_0/W \leqslant 0{,}50$.

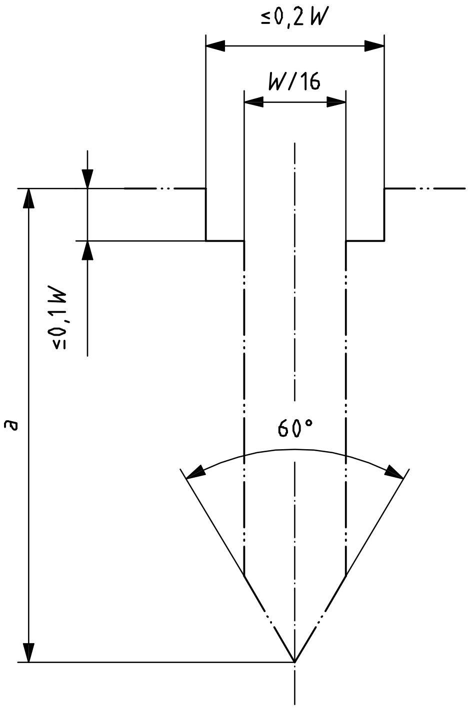
NOTE 4 $L/W > 1{,}5$.

Key

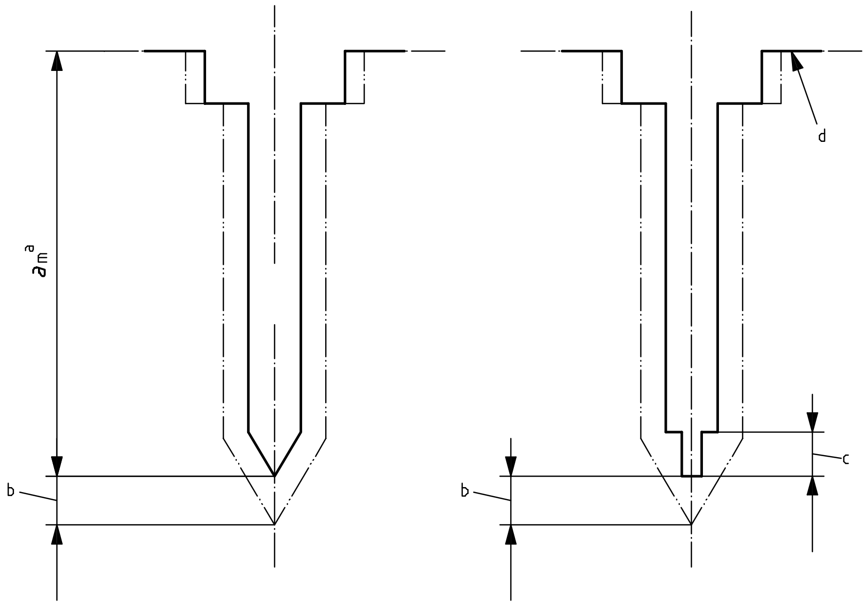
[a] Clamping area.

Figure 3 — Middle-cracked tension specimen

Dimensions in millimetres



a) **Envelope**



b) **Notch geometries** (not to scale)

Key

[a] Machined notch, a_m.

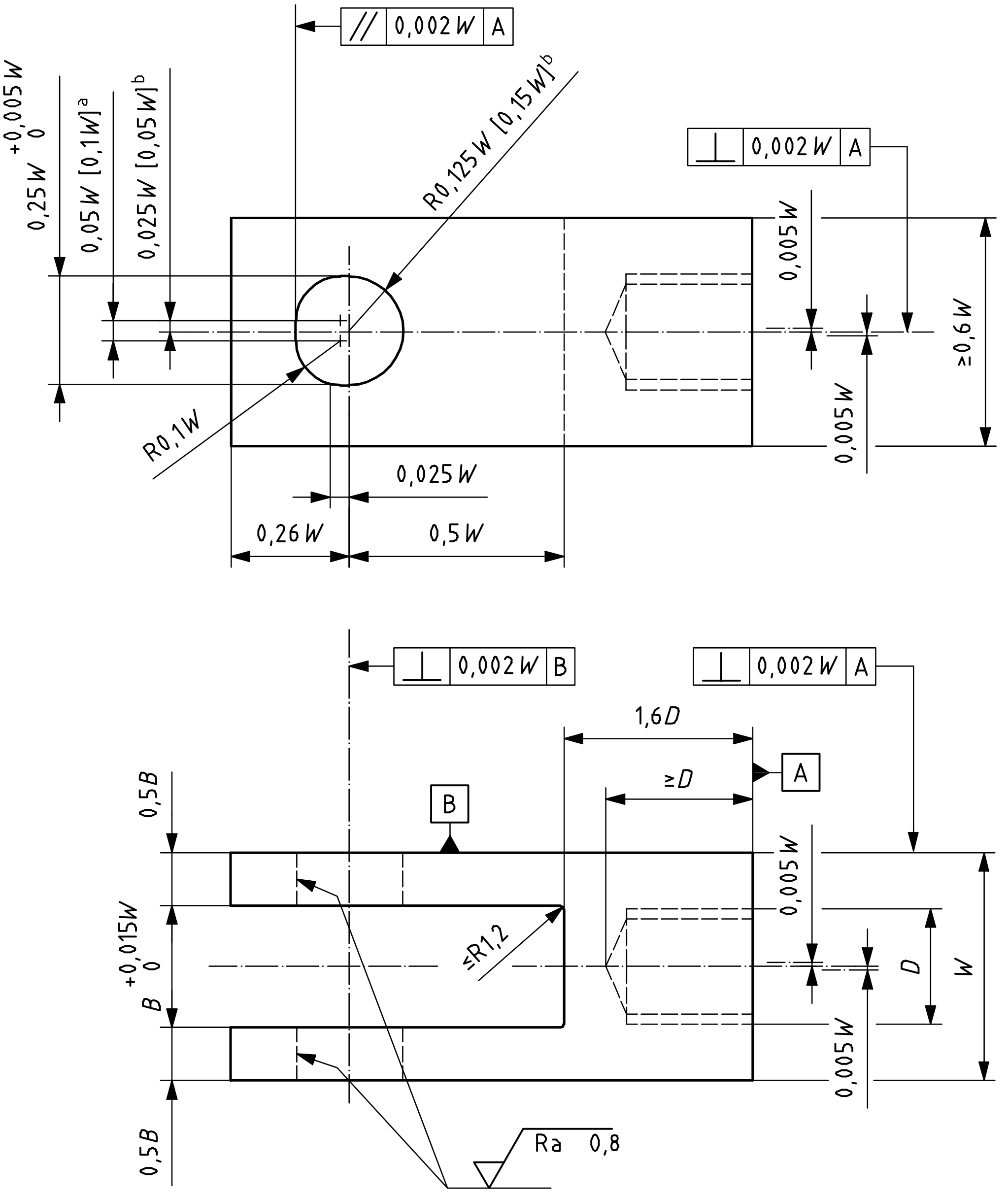
[b] Fatigue precrack.

[c] Spark-eroded or machined slit.

[d] Edge of bend specimen or load line of compact specimen.

Figure 4 — Acceptable fatigue crack envelope and crack starter notch

Dimensions in millimetres
Values of surface toughness (Ra) in micrometres



NOTE 1 Pin diameter $= 0{,}24W_{-0{,}005W}^{\;0}$.

NOTE 2 Corners of clevises may be removed if necessary to accommodate clip gauge.

NOTE 3 Clevis and pin hardness $\geqslant$ 40 HRC.

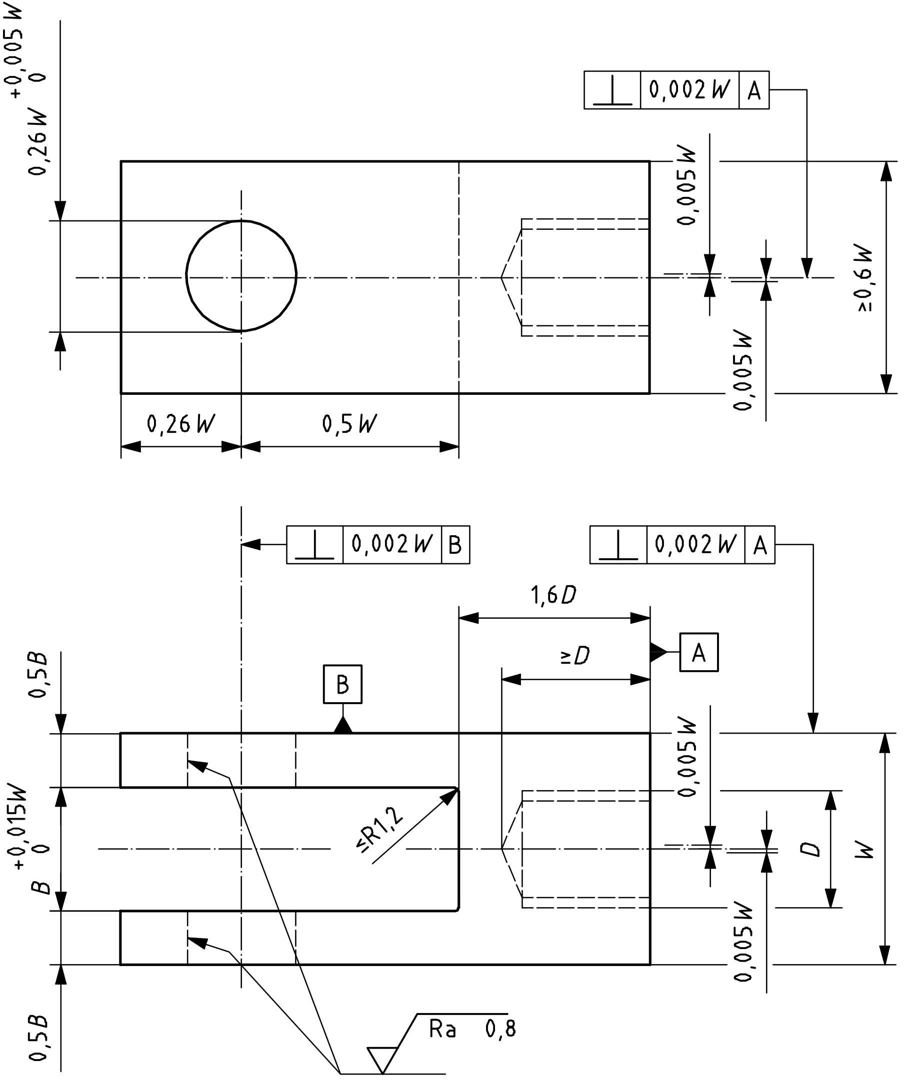
Key

[a] Loading flat.

[b] For specimens showing large displacements, clevis hole dimensions shall be enlarged to the values shown in square brackets.

Figure 5 — Typical design of compact specimen loading clevis with flat-bottomed hole to accommodate load-pin rotation and translation

Dimensions in millimetres
Values of surface toughness (Ra) in micrometres

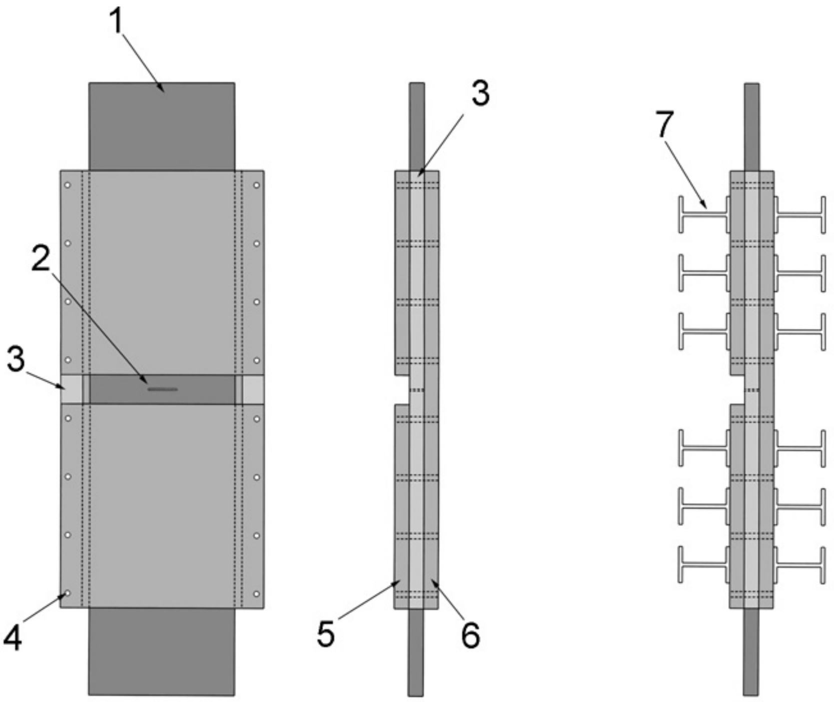


NOTE 1 Pin diameter $= 0{,}24W_{-0{,}005W}^{\;0}$.

NOTE 2 Corners of clevises may be removed if necessary to accommodate clip gauge.

NOTE 3 Clevis and pin hardness ⩾ 40 HRC.

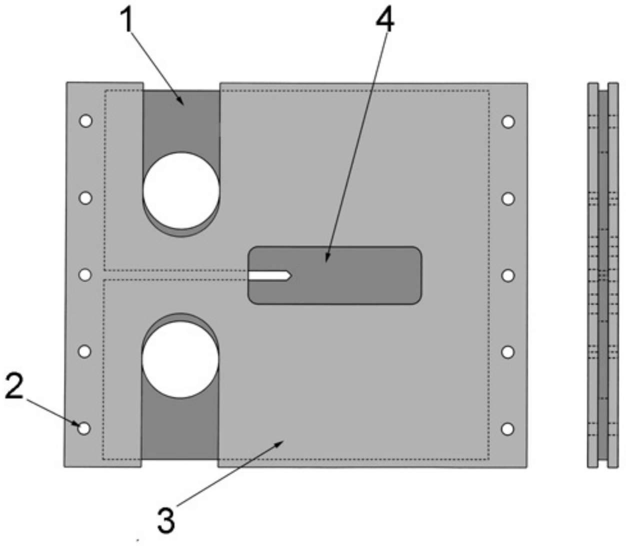
Figure 6 — Typical design of compact specimen loading clevis with oversized circular loading pin hole



Key

1 M(T) specimen
2 crack viewing region
3 spacer strip
4 bolt holes
5 front anti-buckling plate (2 pieces)
6 back anti-buckling plate (1 piece)
7 I-beams

a) Middle-cracked tension specimen anti-buckling guides

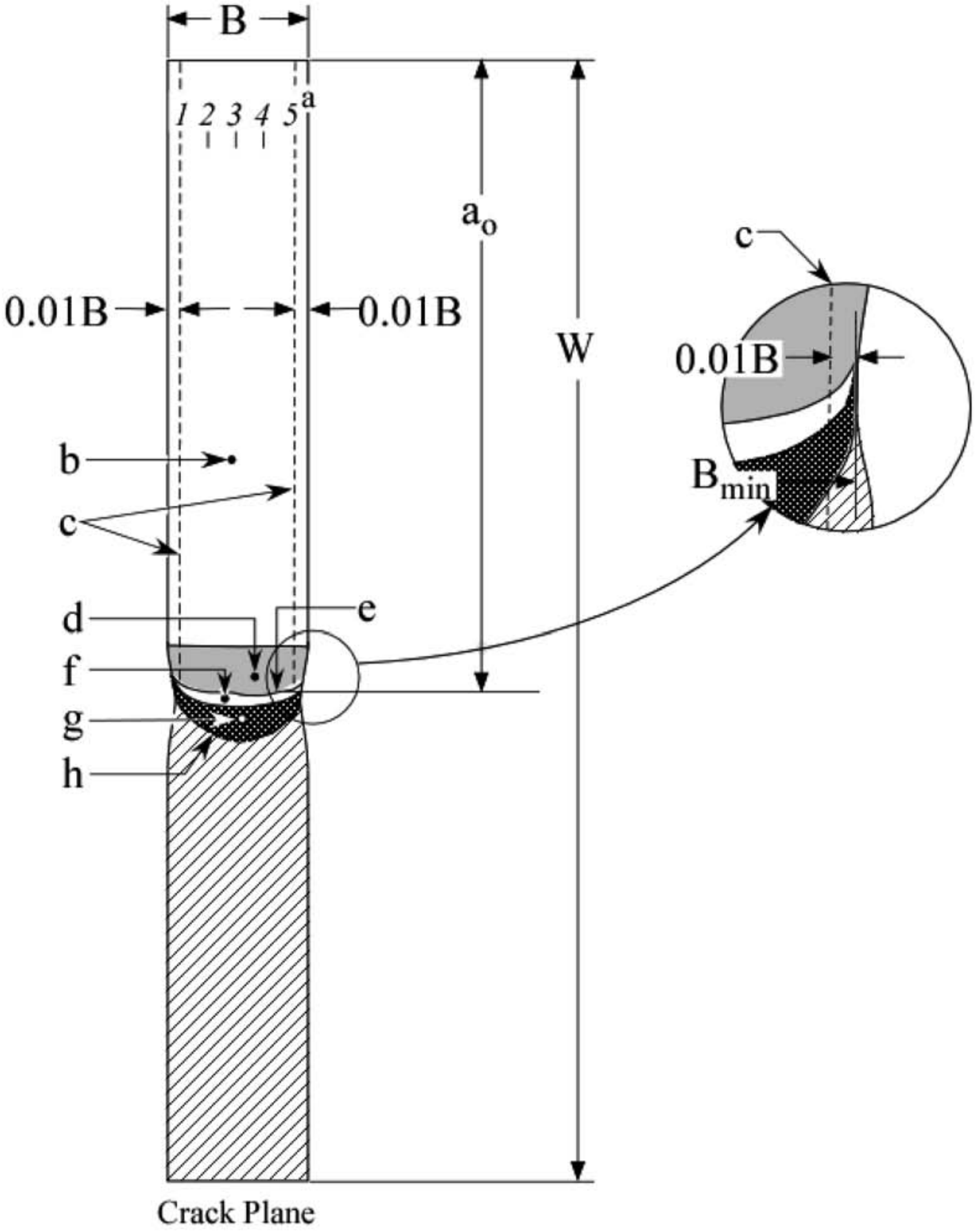


Key

1 C(T) specimen
2 bolt holes
3 anti-buckling plates (front and back)
4 crack viewing region

b) Compact specimen anti-buckling guides

Figure 7 — Anti-buckling guides



Key

a measure initial and final crack lengths at positions 1 to 5 [see Equation (7)]

b machined notch

c reference lines

d fatigue precrack

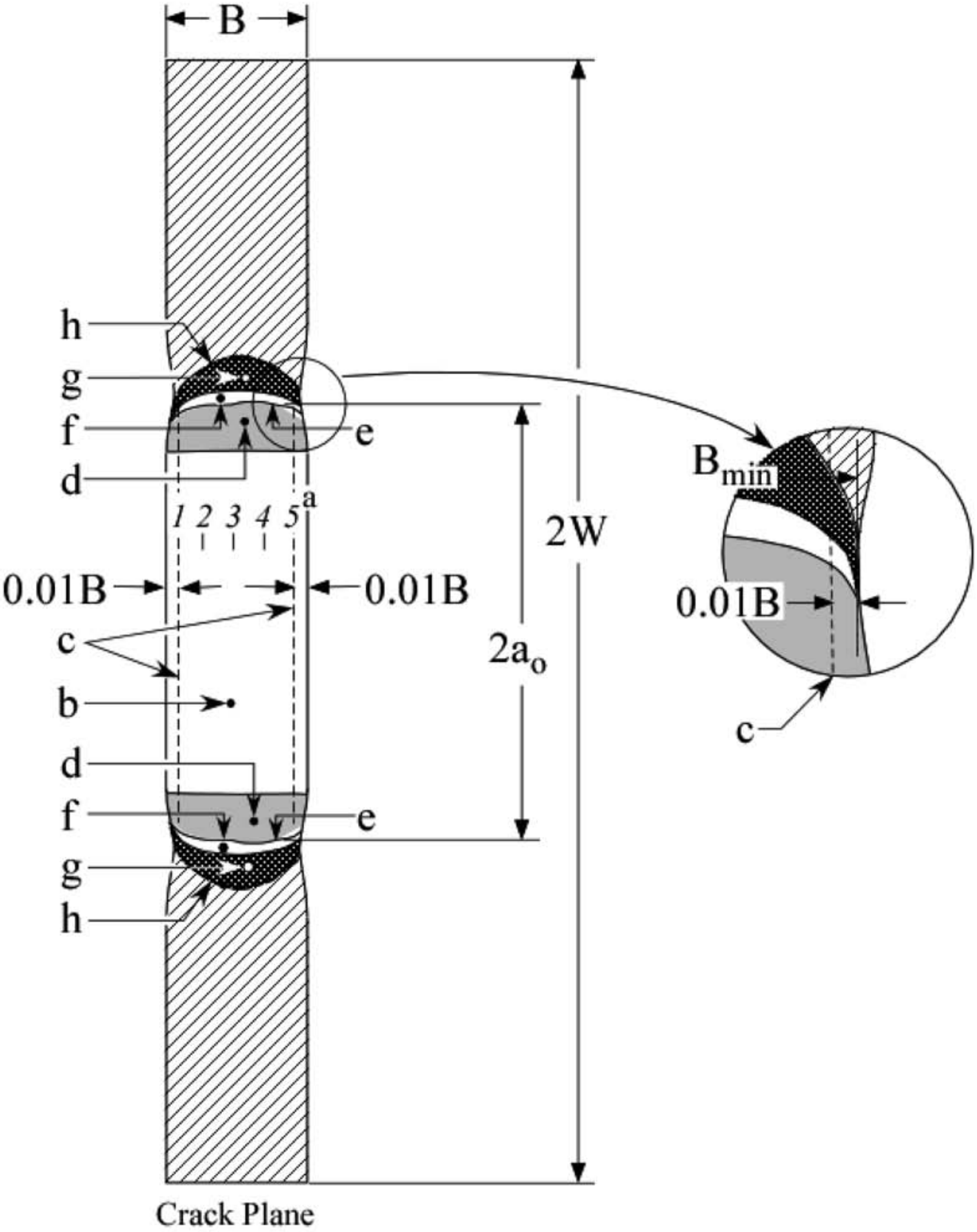
e initial crack front

f stretch zone

g crack extension

h final crack front

Figure 8 — Measurement of crack lengths on compact specimens

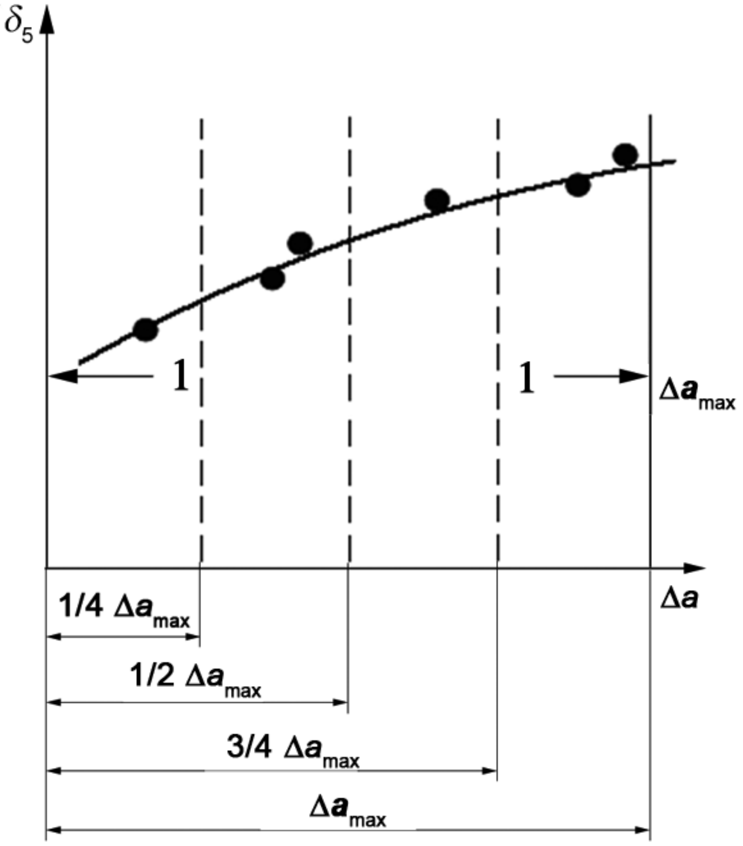


Key

a measure initial and final crack lengths at positions 1 to 5 [see Equation (7)]
b machined notch
c reference lines
d fatigue precrack
e initial crack front
f stretch zone
g crack extension
h final crack front

NOTE The average of both cracks represents the crack lengths of the middle-cracked tensile specimen.

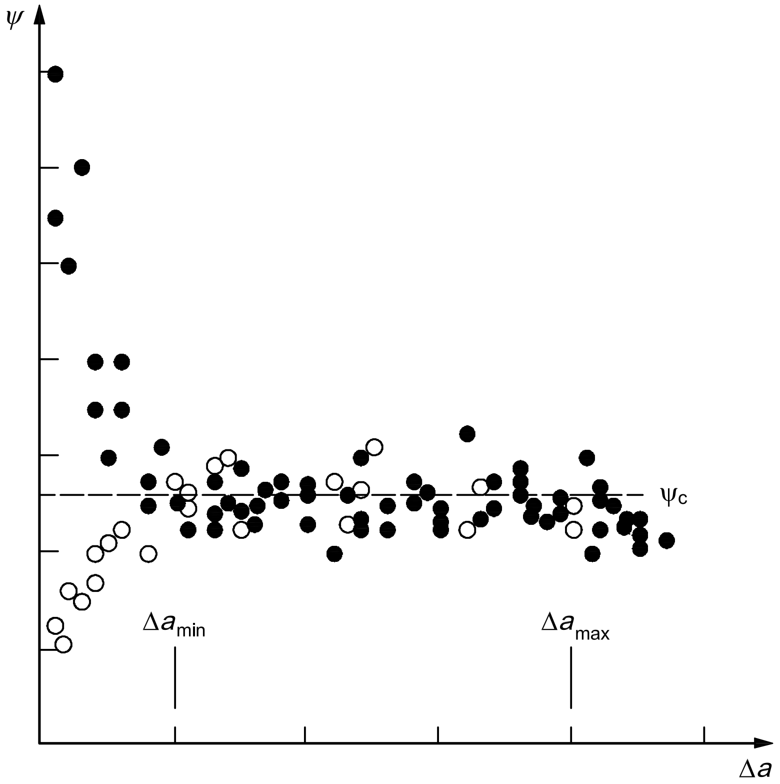
Figure 9 — Measurement of crack lengths on middle-cracked tension specimens



Key

Δa crack extension
δ_5 fracture resistance
1 exclusion lines

Figure 10 — Data spacing for R-curve determination



Key

Δa	crack extension, mm
ψ	crack tip opening angle, degrees
ψ_c	is a constant
●	exterior surface
o	interior region

Figure 11 — Determination of critical CTOA, ψ_c, value

Annex A
(informative)

Examples of test reports

It is the content and not the format of the test reports that is important.

A.1 Specimen, material and test environment

Specimen identifier: __________ Operator: ______________________ Date: ________________

Specimen

Type (compact or middle-cracked tension) ________________

Crack plane orientation ________________

Location within product ________________

Material

Designation ______________________

Form and condition ______________________

Specimen basic dimension

B = ________________ [mm]

W = ________________ [mm]

a_0/W (nominal) = ________________

Tensile properties

Temperature = ____________ [°C]

	Referenced (R)		Measured (M)
E =	____________	[MPa]	____________
n =	____________		____________
$R_{p0,2}$ =	____________	[MPa]	____________
R_m =	____________	[MPa]	____________

Precracking

Fatigue temperature = ____________ [°C]

Final F_f = ____________ [kN]

Final K_f = ____________ [MPa·$\sqrt{m}$]

Final K_f/E = ____________ [$\sqrt{m}$]

Basic test information

Type of displacement control ___________ crack mouth opening/load-line/crosshead

Displacement rate ___________ [mm/min]

Test temperature ___________ [°C]

A.2 Data qualification

Measured crack length information Specimen identifier ___________

Crack measurement table

Point	**Position** mm	**Precrack length** mm	Δa mm
1			
2			
3			
4			
5			
6			

a_0 Average initial crack length [a] ____________________ [mm]

$a_0 - a_m$ Average fatigue precrack length [a] ____________________ [mm]

Δa Average crack extension [a] ____________________ [mm]

$a_0 + \Delta a_f$ Average final crack length [a] ____________________ [mm]

Estimated crack lengths

$a_{0,est}$ Estimated fatigue crack length _______________ [mm]

$a_{f,est}$ Estimated final crack length _______________ [mm]

Fracture surface appearance

Occurrence of cleavage __________ (yes/no)

Describe below any unusual features of the fracture surface, for example lamellar tearing, spikes, metallurgical features:

[a] See 5.6.

A.3 Resistance curve data

Data point No.	F [kN]	a [mm]	Δa [mm] [a]	δ_5 [mm]

[a] UC = Unloading Compliance.
ACPD = Alternating Current Potential Drop.
DCPD = Direct Current Potential Drop.

A.4 Crack tip opening angle

Data point No.	F [kN]	a [mm]	Δa [mm] [a,b]	ψ_1[°] [c]	ψ_2 [°] [c]	ψ_3[°] [c]

[a] See 5.6.2.

[b] Measurements at specimen surfaces.

[c] OM = Optical method.

DIC = Digital imaging correlation method.

A.5 Qualification of δ_5 R-curve

a_0 ________________ [mm]

B ________________ [mm]

$W - a_0$ ________________ [mm]

Coefficients of power law fit to data $\delta_5 = \alpha + \beta\Delta a^{\gamma}$:

$\alpha =$ _________

$\beta =$ _________

$\gamma =$ _________

$\Delta a_{\text{max}} = 0{,}25\ (W - a_0)$ ____________ [mm]

Measured final crack extension
(if using a single-specimen method) ____________ [mm]

Estimated final crack extension
(if using a single-specimen method) ____________ [mm]

Percentage error in final crack length estimate versus measurement ____________ [%]

Crack path deviation α ____________ [°]

Requirements (see 7.4):

The data should be qualified in accordance with 5.6.3.2 and 7.3.

If all requirements are met, this power law represents a δ_5 R-curve in accordance with this International Standard.

A.6 Qualification of ψ_c

a_0 ________________ [mm]

B ________________ [mm]

$W - a_0$ ________________ [mm]

Δa_{min} ________________ [mm]

$\Delta a_{\text{max}} = (W - a_0) - 4B$ ____________ [mm]

Measured final crack extension
(if using a single-specimen method) ____________ [mm]

Estimated final crack extension
(if using a single-specimen method) ____________ [mm]

Percentage error in final crack length estimate versus measurement ____________ [%]

Crack path deviation ____________ [°]

Requirements (see 7.5):

The data should be qualified in accordance with 5.6.3.2 and 7.3.

If all requirements are met, ψ_c represents a valid critical CTOA in accordance with this international Standard.

Annex B
(informative)

Apparatus for measurement of crack opening displacement, δ_5

The basic arrangement for measuring δ_5 is shown in Figure B.1, where δ_5 is the displacement measured at the surface of the specimen near the original fatigue crack tip over an initial gauge length of 5 mm. The area around the expected fatigue crack propagation path should be polished. After fatigue precracking, Vickers hardness indentations are placed 2,5 mm above and below 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 held against the specimen using the lever mechanism shown in Figure B.2 for the compact specimen. Similar arrangements may be used for middle-cracked tension specimens. Digital imaging techniques may also be used. Figure B.3 shows a detailed drawing of a δ_5 clip gauge. (See References [8] and [9].)

Dimensions in millimetres

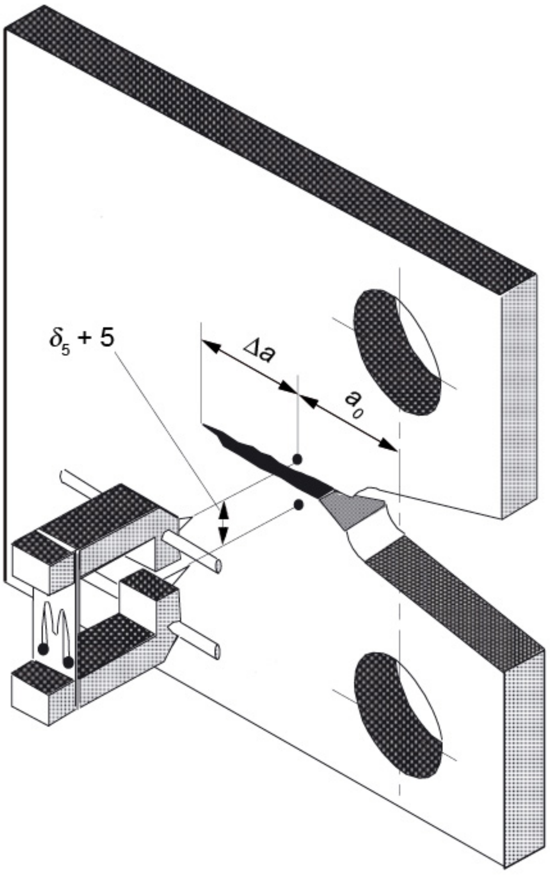


Figure B.1 — Basic arrangement for measuring δ_5

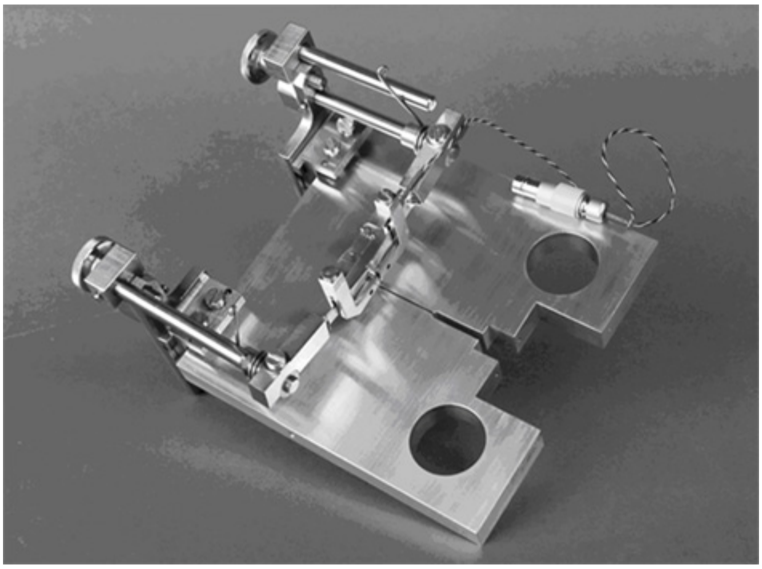
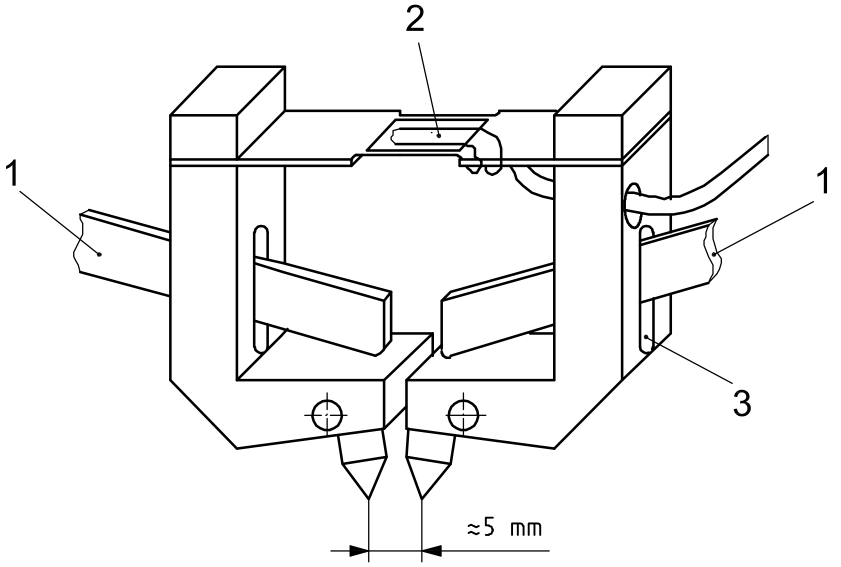


Figure B.2 — Attachment of δ_5 clip gauge to a compact specimen



Key

1 attachment arm

2 strain gauge

3 slit for calibrator attachment

Figure B.3 — Drawing of a δ_5 clip gauge

Annex C
(informative)

Determination of the crack tip opening angle, ψ

C.1 General

Several methods may be used to determine CTOA:

a) direct measurements during stable tearing (optical microscopy and digital imaging correlation);

b) post-test measurements (microtopography);

c) finite element analyses;

d) indirect determination using δ_5.

Direct measurement of ψ (CTOA) during stable tearing is done by Optical Microscopy (OM) or Digital Image Correlation (DIC) [10], [11]. Both methods produce nearly identical results [10]. Microtopography involves a post-test examination of the fracture surfaces to reconstruct the stable tearing process [16]-[20]. This approach allows one to determine CTOA values at the interior of fracture specimens. The finite element method is used to determine a critical CTOA value that fits the failure force of fracture specimens [12]-[15]. Using this approach, the critical CTOA value is effectively an average value through the thickness that accounts for the constraint effects along the crack front. Finite element analyses with constant critical CTOA values indicate that the δ_5 curves for a wide range of materials and specimen configurations are unique up to maximum load [19], demonstrating a unique relationship between CTOA and δ_5.

Direct measurements of the CTOA are made in the range of 0,5 mm to 1,5 mm behind the crack tip (see Figure C.1). For Δa less than Δa_{min}, the measurement distance from the crack tip may be less than 0,5 mm. Calculations of CTOA using finite element methods are made within this same range, customarily at 1 mm behind the crack tip.

C.2 Direct measurement methods

C.2.1 Optical microscopy (OM)

The OM method uses the following instruments:

a) a long focal length microscope;

b) a video camera with a resolution of 512 × 512 pixels to obtain images of the crack under stable tearing;

c) a video recorder to store the images;

d) a PC with both monitor and software to precisely control the three-dimensional positioning of the long focal length microscope and to analyse the resulting images to obtain CTOA.

To obtain clear images of the crack using OM, the surface of the specimen shall be polished to a mirror finish and lighting of the crack region shall be carefully controlled so that the crack tip region has optimum contrast and clarity. Typical images obtained using OM are shown in Figure C.2. The first image, Figure C.2a), shows a fatigue crack which has grown approximately 0,75 mm under stable tearing. The second and third images, Figures C.2b) and C.2c), show the same crack after stable tearing of approximately 1,3 mm and 6 mm, respectively. The CTOA is measured by recalling an individual image recorded on video tape and

a) locating the crack tip,

b) locating three opposing points on the crack surfaces in the range of 0,5 mm to 1,5 mm behind the crack tip,

c) constructing a straight line from the crack tip to each point, and

d) computing the angle, ψ, between each pair of straight lines.

The value of the angle ψ for a given crack length is defined as the average of the values ψ_1, ψ_2, and ψ_3 from three pairs of lines. It is important to note that OM measures CTOA in the deformed configuration without regard for the deformations in the surrounding material.

C.2.2 Digital image correlation (DIC) method

The DIC method requires the following:

a) scientific grade CCD, CMOS or similar camera;

b) lenses and extenders to increase magnification (i.e., resolution) to the range 80-130 pixels/mm (as an example, a 200 mm lens with 2× magnifier and several extension tubes used with a camera having a 1 024 × 1 024 pixel array can produce a resolution of 125 pixels/mm);

c) translation stage to move camera parallel to the specimen surface so that the advancing crack tip always remains within the field of view (for video-tracking the extending crack);

d) video monitor for observing crack-tip region during experiment;

e) capability of converting image data to digital values for data storage;

f) ability to produce a random pattern on the specimen surface that has sufficient contrast for pattern matching (with “spatial” frequency of the pattern in the order of 3-5 pixels/mm so as to minimize the size of local area (subset) used for measurement);

g) software to perform image correlation and to determine subset displacements.

The DIC method is similar to the OM method, but differs in that

- the camera is translated parallel to the specimen surface during the experiment, and
- crack opening displacement is determined by measuring the separation of selected areas (called subsets) on the specimen surface. After each increment of camera translation, the current and previous crack-tip region images are overlapped by at least 100 pixels so as to create a continuous record of crack length.

The minimum required image resolution is 80-130 pixels/mm, with a resolution above 100 pixels/mm preferred. A high-contrast, white-light, random speckle pattern is applied to the specimen surface, usually by lightly spraying the surface with white acrylic paint and then dusting it with black laser-printer toner powder prior to drying. If the pattern is not sufficiently dense after drying, it is removed and the process repeated until successful. Alternatively, the toner is applied after the paint dries and the specimen is then baked at 90 °C for 25 min to adhere the powder to the surface. Less commonly, a surface pattern is applied using lithographic techniques, or an optical image of the bare specimen surface is used providing that such a surface is amenable to image matching.

CTOA is determined from crack-tip-region images recorded during crack extension. The stored images are post-processed to determine the amount of crack extension, and then to estimate CTOA for that crack extension. A typical pair of subsets for estimating CTOA is shown in the crack-tip-region images of Figure C.3. Subsets are typically 12 × 12 to 20 × 20 pixels in size and are chosen to be as close to the crack plane as possible. Figure C.3 a) shows subsets at an initial selected crack length. These subsets are considered as reference images. Their separation distance (at the specimen surface) is designated as d_1. Figure C.3 b) shows the same pair of subsets after additional crack extension, $r_{1\text{-}2}$. Typically, crack extension of 0,5 to 1,5 mm (about 1 mm in the case shown) is used to define CTOA at nominally 1 mm behind the previous crack tip. The new separation is d_2.

The crack-opening displacement vectors (designated as u_i and l_i respectively for the upper and lower subsets in reference to the nominal crack plane) are computed from the digitized video images. Using the estimated normal vector for the crack line, n_i, the CTOA is calculated as:

$$\psi = 2\arctan\left[\left| \sum_{i=1}^{2} (u_i - l_i)\, n_i \right| / (2 r_{1-2}) \right] \tag{C.1}$$

where:

u_i is the horizontal displacement of the upper subset, defined to be perpendicular to the column direction of the recording camera CCD array (pixels);

u_2 is the vertical displacement of the upper subset, defined to be parallel to the column direction of the recording camera CCD array (pixels);

l_1 is the horizontal displacement of the lower subset, defined to be perpendicular to the column direction of the recording camera CCD array (pixels);

l_2 is the vertical displacement of the lower subset, defined to be parallel to the column direction of the recording camera CCD array (pixels);

$r_{1\text{-}2}$ is the amount of crack extension between Figures C.3 a) and C.3 b), generally defined by a straight line between the crack tip locations;

n_1, n_2 are the vectors defined to be perpendicular to the crack line defined by the increment of growth.

The values for u_i and l_i are determined by computer computation of the two-dimensional displacement components for the upper and lower subsets with sub-pixel accuracy in order to render the most accurate estimates of CTOA. Typically, the software performs digital image correlation to optimally measure the displacement of a reference subset [see Figure C.3 a)] after a prescribed increment of crack growth [see Figure C.3 b)].

The average of ψ values between Δa_min and Δa_max (as defined in 6.4) is taken as the critical value, ψ_c.

Care is to be exercised in the choices of

- the amount of crack extension, and
- the location of the subsets to be used for estimating crack opening displacement.

The crack opening displacement determined from the two sequential images as prescribed by this method will have two components: displacement due to the crack's yawn and plastic deformation of the finite-sized subset. Since global plastic deformation to fracture can exceed 10 %, it is important to select the reference subsets to be very close to the reference crack-tip location so that subsequent crack extension will only minimally deform the subsets and cause only minimal error in the CTOA determination. Thus, for CTOA estimated at 1 mm behind the crack tip, the crack extension between sequential images shall not exceed 1 mm.

As a general rule, small subsets (i.e., no larger than 20 × 20 pixels) shall be selected, and located no further from the crack line than necessary. Moreover, they shall be selected such that they have sufficient visual contrast for accurate pattern matching (i.e., for the greatest possible accuracy of DIC analysis).

The primary source of error in ψ estimates is the (mis)identification of the crack tip. This can be related to insufficient contrast between the specimen surface and the crack, insufficient crack opening at the crack tip, and failure of the paint to crack in concert with the specimen crack. To minimize the errors caused by these effects, ψ data shall be taken only from subsets that are at least 0,6 mm behind the crack tip.

C.3 Post-test measurement method

C.3.1 Microtopography

C.3.2 General

Microtopography is a post-test measurement technique for determining ψ (and other parameters). It accomplishes this by direct measurement and analysis of fracture surface deformation, and requires no special instrumentation or considerations during the test (although CMOD and load-line displacement data can be gathered to verify accuracy of the analysis). A single specimen provides data for the entire $\psi - \Delta a$ curve. Microtopography offers the added benefit of examining ψ within the specimen interior. (Even in 2,5-mm aluminium sheet specimens, ψ can vary significantly through the thickness in the early stage of crack extension.)

Microtopographic analysis for ψ is possible because irreversible plastic deformation occurs at the tip of the advancing crack. The fracture process at the crack tip, which produces ψ, leaves a record in the fracture surfaces trailing the advancing crack tip. In microtopography, the fracture surface heights are measured and recorded for mating specimen halves following normal post-test separation (by some nominally elastic method, typically fatigue or cleavage fracture). Two discretely defined mathematical surfaces, $U'(x,y)$ and $L'(x,y)$, corresponding to the physical upper and lower fracture surfaces, are obtained. Spatial increments in y (crack growth direction) of 0,1 mm are normally adequate for ψ analysis. Height resolution shall be appropriate for adequate accuracy of crack surface height measurement. Lower nominal ψ requires finer resolution in height measurement. The x and y coordinates of the two data sets shall be appropriately registered such that common points of instantaneous material separation correlate. A surface separation difference function is then defined

$$D_j(x,y) = \left[U_0(x,y) \cdot P_j\left(a_j, y\right)/2\right] - \left[L_0(x,y) \cdot P_j\left(a_j, y\right)/2\right] + \left(z_{j-1} + \Delta z_j\right) \qquad \text{(C.2)}$$

where

j represents an increment of crack opening, Δz, and corresponding crack extension, Δa;

$L_0 = L'$;

$U_0 = U' - t(x,y)$, where $t(x,y)$ is a planar surface tilt correction function, defined such that the initial difference values, $D_0(x,y)$, are nominally zero in the region of the fatigue precrack;

$P_j(y)$ is the global specimen rotation correction term (angular correction function), providing a planar rotation about the x-axis, centred at the incremental specimen centre of rotation, R_j;

P is a linear function of a_j and y, and $P_0 = 0$. The initial state prior to crack opening and advance is thus defined. D values less than zero (nominal) have no physical meaning and represent the area ahead of the crack tip that has not yet separated due to crack extension. The equation

$$D_f(x,y) = [U_0 \cdot P_j(a_j,y)/2] - [L_0 \cdot P_f(a_f,y)/2] + (z_{f-1} + \Delta z_f) \qquad \text{(C.3)}$$

is used to define P such that the difference function, D_f, is nominally zero in the post-test elastic fracture region. P_j is always zero for symmetric specimens, e.g. M(T), with nominally symmetric crack extension. D_0 and D_f represent the two reference states in the crack extension process, initial and final respectively. The incremental crack length, $a_j(x)$, is located at the y value where $D_j(x,y) = 0$ (the incremental crack tip border on the x–y plane). An example of D_j versus y (the nominal crack extension direction) at a fixed x position, for different amounts of crack opening / extension is shown in Figure C.4. The relevant analysis parameters are identified.

The average slope, C_j, of the surface (profile) D_j:

$$Cj = \Delta Dj/\Delta y_{|y:[(a_j - 1\ \text{mm}),\ a_j]} \tag{C.4}$$

in the y-direction, at the x location of choice (typically mid-thickness), in the range y: $[(a_j - 1\ \text{mm}),\ a_j]$ (as defined in this International Standard, and $y = a_j$ is the instantaneous crack tip position), relates to the incremental value ψ by

$$\psi_j = 2\arctan\left(-C_j/2\right) \tag{C.5}$$

A linear least-squares fit of the discrete height data in the defined range of y defines the average slope, C_j. The data should be examined for outlying points (not in the general trend of D), or the D_j function can be smoothed prior to analysis to eliminate measurement errors and minor data point correlation errors. The resultant data, ψ_j versus Δa_j, can thus be developed, plotted and analysed. It must be emphasized that early crack opening is associated with crack tip blunting (CTOD is the defining parameter in that region) and no significant tearing. ψ has no practical meaning in this regime. Inferring ψ from C_j measurements in this region without regard for the deformation process will lead to faulty results, due to the blunting and nonlinear nature of the D function in this zone. ψ shall only be calculated from C_j determined from data collected within the tearing zone region (see Figure C.4). The transition from blunting to stable tearing is normally identified by a change from rapidly increasing $|C_j|$ to a significantly lower, more slowly changing $|C_j|$.

C.3.3 Errors associated with rotation correction function, P

Bulk plastic deformation not directly associated with crack advance will also occur in differing amounts during the ductile fracture process.

NOTE This bulk plasticity, typically through the remaining ligament region, contributes to global specimen rotation. This is a significant factor in the conventional CTOD analysis because local crack tip opening is inferred from a crack mouth opening CMOD measurement. The ratio, H = CMOD/CTOD, depends on crack length, a, and the position of the global centre of rotation, $R \approx 0{,}4\ (W - a)$. The ratio H typically ranges from 4 to 6, and is established through inference equations. In the microtopography method, the corresponding effect of global specimen rotation on local CTOD is:

$S = (R - \text{CTOD}/2)R \approx 0{,}95 - 0{,}98$

in typical-sized specimens. Observe that, at lower CTOD, and hence lower toughness where CTOD is more critical, the ratio approaches 1,0 (no error).

In asymmetric specimens, such as compact specimens, this global specimen rotation also rotates the fracture surfaces behind the instantaneous crack tip. However, the error introduced by the global rotation of asymmetric specimens is essentially self-limiting to some small percentage of the measured value of ψ. For higher toughness materials, where the bulk plasticity is more extensive and global rotations are larger, the values of ψ are correspondingly larger. The converse is true for lower toughness materials: global rotations are smaller in proportion to the smaller values of ψ.

C.4 Finite element calculation of the critical crack tip opening angle, ψ_c

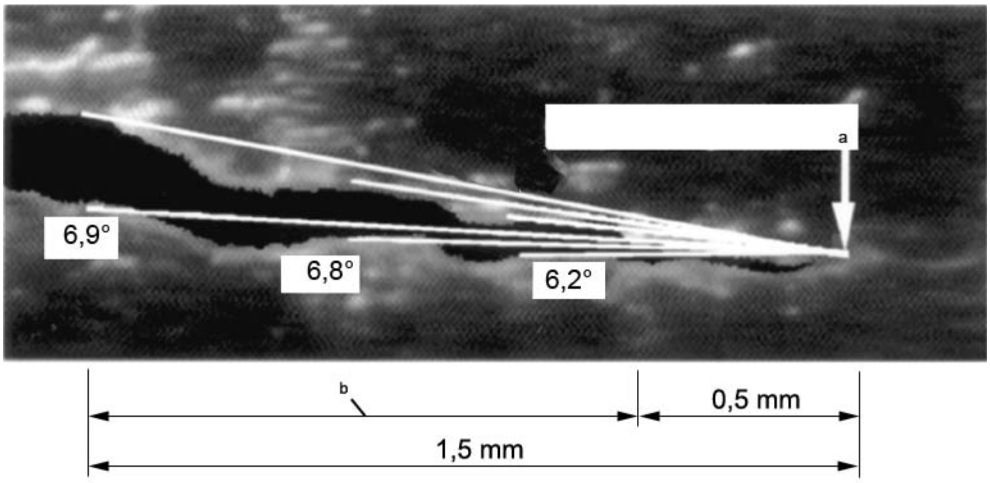
Elastic-plastic finite-element (FE) analysis codes have been used to determine the critical ψ_c from load versus crack extension data. The approach assumes a constant value of ψ_c from initiation to instability, and finds, by trial and error, the ψ_c value that fits the maximum load. FE codes used to date have included two-dimensional constant and linear-strain codes, a shell code, and three-dimensional linear-strain codes. One study [12] of stable tearing behaviour for a variety of materials found 0,5-mm constant-strain elements were required in the crack tip region to fit the load-crack-extension behaviour along the line of crack extension. Two other studies using a three-dimensional FE code [13] and a shell code [14] with linear-strain elements found that 1-mm size elements were sufficient to model stable tearing for a wide range of cracked specimens (restrained against buckling). If the crack length and uncracked ligament criteria ($a/B > 4$ and $b/B > 4$) are met, then the critical value ψ_c will be independent of specimen type (compact or middle-cracked tension). ψ_c values so obtained have been successfully used to predict the stable tearing behaviour of complex structures of thin-sheet aluminium alloy [15].

C.5 Indirect determination

C.5.1 Correlation between δ_5 R-curves and ψ

The measurement of δ_5 R-curves is simpler and less costly than the measurement of ψ_c values. Thus, it would be desirable to be able to derive ψ_c values from δ_5 measurements. Such correlations have yet to be developed but finite element analyses of crack extension simulations have indicated such a possibility.

Figure C.5 shows the results of elastic-plastic, finite-element analyses of a wide range of specimen widths for compact and middle-cracked tension specimens made of a 2024-T351 ($B = 6{,}35$ mm) aluminium alloy. The analyses were performed with a constant ψ_c value of 6,35°. A δ_5 R-curve was obtained from the analysis of each specimen. The results are shown only to the maximum load of each specimen. These results demonstrate that a unique δ_5 R-curve is related to a constant ψ_c value. Further study is required to obtain analytical or numerically derived relationships between these two fracture parameters.

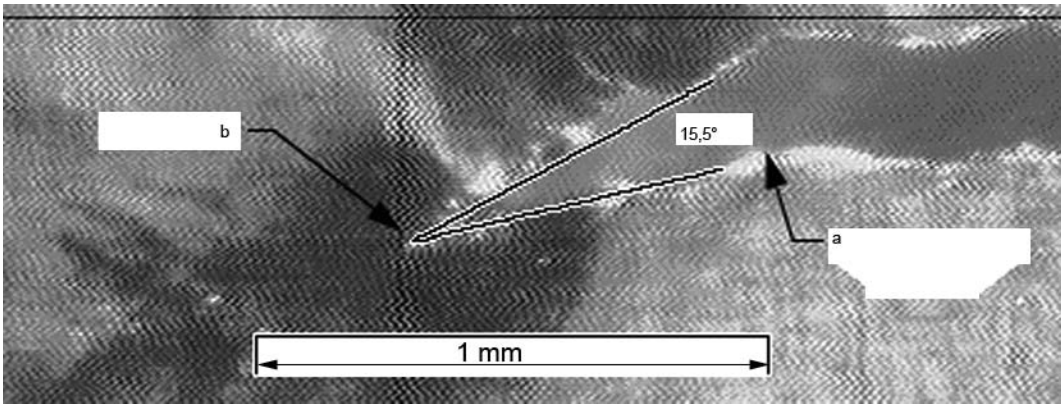


Key

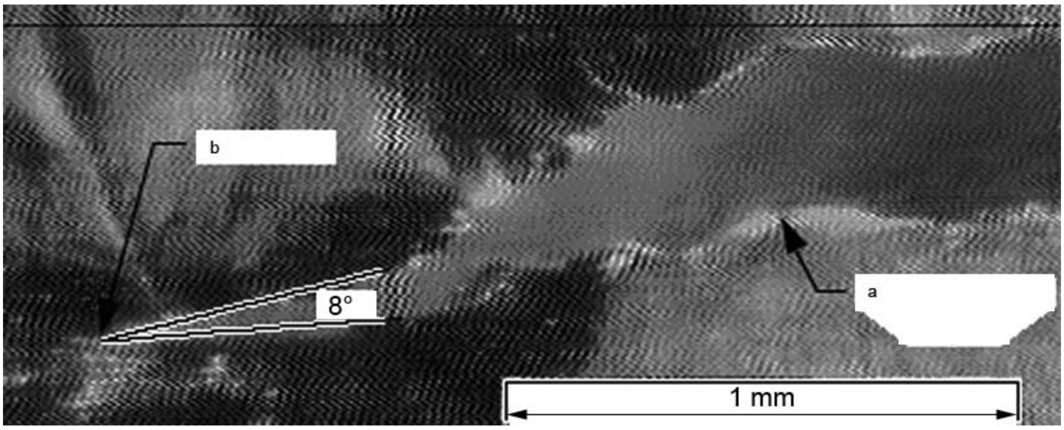
[a] Crack tip.

[b] Measurement range.

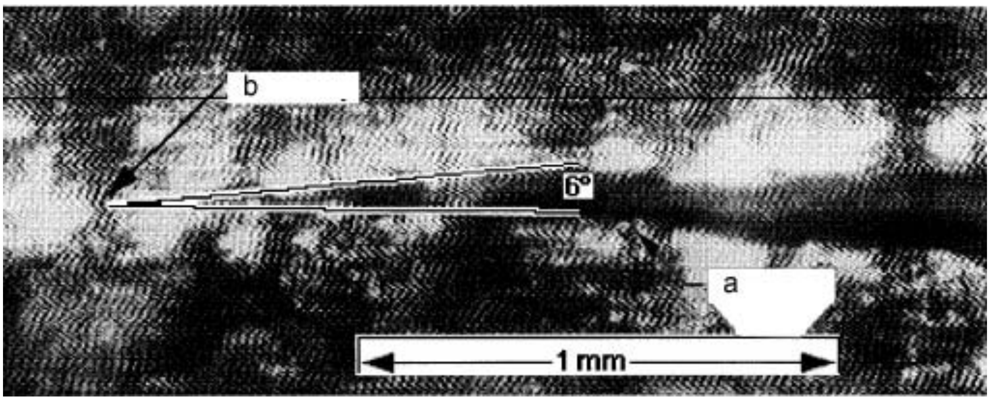
Figure C.1 — Measurement range for CTOA values from optical microscopy (OM)



a) OM image after about 0,75 mm of stable tearing



b) OM image after about 1,3 mm of stable tearing



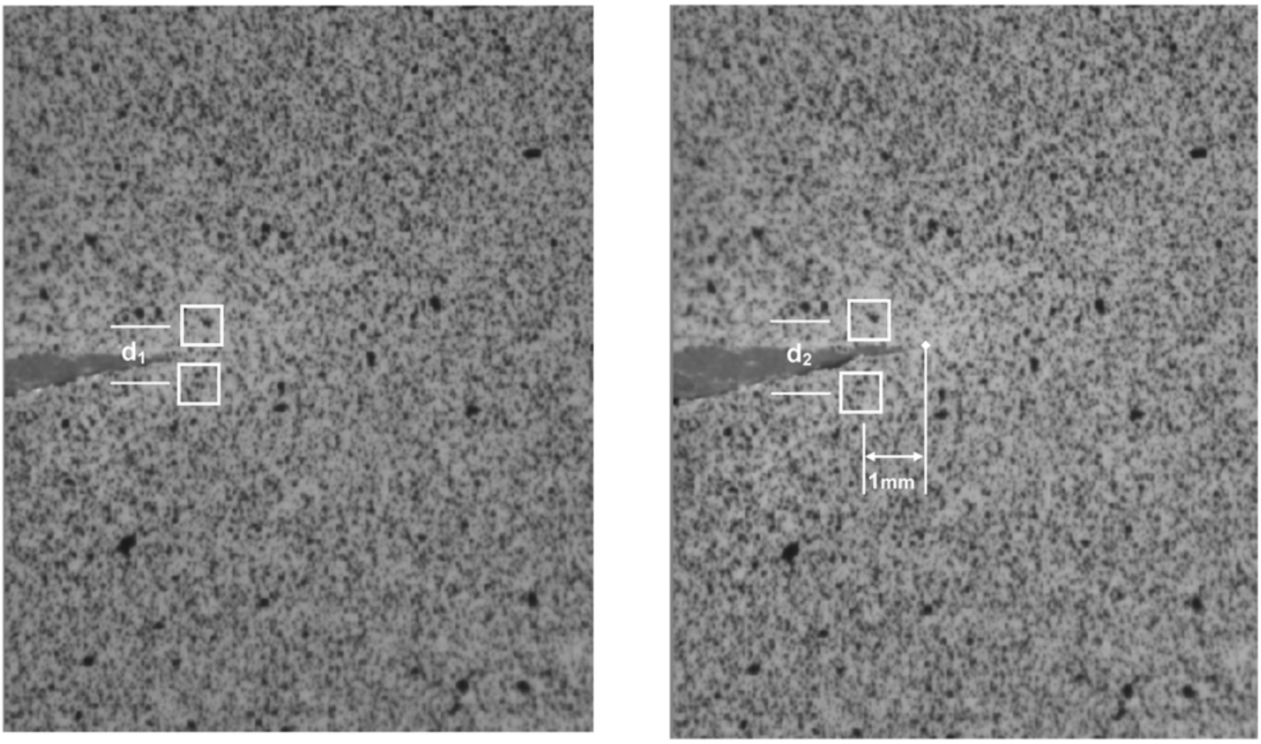
c) OM image after about 6 mm of stable tearing

Key

[a] Tip of fatigue precrack.

[b] Crack tip after stable tearing.

Figure C.2 — Typical OM images and CTOA measurements for stable tearing cracks in 2,3 mm thick 2024-T3 aluminium alloy sheet

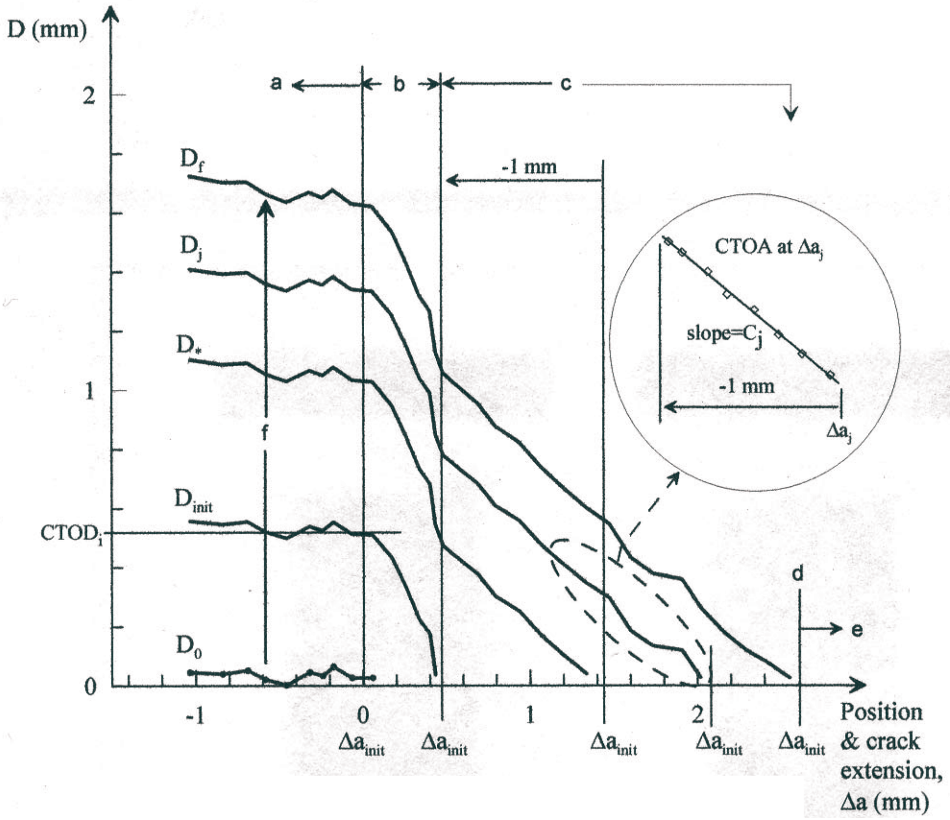


a) Image of reference crack-tip region (after initial crack extension)

b) Image of subsequent crack-tip region (after further crack extension)

NOTE The dimensions d_1 and d_2 are the “vertical” separations of the white “boxes” before and after approximately 1 mm of stable crack extension.

Figure C.3 — Images of specimen after a) initial and b) subsequent crack extension (Specimen surface high-contrast, random “speckle” pattern is used to determine CTOA by DIC method.)



Key

D function states represented

D_o	start state, precrack closed
D_{init}	tearing initiation state
D_*	state for first valid CTOA
D_j	intermediate growth state
D_f	end of tearing growth
Δa	position and crack extension

[a] precrack region.

[b] blunting region.

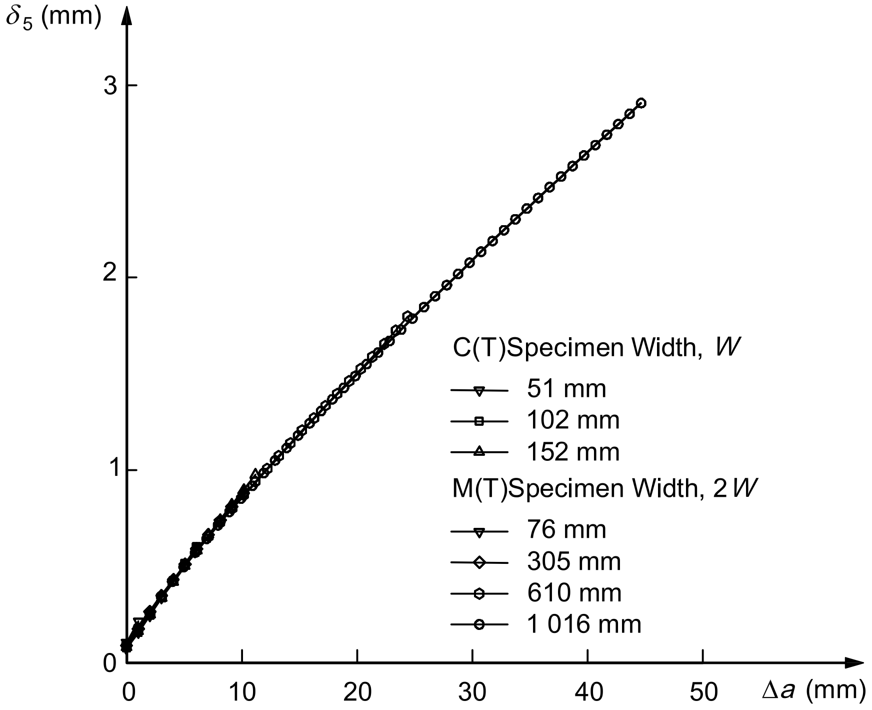
[c] tearing region.

[d] end of tearing growth.

[e] post-test region (fatigue or cleavage).

[f] representative fracture increments.

Figure C.4 — Graphical depiction of CTOA analysis from surface height difference function $D(x,y)$



Analysis:
2024-T351 (LT)
B = 6,35 mm
C(T): a/W = 0,4
M(T): $2a/W$ = 1/3
ψ_c = 6,35°

Figure C.5 — δ_5 R-curve calculated from constant ψ_c for various specimen configurations

Annex D
(informative)

Determination of point values of fracture toughness

D.1 Determination and qualification of $\delta_{5(0,2\text{BL})}$

The R-curve is plotted and fitted in accordance with 6.3 (see Figure D.1).

A blunting line is constructed on the plot using

$$\delta_5 = 1{,}87\left(R_\text{m}/R_{\text{p}0,2}\right)\Delta a \tag{D.1}$$

where R_m and $R_{\text{p}0,2}$ are determined at the temperature of the test.

Crack extension offset lines are drawn parallel to the blunting line at crack extension offsets of 0,10 mm, 0,30 mm and 0,50 mm (see Figure D.1). One data point is required to lie between the 0,10 mm and 0,30 mm crack extension offset lines and at least two data points between the 0,10 mm and 0,50 mm crack extension offset lines.

An additional line is drawn parallel to the blunting line at a 0,20 mm crack extension offset. The intersection of that line with the best-fit curve defines $\delta_{5(0,2\text{BL})}$.

$\delta_{5,\text{max}}$ is calculated for each compact specimen as the smallest of

$$\delta_{5,\text{max}} = B/30 \tag{D.2}$$

$$\delta_{5,\text{max}} = a_0/30 \tag{D.3}$$

$$\delta_{5,\text{max}} = (W - a_0)/30 \tag{D.4}$$

If $\delta_{5(0,2\text{BL})}$ is less than or equal to $\delta_{5,\text{max}}$ so determined, then it is insensitive to the size of the specimen.

If $\delta_{5(0,2\text{BL})}$ is less than or equal to $\delta_{5,\text{max}}$ from Equations (D.3) and (D.4), but exceeds $\delta_{5,\text{max}}$ from Equation (D.2), then it is insensitive to the in-plane dimensions of the specimen, but may be thickness dependent.

If the slope $(\text{d}\delta_5/\text{d}a)_{0,2\text{BL}}$ of the $\delta_5 - \Delta a$ curve at its intersection with the 0,20 mm offset blunting line fails to meet the following criterion

$$1{,}87\left[\frac{R_\text{m}}{R_{\text{p}0,2}}\right] > \left[2\left(\frac{\text{d}\delta_5}{\text{d}a}\right)\right]_{0,2\text{BL}} \tag{D.5}$$

then the $\delta_{5(0,2\text{BL})}$, determined as the intersection of the 0,20 mm crack extension blunting line with the best-fit curve, is qualified.

NOTE Similar criteria for middle-cracked tension specimens are not available.

D.2 Determination and qualification of $\delta_{5,i}$

The R-curve data points are plotted in accordance with 6.3.

The critical stretch zone width Δa_{szw} is determined as described in ISO 12135 or in Reference [2].

A line is drawn parallel to the δ_5 axis at an offset of Δa_{szw} (see Figure D.2). Using the procedure of 6.3.2, a best-fit curve is fitted through all $\delta_5 - \Delta a$ data that exceed Δa_{szw}. The intercept of the best-fit curve with the Δa_{szw} line defines $\delta_{5,i}$.

A line is drawn from the origin through the intersection of the best-fit curve with the Δa_{szw} line (see Figure D.2). At least one $\delta_5 - \Delta a$ data point shall lie within 0,20 mm of this line.

If $\delta_{5,i}$ determined on compact specimens is less than or equal to $\delta_{5,\max}$ from Figure D.1, then it is insensitive to the size of the specimen.

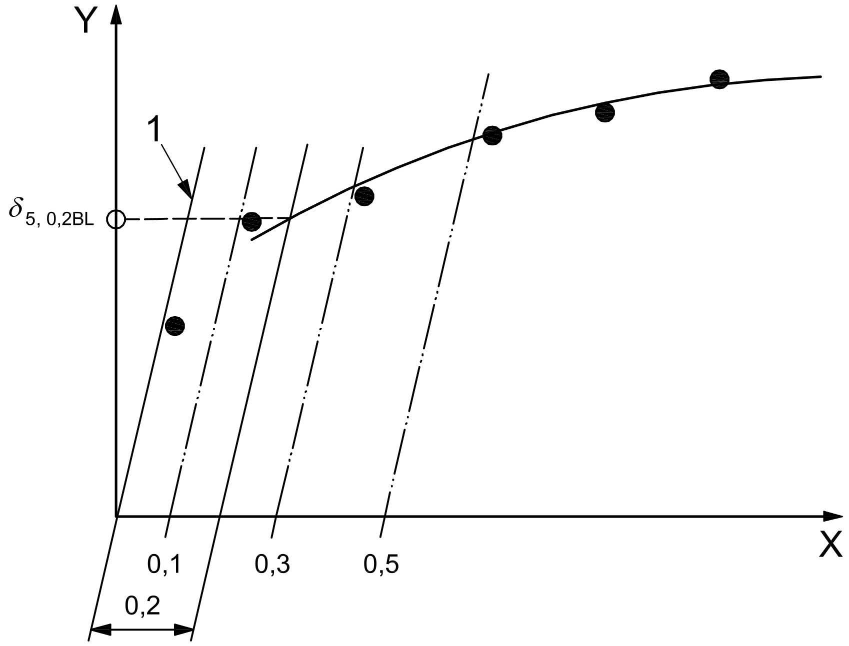
If $\delta_{5,i}$ is less than or equal to $\delta_{5,\max}$ from Equations (D.3) and (D.4), then it is insensitive to the in-plane dimensions of the specimen, but it may be thickness dependent.

The slopes $(\mathrm{d}\delta_5/\mathrm{d}a)_i$ of the $\delta_5 - \Delta a$ curve at the point $\delta_{5,i}$ (determined as described above) and $(\mathrm{d}\delta_5/\mathrm{d}a)_\mathrm{L}$ of the line drawn from the origin to the intersection of the best-fit curve with the Δa_{szw} line (also described above) are determined. If

$$\left(\mathrm{d}\delta_5/\mathrm{d}a\right)_\mathrm{L} < 2\left(\mathrm{d}\delta_5/\mathrm{d}a\right)_i \tag{D.6}$$

then the $\delta_{5,i}$ determined as the intersection of the best-fit curve with the Δa_{szw} line does not qualify.

NOTE Similar criteria for middle-cracked tension specimens are not available.



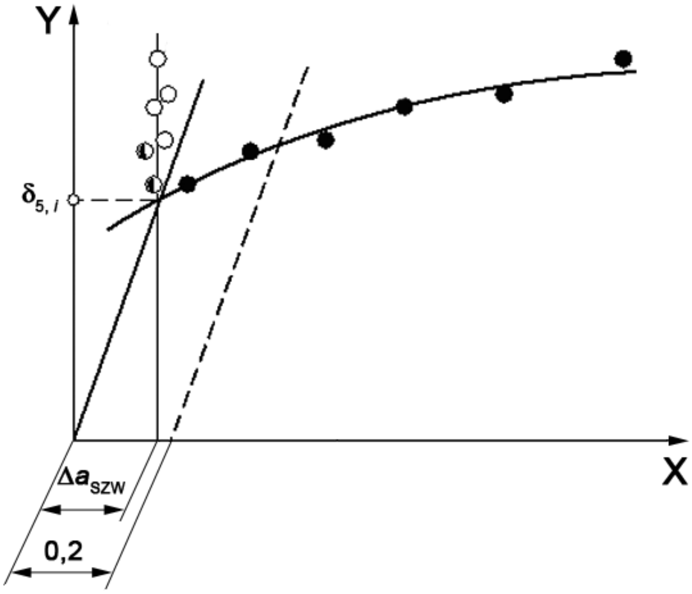
Key

X crack extension, Δa, mm

Y fracture resistance, δ_5, mm

1 blunting line

Figure D.1 — Data distribution for the determination of $\delta_{5,0,2/\text{BL}}$



Key

X crack extension, Δa, mm

Y fracture resistance, δ_5, mm

● $\delta_5 - \Delta a$ data

o valid stretch zone width data

◐ invalid stretch zone width data

Figure D.2 — Determination of $\delta_{5,i}$

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