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Metallic materials — Unified method of test for the determination of quasistatic fracture toughness

Matériaux métalliques — Méthode unifiée d'essai pour la détermination de la ténacité quasi statique

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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.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

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For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

The committee responsible for this document is ISO/TC 164, *Mechanical testing of metals*, Subcommittee SC 4, *Toughness testing — Fracture (F), Pendulum (P), Tear (T)*.

This second edition cancels and replaces the first edition (ISO 12135:2002), which has been technically revised. It also incorporates the Technical Corrigendum ISO 12135:2002/Cor 1:2008.

Metallic materials — Unified method of test for the determination of quasistatic fracture toughness

1 Scope

This document specifies methods for determining fracture toughness in terms of *K*, *δ*, *J* and *R*-curves for homogeneous metallic materials subjected to quasistatic loading. Specimens are notched, precracked by fatigue and tested under slowly increasing displacement. The fracture toughness is determined for individual specimens at or after the onset of ductile crack extension or at the onset of ductile crack instability or unstable crack extension. In some cases in the testing of ferritic materials, unstable crack extension can occur by cleavage or ductile crack initiation and growth, interrupted by cleavage extension. The fracture toughness at crack arrest is not covered by this document. In cases where cracks grow in a stable manner under ductile tearing conditions, a resistance curve describing fracture toughness as a function of crack extension is measured. In most cases, statistical variability of the results is modest and reporting the average of three or more test results is acceptable. In cases of cleavage fracture of ferritic materials in the ductile-to-brittle transition region, variability can be large and additional tests may be required to quantify statistical variability. Special testing requirements and analysis procedures are necessary when testing weldments and these are described in ISO 15653 which is complementary to this document.

When fracture occurs by cleavage or when cleavage is preceded by limited ductile crack extension, it may be useful to establish the reference temperature for the material by conducting testing and analysis in accordance with ASTM E1921.[2]

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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 — Calibration and verification of static uniaxial testing machines — Part 1: Tension/compression testing machines — Calibration and verification of the force-measuring system*

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

3 Terms and definitions

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

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1
stress intensity factor
K
magnitude of the elastic stress-field singularity for a homogeneous, linear-elastic body

Note 1 to entry: The stress intensity factor is a function of applied force, crack length, specimen size and specimen geometry.

3.2
crack-tip opening displacement
δ
<rotation point equation> relative displacement of the crack surfaces normal to the original (undeformed) crack plane at the tip of the fatigue precrack, evaluated using the rotation point formula

3.3
crack-tip opening displacement
δ_J
<from *J*> estimate of the crack-tip opening displacement, obtained from *J*

3.4
***J*-integral**
line or surface integral that encloses the crack front from one crack surface to the other and characterizes the local stress-strain field at the crack tip

3.5
J
loading parameter, equivalent to the *J*-integral, specific values of which, experimentally determined by this method of test (J_c, J_i, J_u,...), characterize fracture toughness under elastic-plastic conditions

3.6
stable crack extension
crack extension which stops or would stop when the applied displacement is held constant as a test progresses under displacement control

3.7
unstable crack extension
abrupt crack extension occurring with or without prior stable crack extension

3.8
pop-in
abrupt discontinuity in the force versus displacement record, featured as a sudden increase in displacement and, generally, a decrease in force followed by an increase in force

Note 1 to entry: Displacement and force subsequently increase beyond their values at pop-in.

Note 2 to entry: When conducting tests by this method, pop-ins may result from unstable crack extension in the plane of the precrack and are to be distinguished from discontinuity indications arising from: i) delaminations or splits normal to the precrack plane; ii) roller or pin slippage in bend or compact specimen load trains, respectively; iii) improper seating of displacement gauges in knife edges; iv) ice cracking in low-temperature testing; v) electrical interference in the instrument circuitry of force and displacement measuring and recording devices.

3.9
crack extension resistance curves
R-curves
variation in δ_J or *J* with stable crack extension

4 Symbols and designations

See Table 1.

Table 1 — Symbols and their designations

Symbol	Unit	Designation
a	mm	Nominal crack length (for the purposes of fatigue precracking, an assigned value less than a_o)
a_f	mm	Final crack length ($a_o + \Delta a$)
a_i	mm	Instantaneous crack length
a_m	mm	Length of machined notch
a_o	mm	Initial crack length
A_p	J	Plastic component of the area under the force vs. notch opening displacement diagram (Figure 17)
Δa	mm	Stable crack extension including blunting
Δa_{max}	mm	Crack extension limit for δ or J controlled crack extension
B	mm	Specimen thickness
B_N	mm	Specimen net thickness between side grooves
C	m/N	Specimen elastic compliance
E	GPa	Modulus of elasticity at the pertinent temperature
F	kN	Applied force
F_c	kN	Applied force at the onset of unstable crack extension or pop-in when Δa is less than 0,2 mm offset from the construction line (Figure 2)
F_d	kN	Force value corresponding to the intersection of the test record with the secant line (Figure 16)
F_f	kN	Maximum fatigue precracking force
F_m	kN	Maximum force for a test which exhibits a maximum force plateau preceding fracture with no significant prior pop-ins (Figure 2)
F_Q	kN	Provisional force value used for the calculation of K_Q
F_u	kN	Applied force at the onset of unstable crack extension or pop-in when Δa is equal to or greater than than 0,2 mm offset from the construction line (Figure 2)
J	MJ/m^2	Experimental equivalent to the J-integral
$J_{c(B)}$	MJ/m^2	Size sensitive fracture resistance J at onset of unstable crack extension or pop-in when stable crack extension is less than 0,2 mm offset from the construction line (B = specimen thickness in mm)
J_g	MJ/m^2	J at upper limit of J-controlled crack extension
J_i	MJ/m^2	Size-insensitive fracture resistance J at initiation of stable crack extension
$J_{m(B)}$	MJ/m^2	Size sensitive fracture resistance J at the first attainment of a maximum force plateau for fully plastic behaviour (B = specimen thickness in mm)
J_{max}	MJ/m^2	Limit of J-R material behaviour defined by this method of test
$J_{u(B)}$	MJ/m^2	Size sensitive fracture resistance J at the onset of unstable crack extension or pop-in when the event is preceded by stable crack extension equal to or greater than 0,2 mm offset from the construction line (B = specimen thickness in mm)
$J_{uc(B)}$	MJ/m^2	Size sensitive fracture resistance J at the onset of unstable crack extension or pop-in when stable crack extension cannot be measured (B = specimen thickness in mm)
J_o	MJ/m^2	J uncorrected for stable crack extension
$J_{0,2BL}$	MJ/m^2	Size insensitive fracture resistance J at 0,2 mm stable crack extension offset from the construction line
$J_{0,2BL(B)}$	MJ/m^2	Size sensitive fracture resistance J at 0,2 mm stable crack extension offset from the construction line (B = specimen thickness in mm)
NOTE 1 This is not a complete list of parameters. Only the main parameters are given here, other parameters are referred to in the text.		
NOTE 2 The values of all parameters used in calculations are assumed to be those measured or calculated for the temperature of the test, unless otherwise specified.		

Table 1 *(continued)*

Symbol	Unit	Designation
K	$MPa\sqrt{m}$	Stress intensity factor
K_f	$MPa\sqrt{m}$	Maximum value of K during the final stages of fatigue precracking
K_{Ic}	$MPa\sqrt{m}$	Plane strain linear elastic fracture toughness
$K_{J0,2BL}$	$MPa\sqrt{m}$	Plane strain linear elastic fracture toughness equivalent to $J_{0,2BL}$
K_Q	$MPa\sqrt{m}$	A provisional value of K_{Ic}
q	mm	Load-point displacement
R_m	MPa	Ultimate tensile strength perpendicular to crack plane at the test temperature
$R_{p0,2}$	MPa	0,2 % offset yield strength perpendicular to crack plane at the test temperature
S	mm	Span between outer loading points in a three-point bend test
T	°C	Test temperature
U	J	Area under plot of force F versus specimen load-point displacement q at the load-line
U_e	J	Elastic component of U
U_p	J	Plastic component of U
V	mm	Notch-opening displacement
V_e	mm	Elastic component of V
V_p	mm	Plastic component of V
W	mm	Width of the test specimen
z	mm	For bend and straight-notch compact specimens, the initial distance of the notch opening gauge measurement position from the notched edge of the specimen, either further from the crack tip [$+z$ in Figure 8 b)] or closer to the crack tip ($-z$); or, for a stepped-notch compact specimen, the initial distance of the notch opening gauge measurement position either beyond ($+z$) or before ($-z$) the initial load-line
δ	mm	Crack-tip opening displacement (CTOD) evaluated using the rotation point formula
δ_J	mm	Crack-tip opening displacement (CTOD) evaluated from J
$\delta_{c(B)}$	mm	Size sensitive fracture resistance δ at the onset of unstable crack extension or pop-in when stable crack extension is less than 0,2 mm crack offset from the construction line (B = specimen thickness in mm)
δ_g	mm	δ at the limit of δ-controlled crack extension
δ_{Ji}	mm	Fracture resistance δ_J at initiation of stable crack extension
$\delta_{m(B)}$	mm	Size sensitive fracture resistance δ at the first attainment of a maximum force plateau for fully plastic behaviour (B = specimen thickness in mm)
$\delta_{J,max}$	mm	Limit of δ_J-R defined by this method of test
$\delta_{u(B)}$	mm	Size sensitive fracture resistance δ at the onset of unstable crack extension or pop-in when the event is preceded by stable crack extension equal to or greater than 0,2 mm offset from the construction line (B = specimen thickness in mm)
$\delta_{uc(B)}$	mm	Size sensitive fracture resistance δ at the onset of unstable crack extension or pop-in when stable crack extension Δa cannot be measured (B = specimen thickness in mm)
δ_o	mm	δ uncorrected for stable crack extension
NOTE 1 This is not a complete list of parameters. Only the main parameters are given here, other parameters are referred to in the text.		
NOTE 2 The values of all parameters used in calculations are assumed to be those measured or calculated for the temperature of the test, unless otherwise specified.		

Table 1 *(continued)*

Symbol	Unit	Designation
$\delta_{J0,2BL}$	mm	Size insensitive fracture resistance δ_J at 0,2 mm crack extension offset from construction line
$\delta_{J0,2BL(B)}$	mm	Size sensitive fracture resistance δ_J at 0,2 mm stable crack extension offset from construction line (B = specimen thickness in mm)
ν	—	Poisson's ratio
NOTE 1 This is not a complete list of parameters. Only the main parameters are given here, other parameters are referred to in the text.		
NOTE 2 The values of all parameters used in calculations are assumed to be those measured or calculated for the temperature of the test, unless otherwise specified.		

5 General requirements

5.1 General

The fracture toughness of metallic materials can be characterized in terms of either specific (single point) values (see Clause 6), or a continuous curve relating fracture resistance to crack extension over a limited range of crack extension (see Clause 7). The procedures and parameters used to determine fracture toughness vary depending upon the level of plasticity realized in the test specimen during the test. Under any given set of conditions, however, any one of the fatigue-precracked test specimen configurations specified in this method may be used to measure any of the fracture toughness parameters considered. In all cases, tests are performed by applying slowly increasing displacements to the test specimen and measuring the forces and displacements realized during the test. The forces and displacements are then used in conjunction with certain pre-test and post-test specimen measurements to determine the fracture toughness that characterizes the material's resistance to crack extension. Details of the 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 method can be used is presented in Figure 1. Characteristic types of force versus displacement records obtained in fracture toughness tests are shown in Figure 2.

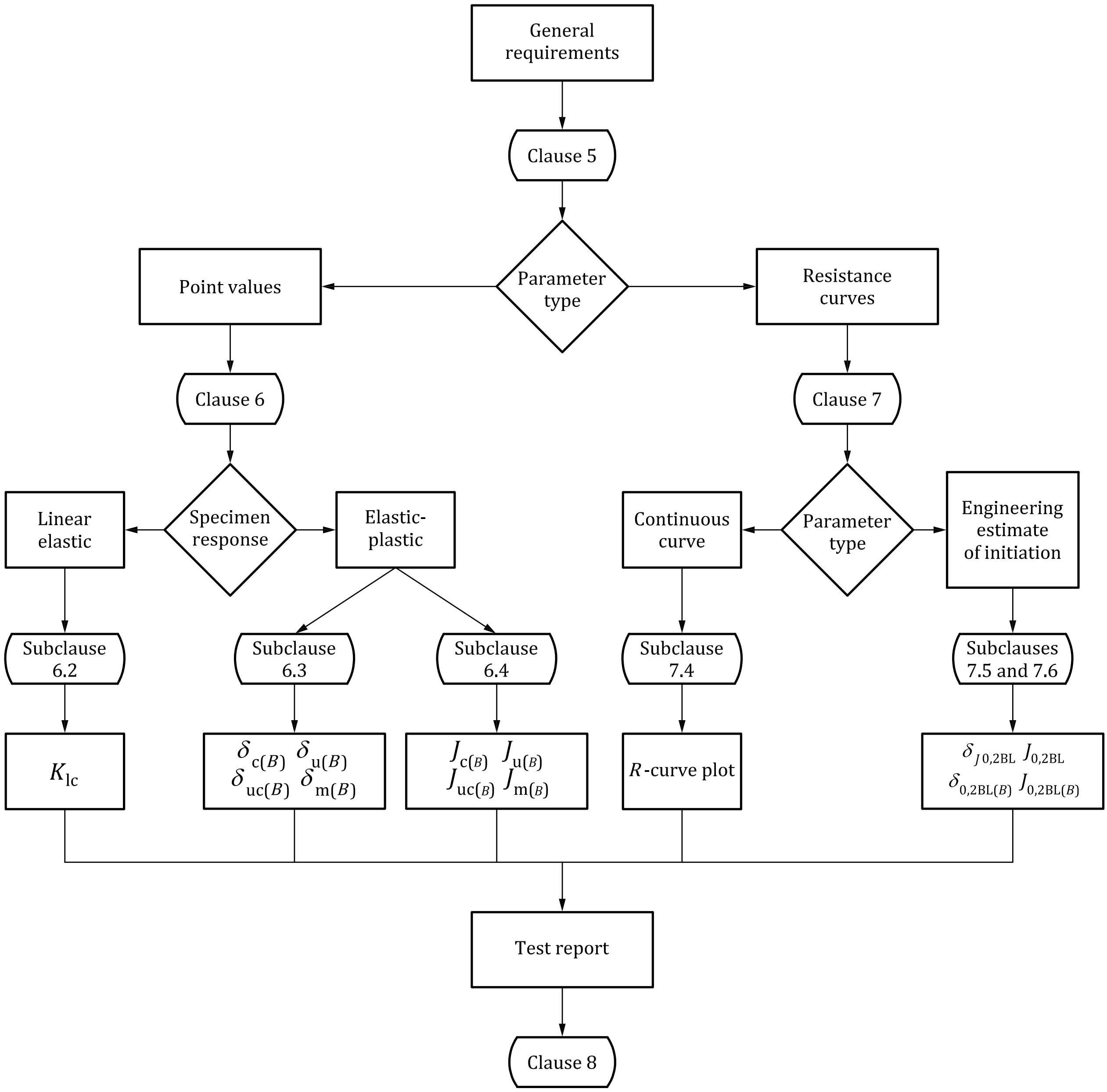
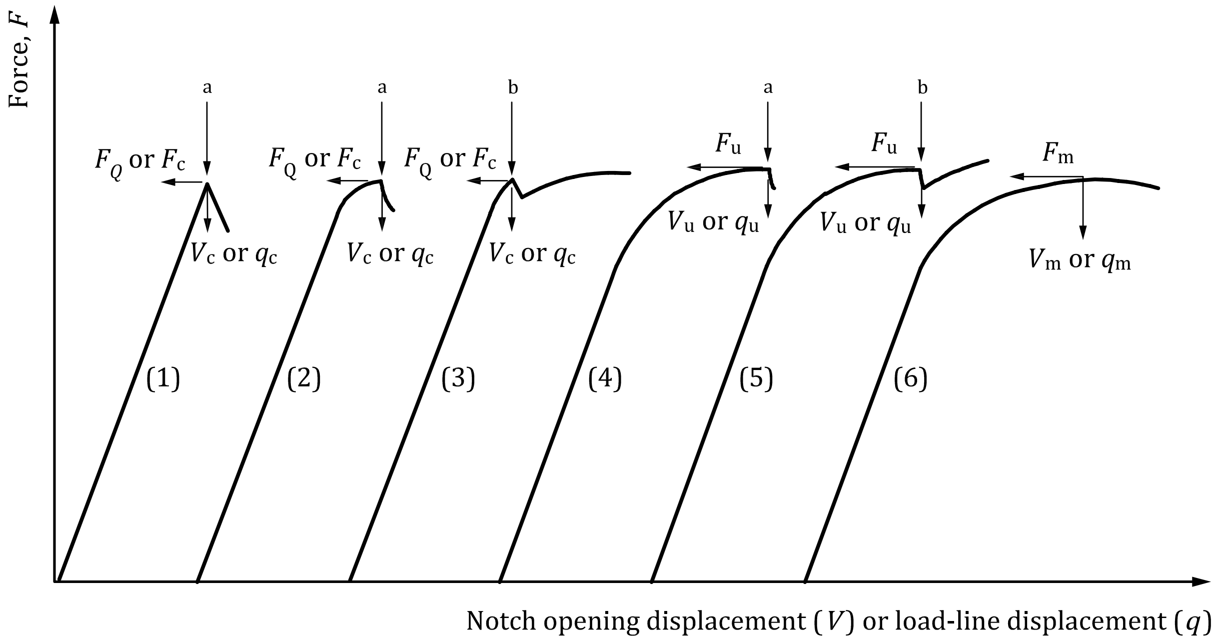


Figure 1 — General flowchart showing how to use the standard method of test



Key

a Fracture.

b Pop-in.

NOTE 1 F_c, F_u and F_m correspond to either δ_c, δ_u and δ_m respectively, or J_c, J_u and J_m respectively.

NOTE 2 Pop-in behaviour is a function of the testing machine/specimen compliance and the recorder response rate.

Figure 2 — Characteristics types of force versus displacement records in fracture tests

5.2 Fracture parameters

Specific (point) values of fracture toughness are determined from individual specimens to define the onset of unstable crack extension or describe stable crack extension.

NOTE K_{Ic} characterizes the resistance to extension of a sharp crack so that i) the state of stress near the crack front closely approximates plane strain, and ii) the crack tip plastic zone is small compared with the specimen crack size, thickness and ligament ahead of the crack.

K_{Ic} is considered a size-insensitive measurement of fracture toughness under the above conditions. Certain test criteria shall be met in order to qualify measurements of K_{Ic}.

The parameters δ_c, J_c, δ_u, J_u, δ_{uc} and J_{uc} also characterize the resistance of a material to unstable extension of a sharp crack. However, these measurements are regarded as size-sensitive and as such characterize only the specimen thickness tested. The specimen thickness is thus noted in millimetre units in parentheses appended to the parameter symbol when reporting a test result.

When stable crack extension is extensive, test procedure and fracture toughness measurement shall be performed as specified in Clause 7. Stable crack extension is characterized either in terms of crack tip opening displacement $\delta_{J0,2BL}$ and fracture toughness $J_{0,2BL}$ parameters, or of a continuous δ_J- and J-resistance curve. The values $\delta_{J0,2BL}$ and $J_{0,2BL}$, regarded as specimen size insensitive, are engineering estimates of the onset of stable crack extension, not to be confused with the actual initiation toughness δ_{Ji} and J_i. Measurement of δ_{Ji} and J_i is described in Annex A.

Two procedures are available for determining $\delta_{0,2BL}$ and $J_{0,2BL}$. The multiple specimen procedure requires several nominally identical specimens to be monotonically loaded, each to different amounts of displacement. Measurements of force and displacement are made and recorded. Specimen crack fronts are marked (e.g. by heat tinting or post-test fatiguing) after testing, thus enabling measurement of stable crack extension on the specimen halves after each specimen is broken open. Post-test cooling of ferritic material specimens to ensure brittle behaviour may be helpful in preserving crack front markings prior to breaking open the specimens.

A minimum of six specimens is required by the multiple-specimen method. When material availability is limited, a single-specimen procedure based on either unloading compliance or the potential drop technique may be used. There is no restriction on the single-specimen procedure providing sufficient accuracy can be demonstrated. In all cases, certain criteria are to be met before $\delta_{J0,2BL}$ or $J_{0,2BL}$ values and δ_J- or J-resistance curves are qualified by this standard method of test.

5.3 Fracture toughness symbols

Fracture toughness symbols identified in this document are given in Table 2.

Table 2 — Fracture toughness symbols

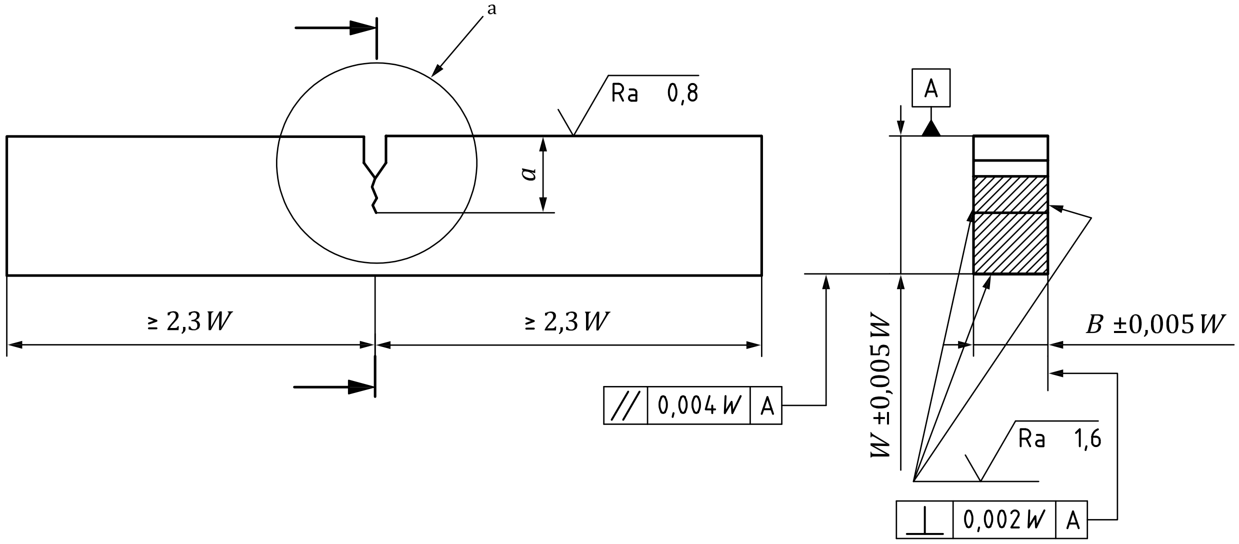
Parameter	**Size insensitive quantities**	**Size sensitive quantities** (specific to thickness B tested)	**Qualifying limits to R-curves**
K	K_{Ic} $K_{J0,2BL}$		
δ, δ_J	δ_{Ji} $\delta_{J0,2BL}$	$\delta_{c(B)}$ $\delta_{J0,2BL(B)}$ $\delta_{u(B)}$, $\delta_{uc(B)}$, $\delta_{m(B)}$	$\delta_{J,g}$, $\delta_{J,g}(\Delta a_{max})$
J	J_i $J_{0,2BL}$	$J_{c(B)}$ $J_{0,2BL(B)}$ $J_{u(B)}$, $J_{uc(B)}$, $J_{m(B)}$	J_g, $J_g(\Delta a_{max})$

5.4 Test specimens

5.4.1 Specimen configuration and size

Dimensions and tolerances of specimens shall conform to Figures 3 to 5.

Surface roughness values in micrometres



Key

a See Figures 6 to 8 and 5.4.2.3.

NOTE 1 Integral or attachable knife edges for clip gauge attachment may be used (see Figures 8 and 9).

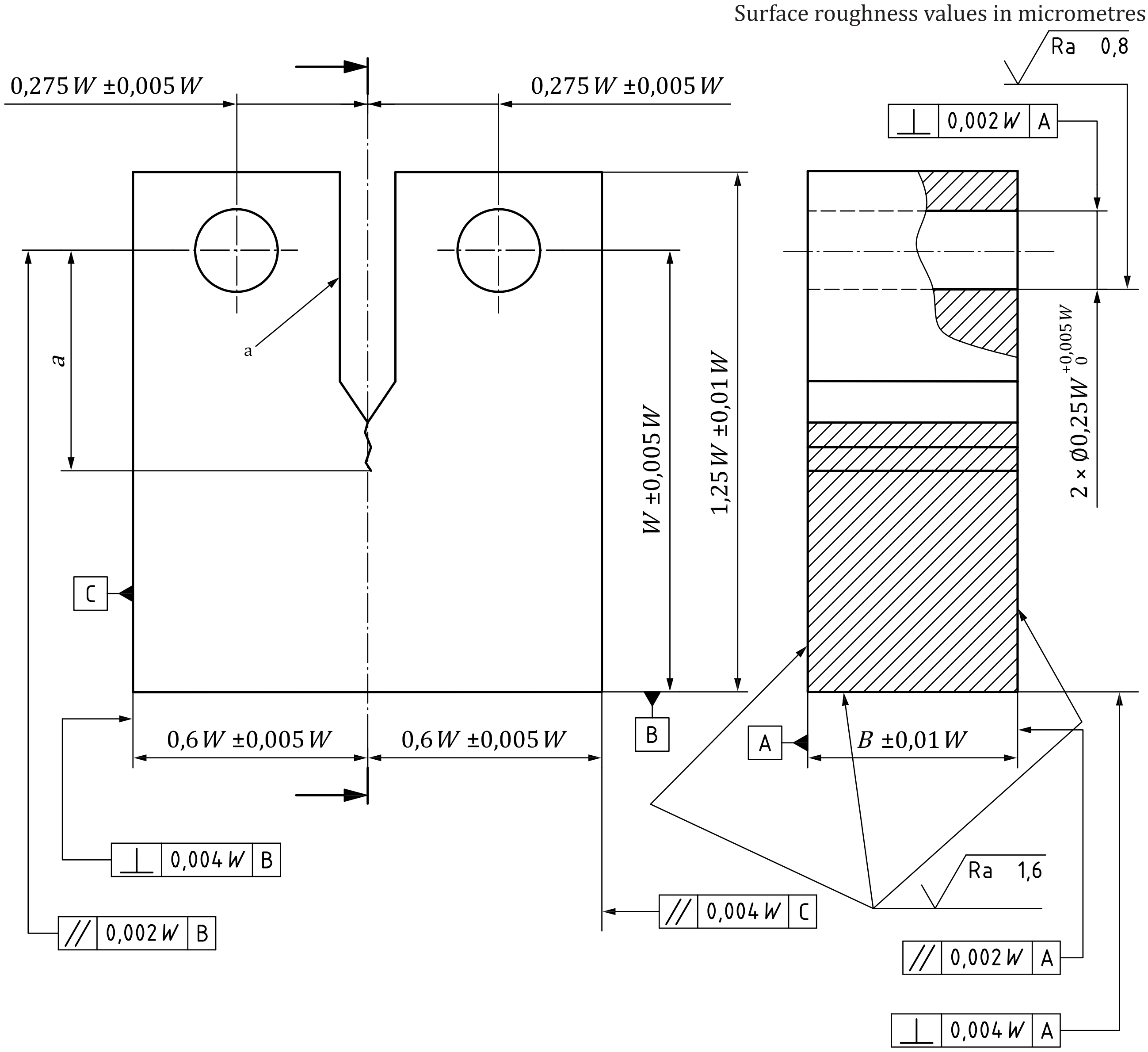
NOTE 2 For starter notch and fatigue crack configuration, see Figure 6.

NOTE 3 1,0 ≤ W/B ≤ 4,0 (W/B = 2 preferred).

NOTE 4 0,45 ≤ a/W ≤ 0,70. For K_{Ic} determination, 0,45 ≤ a/W ≤ 0,55.

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

Figure 3 — Proportional dimensions and tolerances for bend specimen



Key

a See Figures 6 to 8 and 5.4.2.3.

NOTE 1 Integral or attachable knife edges for clip gauge attachment may be used (see Figures 8 and 9).

NOTE 2 For starter notch and fatigue crack configuration, see Figure 6.

NOTE 3 $0{,}8 \le W/B \le 4{,}0$ ($W/B = 2$ preferred).

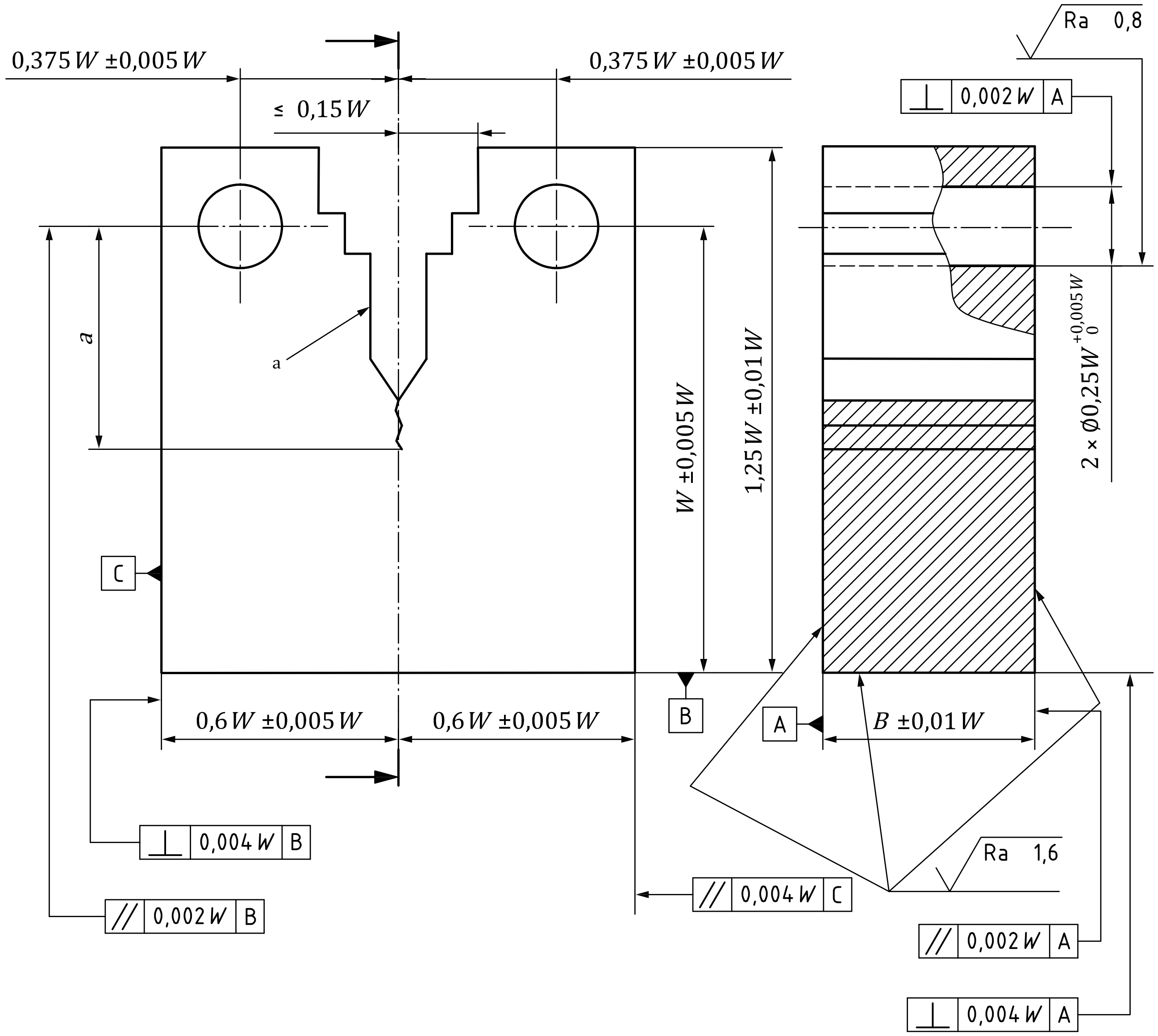
NOTE 4 $0{,}45 \le a/W \le 0{,}70$. For K_{Ic} determination, $0{,}45 \le a/W \le 0{,}55$.

NOTE 5 Alternative pin hole diameter, $\varnothing\ 0{,}188\ W\ ^{+0{,}004\ W}_{0}$.

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

Figure 4 — Proportional dimensions and tolerances for straight-notch compact specimen

Surface roughness values in micrometres



Key

a See Figures 6 to 8.

NOTE 1 Integral or attachable knife edges for clip gauge attachment may be used (see Figures 8 and 9).

NOTE 2 For starter notch and fatigue crack configuration, see Figure 6.

NOTE 3 $0,8 \le W/B \le 4,0$ ($W/B = 2$ preferred).

NOTE 4 $0,45 \le a/W \le 0,70$. For K_{Ic} determination, $0,45 \le a/W \le 0,55$.

NOTE 5 Second step may not be necessary for some clip gauges; configuration optional providing fatigue crack starter notch and fatigue crack fit within the envelope represented in Figure 6.

NOTE 6 Alternative pin hole diameter, $\emptyset\ 0,188\ W\ {}^{+0,004\ W}_{0}$. When this pin size in used, notch opening may be increased to 0,21 *W* maximum.

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

Figure 5 — Proportional dimensions and tolerances for stepped-notch compact specimen

The choice of specimen design shall take into consideration the likely outcome of the test (see Figure 1), any preference for δ or J fracture toughness values, the crack plane orientation of interest (Annex B) and the quantity and condition of test material available.

NOTE 1 All specimen designs (Figures 3 to 5) are suitable for determining K_{Ic}, δ and J values, although there are special procedural requirements for J values calculated from measurements made away from the load line. Table 3 provides guidance on specimen size for K_{Ic} measurement.

Table 3 — Minimum recommended thickness for K_{Ic} testing

$\frac{R_{p0,2}}{E}$	B mm
≥0,005 0 <0,005 7	75
≥0,005 7 <0,006 2	63
≥0,006 2 <0,006 5	50
≥0,006 5 <0,006 8	44
≥0,006 8 <0,007 1	38
≥0,007 1 <0,007 5	32
≥0,007 5 <0,008 0	25
≥0,008 0 <0,008 5	20
≥0,008 5 <0,010 0	13
≥0,010 0	7

NOTE 2 When notch opening displacement V is measured on the load line, $V = q$ for the stepped-notch compact specimen (see Figure 5). The stepped-notch specimen is thus equally useful for the determination of values of K_{Ic}, δ and J.

NOTE 3 For both the bend and compact configurations, a specimen width-to-thickness ratio (W/B) of 2 is preferred, but values ranging from 1 to 4 for bend specimens and 0,8 to 4 for compact specimens are allowed. Evidence suggests that specimen proportions of $W/B = 4$ yield slightly higher R-curves than the lesser proportions of $W/B = 2$.

5.4.2 Specimen preparation

5.4.2.1 Material condition

Specimens shall be machined from material in the final heat treated and/or mechanically worked condition.

NOTE 1 In the exceptional circumstance where a material cannot be machined in its final heat treated condition, such final heat treatment may be carried out after machining provided that the specimen's required dimensions and tolerances, shape, and surface finishes are met, and full account is taken of the effects of specimen dimensions on the metallurgical condition induced by certain heat treatments, for example, water quenching of steels.

NOTE 2 Residual stresses can influence the measurement of quasistatic fracture toughness. The effect can be significant when test coupons are taken from material that characteristically embodies residual stress fields; e.g. weldments, complex shapes, such as die forgings, stepped extrusions, castings where full stress relief is not possible, or parts with intentionally-induced residual stresses. Specimens taken from such products that contain residual stresses will likewise themselves contain residual stress. While extraction of the specimen in itself partially relieves and redistributes the pattern of residual stress, the remaining magnitude can affect the test result. Residual stress is superimposed on applied stress and results in actual crack-tip stress intensity that is different from that based solely on externally applied forces or displacements. Distortion during specimen machining, specimen configuration dependence, and irregular crack extension during fatigue precracking (such as excessive crack front curvature or out-of-plane growth) will often indicate influential residual stresses. Crack-mouth-opening displacement at zero applied force (crack closure effect) is indicative of residual stresses that can affect the subsequent fracture toughness measurement. Methods for dealing with residual stresses in samples taken from weldments are described in ISO 15653.

5.4.2.2 Crack plane orientation

The orientation of the crack plane shall be

— decided before machining,

— identified in accordance with the coordinate systems in Annex B and ISO 3785,

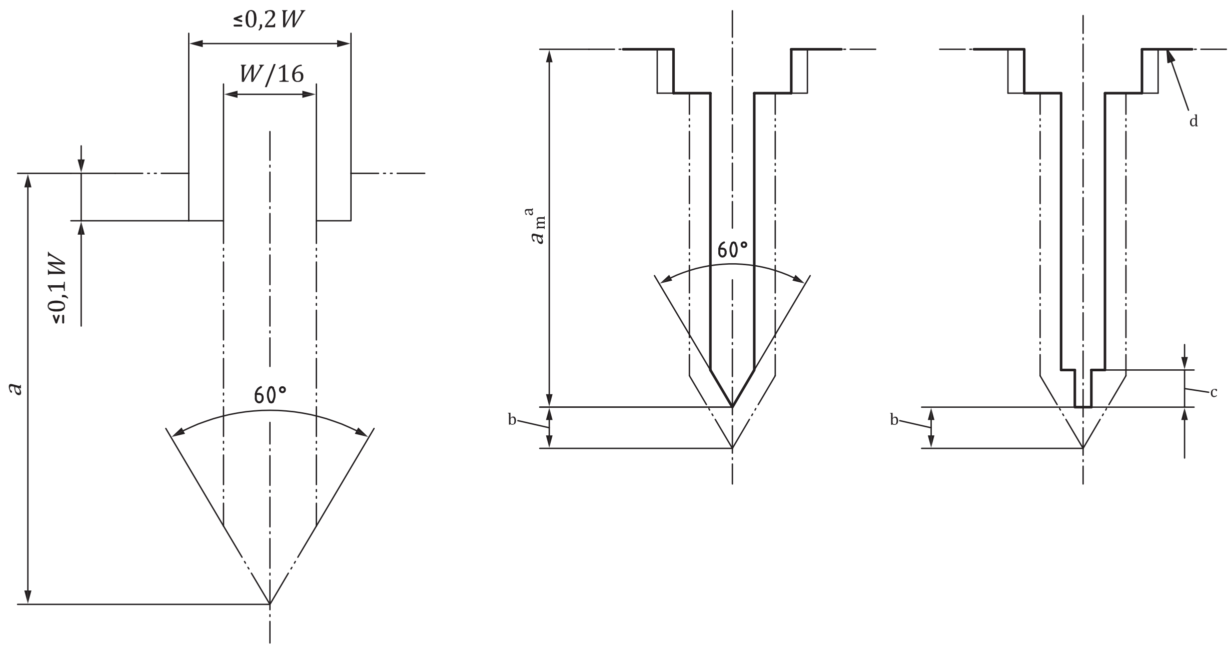
— then recorded along with other specimen and material information. An example test report is provided in C.1.

NOTE Fracture toughness values depend on crack plane orientation and direction of crack extension in relation to the principal directions of mechanical working, grain flow and other anisotropy.

5.4.2.3 Machining

a) The specimen notch profile shall not exceed the envelope shown in Figure 6. The root radius of a milled notch shall not be greater than 0,10 mm. Sawn, disk ground, or spark-eroded notches shall not have a width (at the tip) greater than 0,30 mm (Figure 6). The plane of the specimen notch shall be perpendicular to the specimen surfaces to within 2°.

(not to scale)



a) Envelope **b) Notch geometries**

Key

a Machined notch.

b Fatigue precrack.

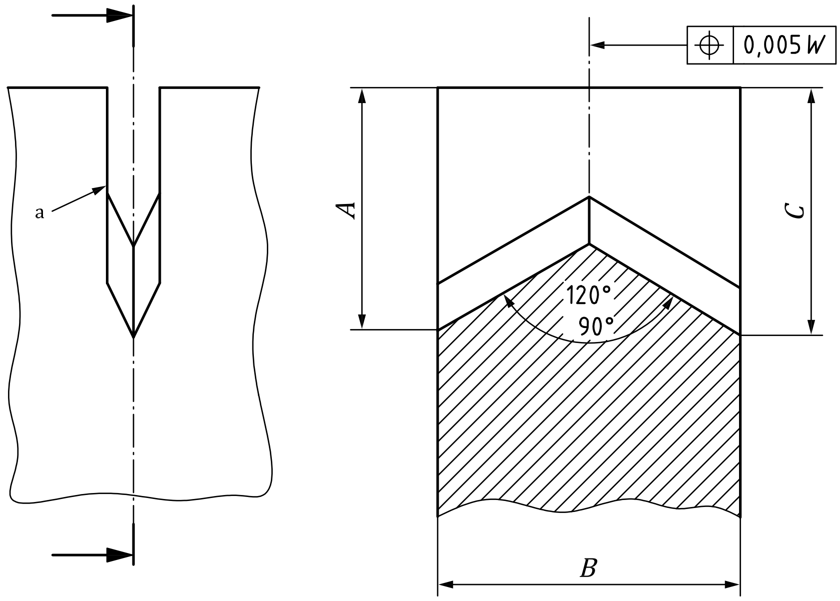
c Spark eroded or machined slit.

d Edge of bend specimen or load-line of compact specimen.

If fatigue crack initiation and/or propagation are a problem, a chevron notch configuration as shown in Figure 7 may be used.

Figure 6 — Acceptable fatigue crack envelope and crack starter notches (see **Figures 7** and **8**)

Dimensions in millimetres



Key

a See Figure 6.

NOTE 1 $A = C \pm 0{,}010\ W$.

NOTE 2 Cutter tip angle 90° maximum.

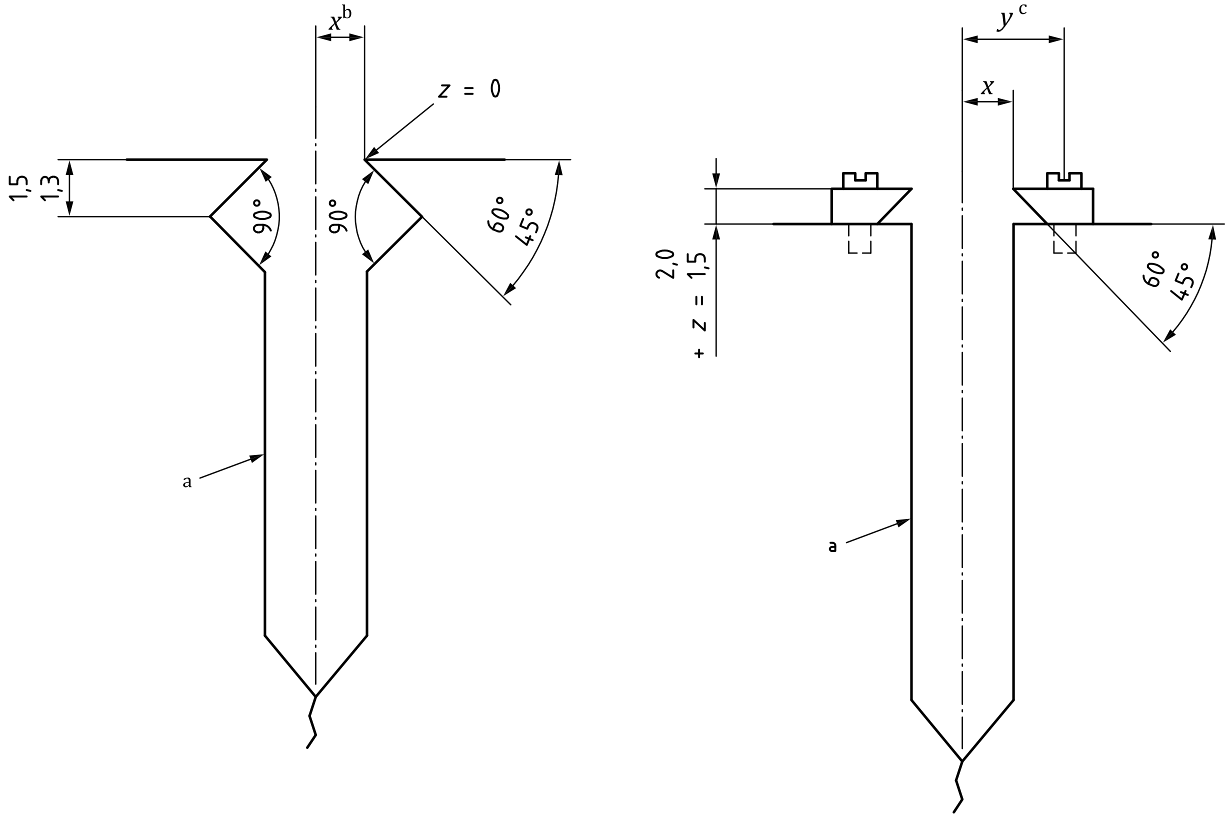
NOTE 3 For the purposes of 8.2.2, a_m is the greater of A and C.

Chevron notch root radii shall not exceed 0,25 mm.

Figure 7 — Chevron notch

b) Specimen knife edges may be integral or attached. Suitable designs are shown in Figures 8 and 9. The dimension $2x$ in Figures 8 and 9 shall be within the working range of the notch opening displacement gauge, and the knife edges shall be square with the specimen surfaces and parallel to each other to within 0,5°. For both types, the notch opening displacement gauge shall be free to rotate about the points of contact between the gauge and knife edge. Consequently, when inward-pointing knife edges or stiff razor blades are used, it may be necessary to use an enlarged notch mouth as shown in Figures 5, 6 and 9. The use of a knife edge/clip gauge for displacement measurement does not preclude the use of other schemes providing they meet the requirements and accuracy of this method. When side grooves are used (see 5.4.2.5), it is recommended that the side grooving be carried out after fatigue precracking.

Dimensions in millimetres



a) Integral type **b) Attached type**

Key

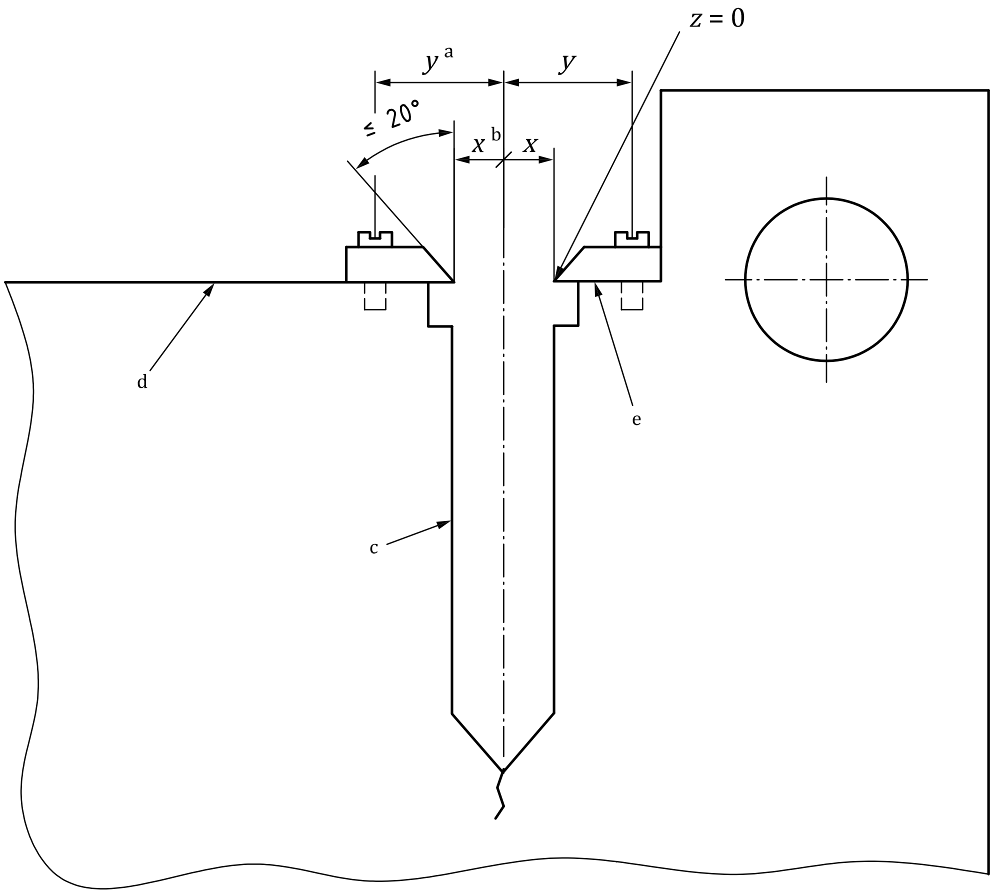
a See Figure 6.

b 2x, see 5.4.2.3 b).

c 2y + screw thread diameter ≤W/2.

NOTE If the knife edges are glued or similarly attached to the edges of the specimen, 2y = distance between extreme points of attachment.

Figure 8 — Outward pointing knife edges and corresponding notch geometries



Key

a 2y + screw thread diameter ≤W/2.

b 2x, see 5.4.2.3 b).

c See Figures 6 and 7.

d Edge of bend or straight compact specimen.

e Load-line stepped compact.

NOTE 1 If the knife edges are glued or similarly attached to the edges of the specimen, 2y = distance between extreme points of attachment.

NOTE 2 If razor blades are used instead of inward pointing knife edges, the displacement will normally be measured at a point half the razor blade thickness above the load line (see 5.5.1).

Figure 9 — Inward-pointing attached knife edges and corresponding notch geometries
(see **Figure 8**)

5.4.2.4 Fatigue precracking

5.4.2.4.1 General

Fatigue precracking shall be performed on specimens machined from material in its finally 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.

The 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 5.5.1 shall be recorded and used to determine the maximum fatigue precracking force F_f in accordance with 5.4.2.4.3 and 5.4.2.4.4.

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

5.4.2.4.2 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.

5.4.2.4.3 Bend specimens

For three-point bend specimens, the maximum fatigue precracking force during the final 1,3 mm or 50 % of precrack extension, whichever is less, shall be the lower between Formula (1):

$$F_f = 0,8 \cdot \frac{B\left(W - a_o\right)^2}{S} \cdot R_{p0,2} \tag{1}$$

where $R_{p0,2}$ is the yield strength at the test temperature or the precracking temperature, whichever is the lower yield strength, and Formula (2):

$$F_f = \xi E \cdot \frac{\left(W \times B \times B_N\right)^{0,5}}{g_1\left(\frac{a_o}{W}\right)} \cdot \frac{W}{S} \cdot \frac{\left(R_{p0,2}\right)_P}{\left(R_{p0,2}\right)_t} \tag{2}$$

where $\xi = 1,6 \times 10^{-4} m^{1/2}$, $\left(R_{p0,2}\right)_P$ and $\left(R_{p0,2}\right)_t$ are the yield strengths at the precracking and test temperatures, respectively, and E is the modulus of elasticity at the test temperature or the precracking temperature, whichever is lower.

NOTE 1 For plain-sided specimens, $B_N = B$.

NOTE 2 Values of $g_1(a_o/W)$ are given in Annex D.

NOTE 3 Additional fatigue precracking requirements are necessary when determining K_{Ic}, see 6.2.4.

5.4.2.4.4 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 lower between Formula (3):

$$F_{\mathrm{f}} = 0,6 \cdot \frac{B\left(W - a_{\mathrm{o}}\right)^2}{2W + a_{\mathrm{o}}} \cdot R_{\mathrm{p0,2}} \tag{3}$$

where $R_{\mathrm{p0,2}}$ is the yield strength at the test temperature or the precracking temperature, whichever is the lower yield strength, and Formula (4):

$$F_{\mathrm{f}} = \xi E \cdot \frac{\left(W \times B \times B_{\mathrm{N}}\right)^{0,5}}{g_2\left(\frac{a_{\mathrm{o}}}{W}\right)} \cdot \frac{\left(R_{\mathrm{p0,2}}\right)_{\mathrm{P}}}{\left(R_{\mathrm{p0,2}}\right)_{\mathrm{t}}} \tag{4}$$

where $\xi = 1,6 \times 10^{-4} \mathrm{m}^{1/2}$, $\left(R_{\mathrm{p0,2}}\right)_{\mathrm{p}}$ and $\left(R_{\mathrm{p0,2}}\right)_{\mathrm{t}}$ are the yield strengths at the precracking and test temperatures, respectively, and E is the modulus of elasticity at the test temperature or the precracking temperature, whichever is lower.

NOTE 1 For plain-sided specimens, $B_{\mathrm{N}} = B$.

NOTE 2 Values of $g_2(a_{\mathrm{o}}/W)$ are given in Annex D.

NOTE 3 Additional fatigue precracking requirements are necessary when determining K_{Ic}, see 6.2.4.

5.4.2.5 Side grooving

Specimens for determination of point measurements of fracture toughness (e.g. K_{Ic}, δ_{c}, J_{c}) may be plain-sided or side-grooved. All specimens for R-curve testing shall be side grooved. Side grooves shall have equal depths and an included angle of 30° to 90° with a root radius of (0,4 ± 0,2) mm. The depth of side grooving, B - B_{N}, shall be 0,2B ± 1 %. Side grooving shall be performed after fatigue precracking except for the case described in Note 2.

NOTE 1 With respect to fully plastic stable crack extension, side grooving of specimens may lower and flatten the R-curve compared to plain-sided specimens of the same nominal dimensions.

NOTE 2 As an aid to precracking some materials, shallow (i.e. less than 5 %) side grooves are allowed prior to fatigue precracking. After fatiguing, these side grooves are to be extended to their full depths.

It is recommended that side grooves with an included angle of 90° be used for austenitic steel specimens because of the large displacements that can occur at the back face of the specimens, producing partial, or complete closure of the side grooves.

5.5 Pre-test requirements

5.5.1 Pre-test measurements

Dimensions of specimens shall conform to Figures 3 to 5. Measurement of thicknesses B and B_{N}, and width W shall be accurate to within ±0,02 mm or ±0,2 %, whichever is larger.

The 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. For side-grooved specimens, the specimen net thickness shall be measured between the side grooves at a minimum of three equally-spaced positions along the crack extension path. The average of these three measurements shall be taken as the net section thickness B_{N}.

Specimen width W shall be measured at a minimum of three equally-spaced positions across the specimen thickness on a line no further than 10 % of the nominal width away from the crack plane. The average of these measurements shall be taken as the width W. When straight-notch compact specimens are used, the dimension from specimen front face to back face (i.e. 1,25 W) shall be measured.

When attached knife edges are used as shown in Figure 8 b), the knife edge thickness z shall be measured. If razor blades are used as knife edges, the half thickness of these shall be taken as the dimension z.

NOTE When integral or attached knife edges are used as shown in Figures 8 a) and 9, the dimension z is equal to zero.

5.5.2 Crack shape/length requirements

A fatigue crack shall be developed from the root of the machined notch of the specimen as follows. For all designs of specimen (see Figures 3 to 5), the ratio a_0/W shall be in the range of 0,45 to 0,70, except for K_{Ic} determination, when a_0/W shall be in the range of 0,45 to 0,55. 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 6.

5.6 Test apparatus

5.6.1 Calibration

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

5.6.2 Force application

The combination of force sensing and recording devices shall conform to ISO 7500-1.

The test machine shall operate at a constant displacement rate.

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

$$F_L = \frac{4}{3} \cdot \frac{B\left(W - a_o\right)^2}{S} \cdot R_m \text{ for bend specimens} \tag{5}$$

and

$$F_L = \frac{B\left(W - a_o\right)^2}{2W + a_o} \cdot R_m \text{ for compact specimens} \tag{6}$$

5.6.3 Displacement measurement

The displacement gauge shall have an electrical output that represents notch-opening displacement V between two precisely located gauge positions spanning the notch mouth. The design of displacement gauge (or transducer where appropriate), knife edges and specimen shall allow free rotation of the points of contact between the gauge and knife edges.

NOTE 1 Examples of two proven displacement gauge designs are given in References [3], [4] and [5], and similar gauges are commercially available.

NOTE 2 Measurement of load-line (i.e. load-point) displacement q (see 5.7.1.3) is described in Annex E.

Displacement gauges for mouth-opening displacement and load-line displacement shall be calibrated in accordance with ISO 9513, as interpreted in relation to this method, and shall be of at least Class 1; however, calibration shall be performed at least weekly when the gauges are in use.

More frequent verification may be required depending on use and agreement between contractual parties.

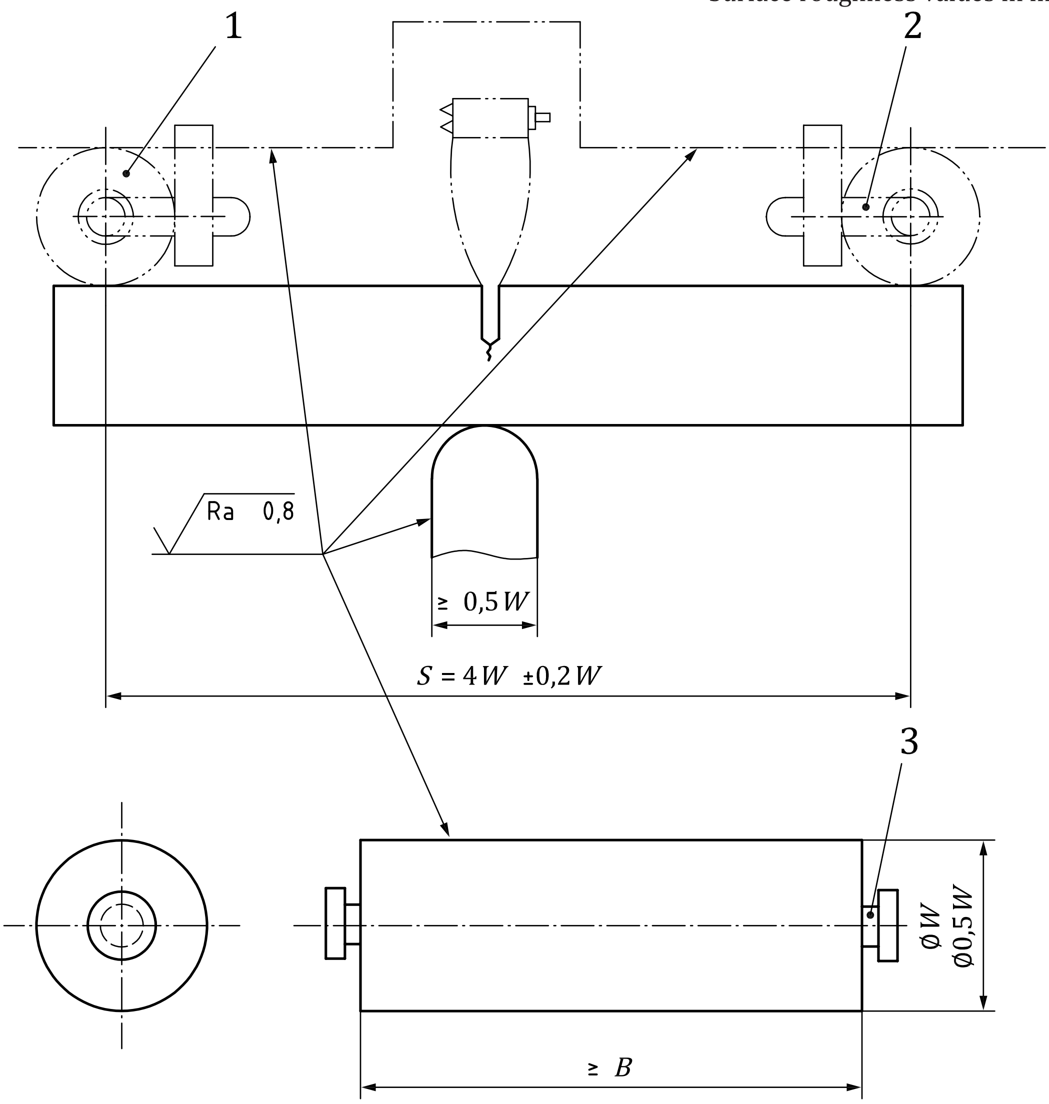
Verification of the displacement gauge shall be performed at the test temperature ±5 °C, unless the temperature of the gauge is different from the temperature of the specimen during the test. In this latter case, the verification of the displacement gauge shall be performed at the temperature at which it is used ±5 °C. The response of the gauge shall be true to ±0,003 mm for displacements up to 0,3 mm, and ±1 % thereafter.

5.6.4 Test fixtures

Three-point bend specimens shall be tested using a loading fixture designed to minimize friction by allowing the rollers to move outwards during loading (see Figure 10). Roller diameters shall be between W and $W/2$.

Loading fixture bearing surfaces shall have a hardness greater than 40 HRC (400 HV) or a yield strength of at least 1 000 MPa.

Surface roughness values in micrometres



Roller details

Key

1 roller

2 rubber band or spring

3 bosses for rubber bands or springs

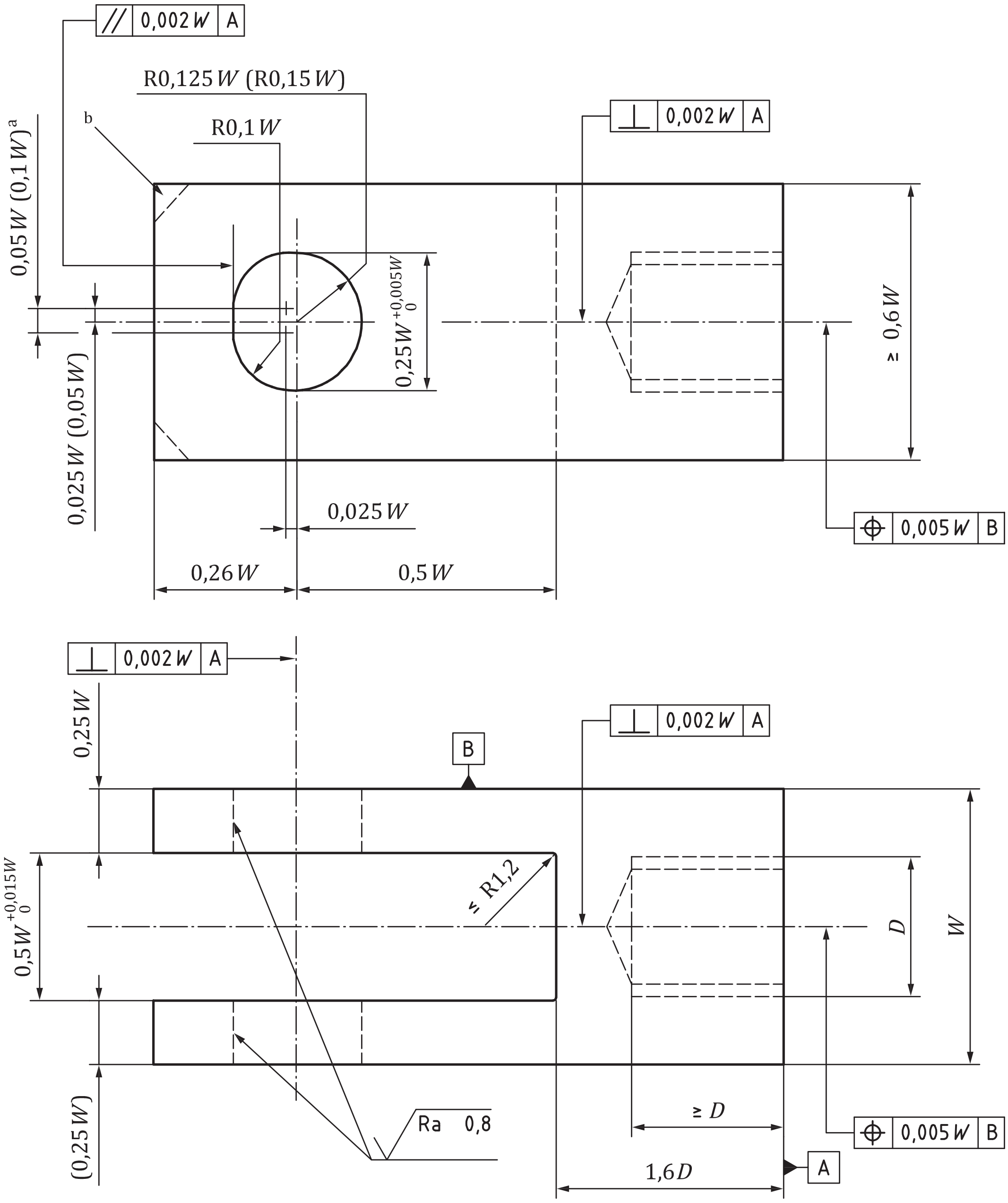
NOTE Fixture and roller pin hardness ≥40 HRC.

Roller pins and specimen contact surface of loading ram have to be parallel to each other to ±0,002 *W*.

Figure 10 — Fixture for three-point bend tests

Compact specimens shall be loaded using a clevis and pin arrangement designed to minimize friction. The arrangement shall ensure alignment as the specimen is loaded in tension. Clevises for resistance-curve measurements shall have flat-bottomed holes (see Figure 11) so that the loading pins are free to roll throughout the test. Round-bottomed holes (see Figure 12) shall not be allowed for single specimen (unloading compliance) tests.

Dimensions in millimetres,
surface roughness values in micrometres



Key

a Loading flat.

b Corners of clevis may be removed if necessary to accommodate clip gauge.

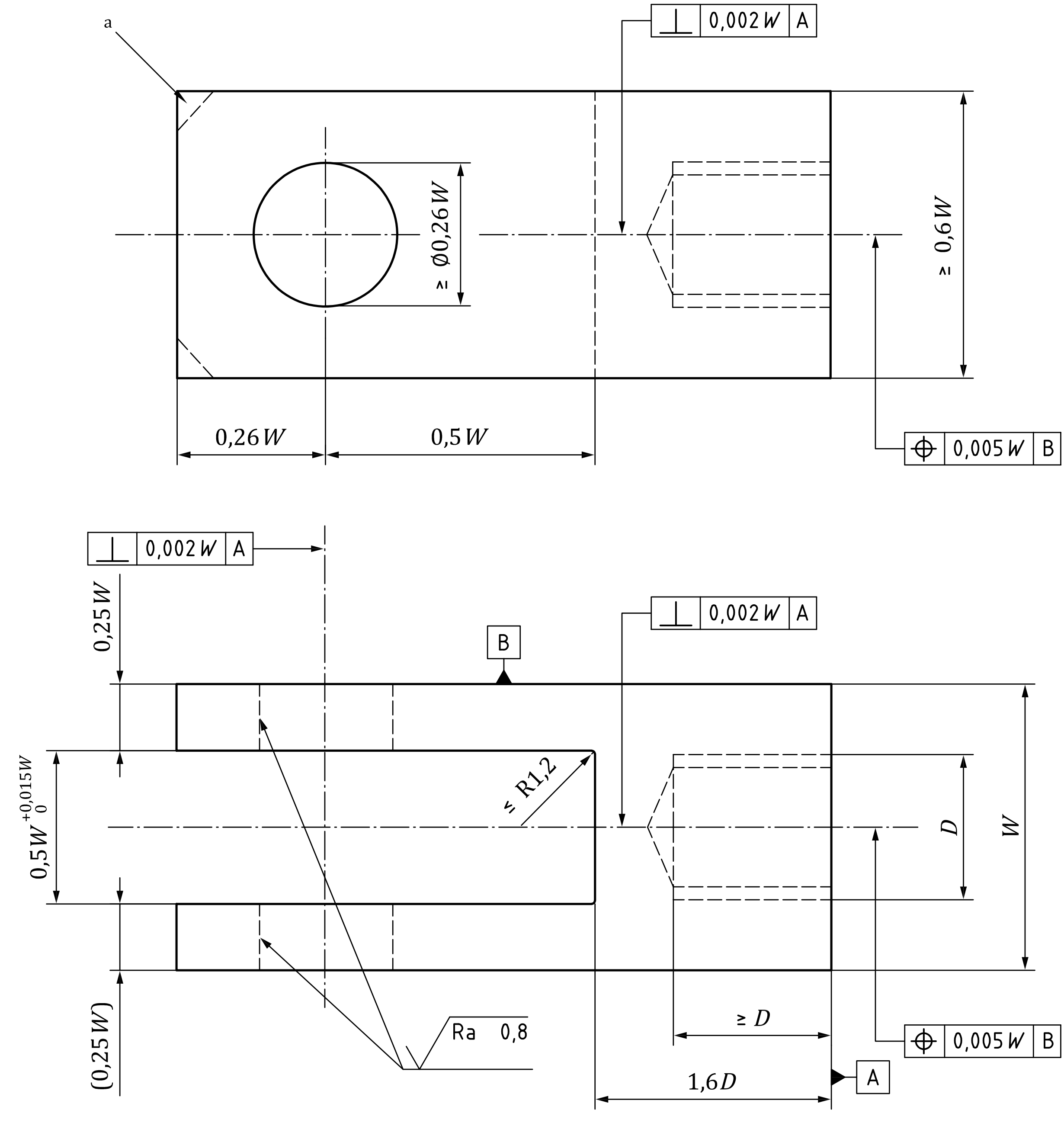
NOTE 1 Pin diameter = $0,24\ W\ {}^{0}_{-0,005\ W}$.

NOTE 2 Clevis and pin hardness ≥40 HRC.

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

Figure 11 — Typical design of compact specimen clevis employing a flat hole to accommodate load-pin

Dimensions in millimetres,
surface roughness values in micrometres



Key

a Corners of clevis may be removed if necessary to accommodate clip gauge.

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

NOTE 2 Clevis and pin hardness ≥40 HRC.

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

Figure 12 — Typical design of compact specimen loading clevis with oversized circular loading pin hole

5.7 Test requirements

5.7.1 Three-point bend testing

5.7.1.1 Specimen fixture alignment

The loading fixture shall be aligned so that the line of action of the applied force passes midway between roller centres within 1 % of the distance between these centres. The span S shall be 4 W ± 1 %. Roller axes shall be parallel to ±1°. The specimen shall be positioned with its crack tip midway between the rollers to ±1 % S, and the crack plane parallel to the roller axes to within ±2°.

5.7.1.2 Crack-tip opening displacement

Crack-tip opening displacement δ is evaluated from notch-opening displacement V or from J.

5.7.1.3 Load-line displacement

Load-line displacement q is used for the determination of J.

NOTE Suitable methods for measuring load-line displacement directly or indirectly are described in Annex E.

5.7.2 Compact tension testing

5.7.2.1 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 to within 0,75 mm with respect to the clevis opening, and at the distance (z) on the front face of straight-notch bend specimens.

5.7.2.2 Crack-tip opening displacement

Crack-tip opening displacement δ is evaluated from notch-opening displacement V. Notch-opening displacement V is measured at the load line of stepped-notch compact specimens, and at the distance (z + 0,25 W) from the load-line on the front face of straight-notch compact specimens.

5.7.2.3 Load-line displacement

The parameter J is evaluated from load-line displacement q. For tests using the stepped-notch compact specimen shown in Figure 5 with integral or inward pointing attached knife edges (Figures 8 and 9 respectively), the displacement gauge shall be securely seated in the knife edges on the load line of the specimen.

NOTE The straight-notch (not stepped-notch) compact specimen does not permit direct measurement of load-line displacement q. However, derivation of q from V is permitted provided that it can be demonstrated that q so derived would be equivalent to directly measured q.

5.7.3 Specimen test temperature

The 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 no further than 5 mm from the crack tip. 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 described in Clause 8.

5.7.4 Recording

Force and corresponding displacement outputs shall be recorded. For analogue recording, the initial slope of the force versus displacement record shall lie between 0,85 and 1,15.

NOTE Nonlinearity often occurs at the beginning of a test record. It is advisable to minimize this nonlinearity by preliminarily loading and unloading the specimen to a force not exceeding the maximum fatigue precracking force, F_f.

5.7.5 Testing rates

Tests shall be carried out under notch-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 MPa $m^{0,5}$ s^{-1} and 3 MPa $m^{0,5}$ s^{-1}. For each series of tests, all specimens shall be loaded at the same nominal rate.

5.7.6 Test analyses

Analyses for point determinations of fracture toughness are given in Clause 6, and those for resistance-curve determinations in Clause 7 (see Figure 1).

5.8 Post-test crack measurements

5.8.1 General

The specimen shall be broken open after testing and its fracture surface examined in order to determine the original crack length a_0, and any stable crack extension Δa that may have occurred during the test.

For some tests, it may be necessary to mark the extent of stable crack extension before opening the specimen. Stable crack extension may be marked by heat tinting or by post-test fatiguing. Care is to be taken to minimize post-test specimen deformation. Cooling ferritic materials may help to ensure brittle behaviour during specimen opening.

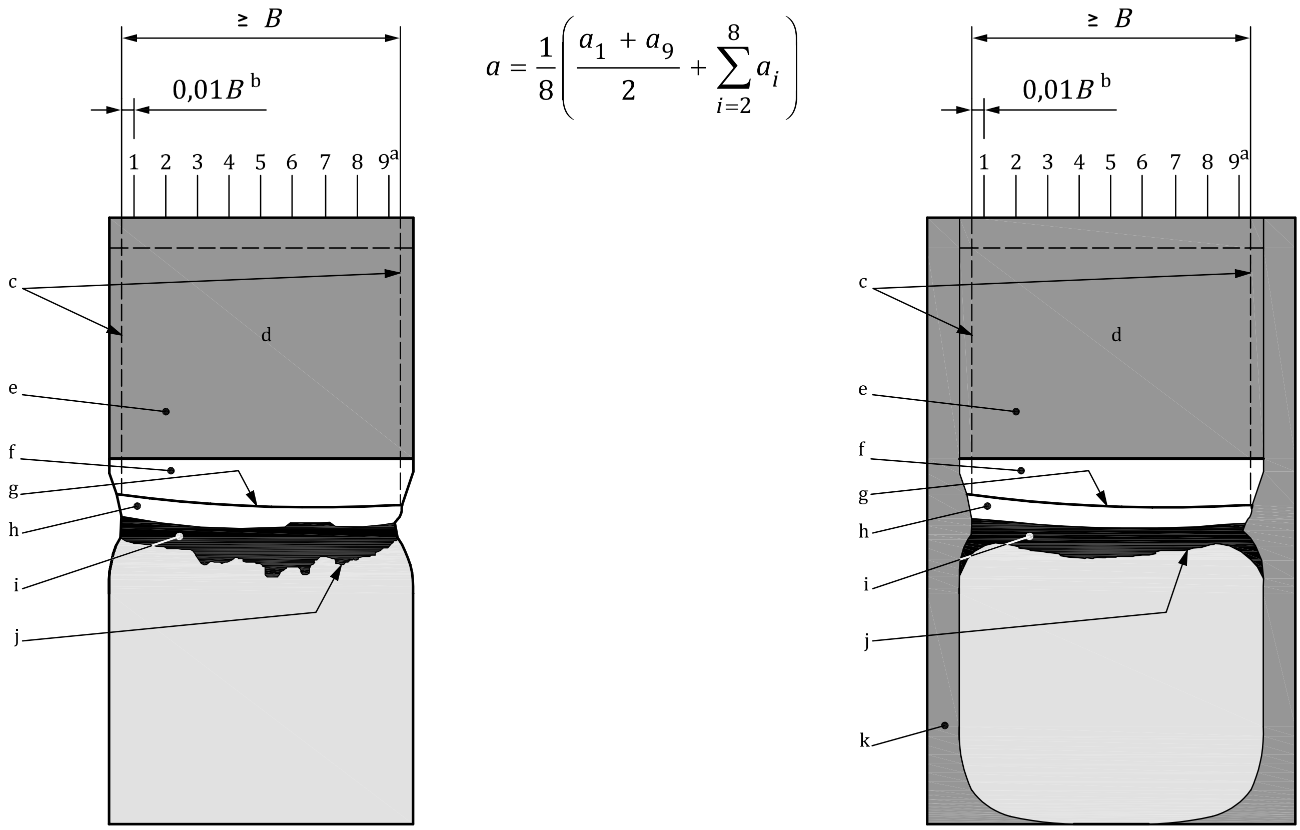
NOTE The reference method for crack length measurement, described below, is the nine point average method. However, the area average method has also been successfully used, and when coupled with digital image processing can provide more accurate crack length estimates.

5.8.2 Initial crack length, a_0

Initial crack length a_0 is measured to the tip of the fatigue crack with an instrument accurate to ±0,1 % or 0,025 mm, whichever is greater. Nine measurements shall be made as indicated in Figures 13 and 14. The value of a_0 is obtained by first averaging the two surface measurements made at positions 0,01 B inward from the surface (or, in the case of side-grooved specimens, from the side-groove roots), and then averaging these values with the sum of the seven equispaced inner measurements:

$$a_0 = \frac{1}{8}\left[\left(\frac{a_1 + a_9}{2}\right) + \sum_{j=2}^{j=8} a_j\right] \quad (7)$$

$$a = \frac{1}{8}\left(\frac{a_1 + a_9}{2} + \sum_{i=2}^{8} a_i\right)$$

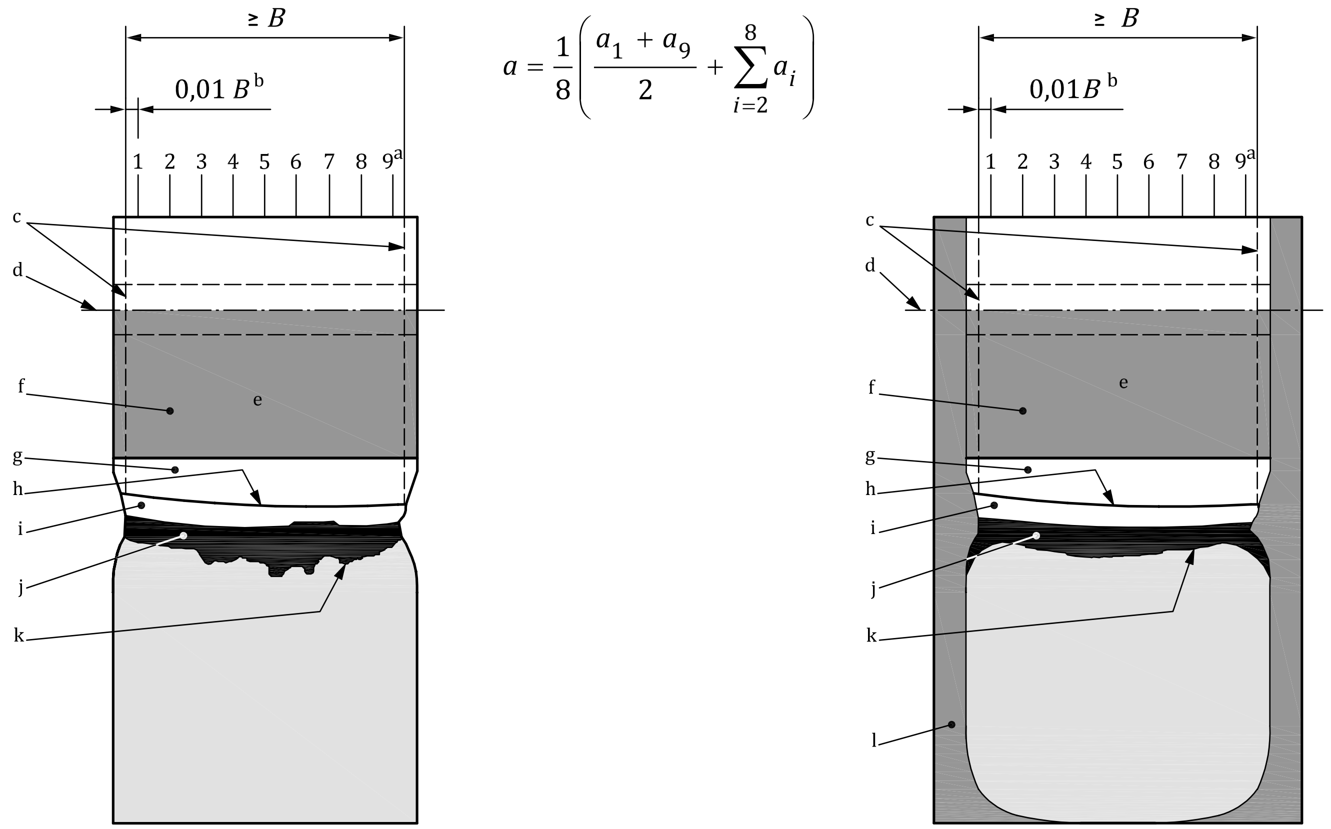


a) Plain sided **b) Side grooved**

Key

a Measure initial and final crack lengths at positions 1 to 9.
b Not to scale.
c Reference lines.
d Crack plane.
e Machined notch.
f Fatigue precrack.
g Initial crack front.
h Stretch zone.
i Crack extension.
j Final crack front.
k Side groove.

Figure 13 — Measurement of crack lengths on bend specimen



$$a=\frac{1}{8}\left(\frac{a_1+a_9}{2}+\sum_{i=2}^{8}a_i\right)$$

a) Plain sided **b) Side grooved**

Key

a	Measure the initial and final crack lengths from centreline of pinhole at positions 1 to 9.	g	Fatigue precrack.
b	Not to scale.	h	Initial crack front.
c	Reference lines.	i	Stretch zone.
d	Centreline of pinhole.	j	Crack extension.
e	Crack plane.	k	Final crack front.
f	Machined notch.	l	Side groove.

Figure 14 — Measurement of crack lengths on compact specimen

The initial crack length a_0 shall conform to the following.

a) The ratio a_0/W shall be within the range 0,45 to 0,70, except for K_{Ic} determination, where a_0/W shall be within the range 0,45 to 0,55.

b) The difference between any one of the central seven points and the nine-point averaged value shall not exceed 0,10 a_0. This requirement does not apply when the area average method is used.

c) No part of the fatigue precrack front shall be closer to the crack starter notch than 1,3 mm or 2,5 % W, whichever is the larger.

d) The fatigue precrack shall be within the envelope shown in Figure 6.

If the above requirements are not satisfied, then the initial crack length does not conform to this test method, and the test result shall be clearly marked as such.

5.8.3 Stable crack extension, Δa

Total crack extension (including any crack tip blunting), Δa, between the initial and final crack fronts shall be measured with an instrument accurate to ±0,025 mm using the nine-point averaging procedure described in 5.8.2. Any irregularities in crack extension, such as spikes and isolated "islands" of crack extension, shall be reported in accordance with Clause 8.

NOTE It may only be practicable 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.

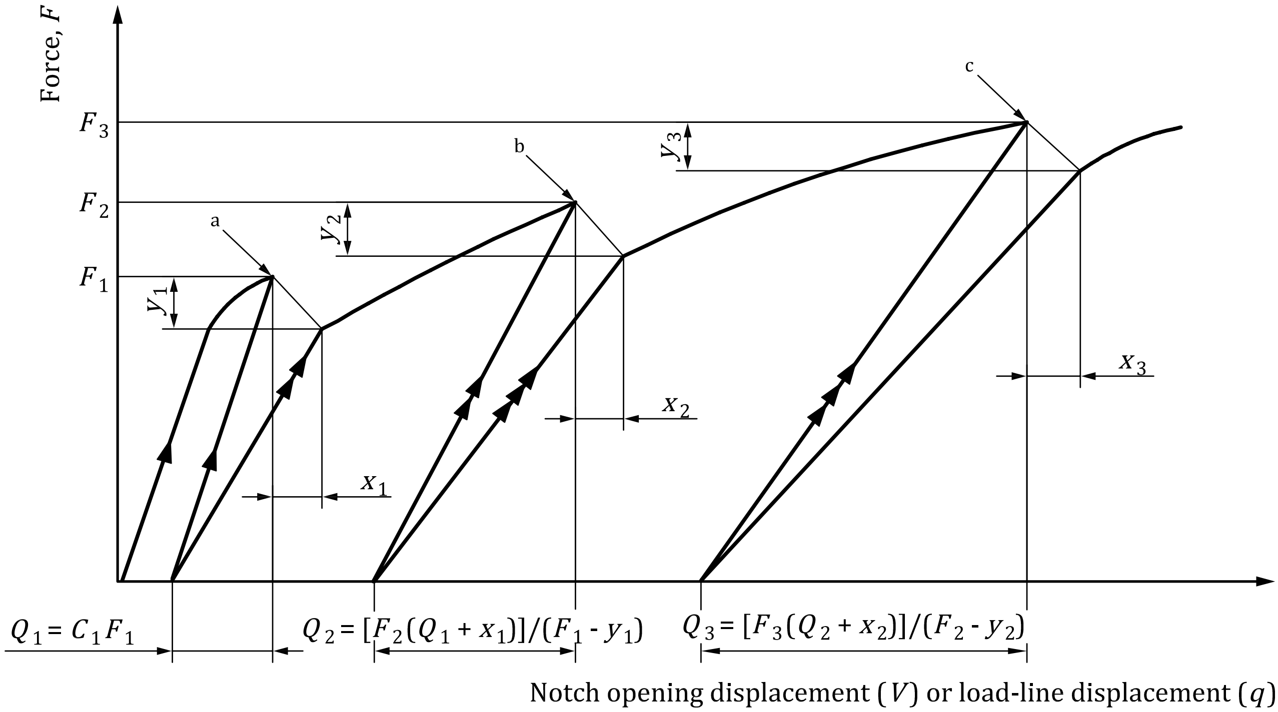
The difference between any one of the central seven final crack length values and the nine-point averaged value shall not exceed 0,10 ($a_0 + \Delta a$).

All individual pre-test and post-test measurements shall be recorded and used for calculations in accordance with Clauses 6 and 7.

5.8.4 Unstable crack extension

When there is evidence of arrested unstable crack extension and this can be associated with pop-in behaviour (see Figure 15), the total amount of stable crack extension prior to each pop-in shall be recorded as specified in 5.8.3.

The total amount of stable crack extension shall include any stable crack extension ahead of the fatigue precrack, which may be associated with pop-ins having occurred prior to the particular pop-in or the fracture event recorded.



Key

a Pop-in 1.

b Pop-in 2.

c Pop-in 3.

NOTE 1 C_1 is the initial compliance.

NOTE 2 Q_1 represents V or q.

NOTE 3 Pop-ins are exaggerated for clarity.

Figure 15 — Assessment of pop-in behaviour (see 6.2.2, 6.3.1 and 6.4.1)

6 Determination of fracture toughness for stable and unstable crack extension

6.1 General

This clause describes the determination of specific (single point) values of fracture toughness indicated in Figure 1 and Table 2 and the force versus displacement behaviour shown in Figure 2.

Fracture toughness values shall be regarded as either

— size insensitive, corresponding to the symbols K_{Ic}, δ_{Ji}, $\delta_{J0,2BL}$, J_i, $J_{0,2BL}$, and $K_{J0,2BL}$, or

— size sensitive, corresponding to the symbols $\delta_{c(B)}$, $\delta_{J0,2BL(B)}$, $\delta_{u(B)}$, $\delta_{uc(B)}$, $\delta_{m(B)}$, $J_{c(B)}$, $K_{Jc(B)}$, $J_{0,2BL(B)}$, $J_{u(B)}$, $J_{uc(B)}$, and $J_{m(B)}$, where (B) represents the thickness of the specimen tested.

Test record discontinuities involving abrupt force drops and corresponding displacement increases of less than 1 % of the current value shall be ignored. All other abrupt discontinuities shall be interpreted as pop-ins. The causes of pop-ins shall be investigated and recorded. When a particular pop-in is not associated with unstable crack extension in the plane of the fatigue precrack, it is not appropriate to determine a value of fracture toughness for that pop-in. When a particular pop-in is associated with unstable crack extension in the plane of the fatigue precrack, or all other causes of the pop-in have been eliminated, the pop-in shall be assessed in accordance with

a) the procedures given in 6.2 for K_{Ic} determination, or

b) the procedures respectively in 6.4 for δ and J toughness determinations.

6.2 Determination of plane strain fracture toughness, K_{Ic}

6.2.1 General

The test record shall be interpreted in accordance with 6.2.2, and a provisional result K_Q calculated in accordance with 6.2.3. Specimen size shall be checked for conformity to 6.2.4 using the provisional value K_Q and the 0,2 % offset yield strength $R_{p0,2}$ appropriate to the specimen at its test temperature.

For the determination of K_{Ic} in accordance with this document, it is recommended that $a_o/W \approx 0{,}5$.

6.2.2 Interpretation of the test record for F_Q

The slope of the initial portion of the force versus displacement record shall be evaluated as the first step in obtaining the provisional force value F_Q. This slope shall be obtained from the most linear portion of the test record, using data up to at least 50 % of F_{max} (see Figure 16). An optimization procedure like that described in Reference [6] can be used to obtain the best fit slope.

As illustrated in Figure 16, a line $0F_d$ is drawn through the intercept with the x-axis with a slope $\Delta F/F$ less than that of the tangent 0A to the linear portion of the record. The magnitude of $\Delta F/F$ shall be as follows:

a) when interpreting the force, F, versus notch-opening displacement, V, record for the bend specimen;

$$\frac{\Delta F}{F} = 0{,}05 \tag{8}$$

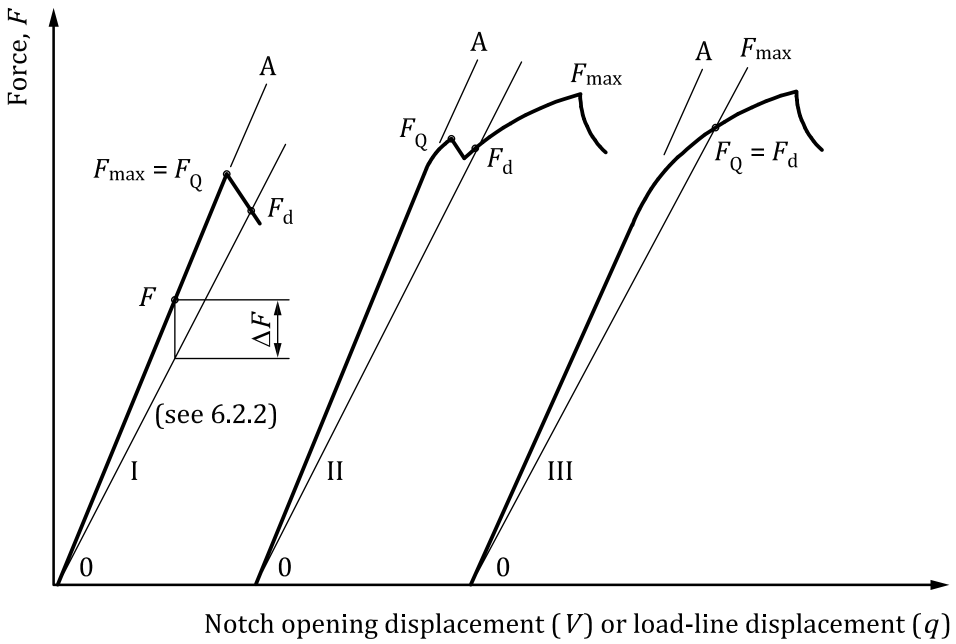
b) when interpreting the force, F, versus load-line displacement, q, record for the bend specimen;

$$\frac{\Delta F}{F} = 0{,}04 \tag{9}$$

NOTE 1 When both V and q are recorded for the bend specimen, only the F versus V record is interpreted.

c) when interpreting either the force, F, versus notch-opening displacement, V, record or the force, F, versus load-line displacement, q, record for the compact specimen.

$$\frac{\Delta F}{F} = 0{,}05 \tag{10}$$



NOTE 2 $\frac{\Delta F}{F}$ offset slopes are exaggerated for clarity.

Figure 16 — Definition of F_Q (for determination of K_Q)

F_Q is the highest force that precedes F_d shown in Figure 16 for types I and II test records, or the force that coincides with F_d shown in Figure 16 for the type III test record.

The maximum force, F_{max}, (see Figure 16) sustained by the specimen is recorded and the ratio, F_{max}/F_Q, calculated. If that ratio exceeds 1,10, K_Q is considered to bear an insufficient relation to K_{Ic} and the record is then interpreted in accordance with 6.3 or 6.4. If F_{max}/F_Q is less than 1,10, K_Q is calculated directly in accordance with 6.2.3.

NOTE 3 In Figure 16, the type II test record corresponds to a pop-in event which is classified as not significant. If the pop-in is significant, anything after F_Q in the test record is not relevant.

6.2.3 Calculation of K_Q

K_Q is calculated from the following relationships using B, B_N and W from 5.5.1, a_o from 5.8.2 and F_Q from 6.2.2.

K_Q is calculated for three-point bend specimens as:

$$K_Q = \frac{S}{W} \cdot \frac{F_Q}{\left(BB_N W\right)^{0,5}} \cdot g_1\left(\frac{a_o}{W}\right) \tag{11}$$

where S is the bending span established in 5.7.1.1 (see Figure 10).

NOTE 1 For plain-sided specimens, $B_N = B$.

NOTE 2 The relationship for $g_1(a_o/W)$ is given in Annex D.

Pay attention to the units used in calculating K_Q from Formula (11). If B and W are in m and F is in MN, then K_Q will be in $MPam^{0,5}$. If B and W are in mm and F is in kN, then the calculated quantity has to be multiplied by $10^{3/2}$ to give K_Q in $MPam^{0,5}$.

K_Q is calculated for compact specimens as:

$$K_Q = \frac{F_Q}{\left(BB_N W\right)^{0,5}} \cdot g_2\left(\frac{a_0}{W}\right) \tag{12}$$

NOTE 3 For plain-sided specimens, $B_N = B$.

NOTE 4 The relationship for $g_2(a_0/W)$ is given in Annex D.

Pay attention to the units used in calculating K_Q from Formula (12). If B and W are in m and F is in MN, then K_Q will be in MPam^{0,5}. If B and W are in mm and F is in kN, then the calculated quantity has to be multiplied by $10^{3/2}$ to give K_Q in MPam^{0,5}.

6.2.4 Qualification of K_Q as K_{Ic}

K_Q is equal to K_{Ic}, if all requirements of this method are met, including the following:

$$a_o, B, \left(W - a_o\right) \geq 2,5\left(\frac{K_Q}{R_{p0,2}}\right)^2 \tag{13}$$

and

$$0,45 \leq \frac{a_o}{W} \leq 0,55 \tag{14}$$

Pay attention to the units when evaluating Formula (13). Thus K_Q has to be in MPam^{0,5} and $R_{p0,2}$ in MPa for a_o, B, and $(W - a_o)$ to be in metres, and

$$K_f \leq 0,6K_Q \cdot \frac{\left(R_{p0,2}\right)_P}{\left(R_{p0,2}\right)_t} \tag{15}$$

where $(R_{p0,2})_P$ and $(R_{p0,2})_t$ are the 0,2 % offset yield strengths at the precracking and test temperatures, respectively.

If the requirements of Formulae (13), (14) and (15), or any of the other requirements of this method are not satisfied, the result does not qualify as K_{Ic}, and the test data shall be assessed in accordance with 6.3 or 6.4 for possible qualification as δ or J values.

6.3 Determination of fracture toughness in terms of δ

6.3.1 Determination of F_c and V_c, F_u and V_u, or F_{uc} and V_{uc}

Values of F and V are taken at the following points on test record types (1) to (5) (see Figure 2):

a) at fracture, when the records are as in Figure 2, types (1), (2) and (4);

b) at the earliest pop-in prior to fracture when the records are as in Figure 2, types (3) and (5), and Figure 15 (see Annex F and Reference [7]);

$$P \geq \frac{\Delta F}{F} \tag{16}$$

c) at fracture, when pop-ins prior to fracture give values for which

$$P < \frac{\Delta F}{F} \tag{17}$$

ΔF, in this case, indicates the force drop observed at the occurrence of the pop-in.

The quantity P in Formulae (16) and (17) is derived as (see Annex F):

$$P = 1 - \frac{Q_1}{F_1} \cdot \frac{F_n - y_n}{Q_n + x_n} \tag{18}$$

where

$\Delta F/F$ is an approximate value given by Formulae (8) and (9), as appropriate to bend or compact specimens;

P is a factor representing the cumulative increase in crack size and compliance due to all pop-ins prior to and including the n^{th} pop-in;

Q_1 is the elastic displacement at pop-in 1 (see Figure 15);

F_n is the force at the n^{th} pop-in;

Q_n is the elastic displacement at the n^{th} pop-in;

y_n is the force drop at the n^{th} pop-in;

x_n is the displacement increase at the n^{th} pop-in.

n is the sequential number (see Figure 15) of the last of the particular series of pop-ins being assessed.

When only one pop-in occurs, $n = 1$. When multiple pop-ins occur, it may be necessary to make successive assessments of Formula (16) with $n = 1, 2, 3$, etc.

Q_n may be determined graphically or analytically (see Figure 15). Alternatively, $(Q_n + x_n)$ may be obtained by unloading the test specimen.

NOTE F and V are used to determine values of δ_0 in accordance with 6.3.4.

When F and V correspond to crack instability (5.8.4) after stable crack extension (5.8.3), so that

$$\Delta a < 0{,}2\ \text{mm} + \frac{\delta}{1{,}87} \cdot \frac{R_{p0,2}}{R_m} \tag{19}$$

they shall be recorded as values F_c and V_c.

When F and V correspond to crack instability (5.8.4) after stable crack extension (5.8.3), so that

$$\Delta a \geq 0{,}2\ \text{mm} + \frac{\delta}{1{,}87} \cdot \frac{R_{p0,2}}{R_m} \tag{20}$$

they shall be recorded as values F_u and V_u.

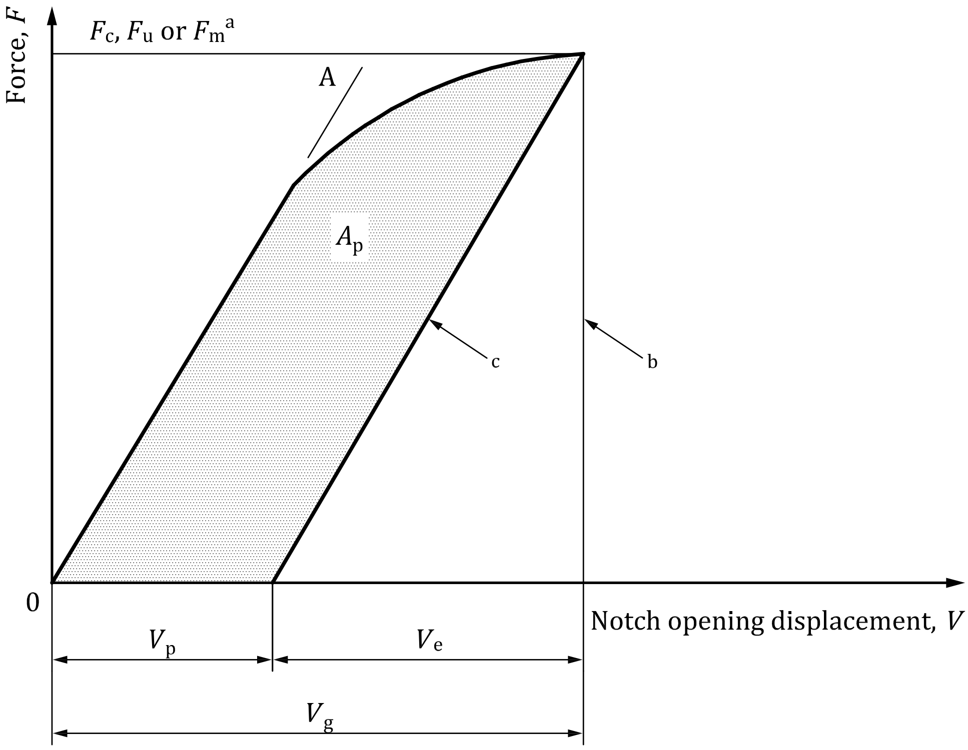
When it is not possible to determine stable crack extension Δa prior to instability (see 5.8.3), F and V shall be recorded as F_{uc} and V_{uc}.

6.3.2 Determination of F_m and V_m

When the test record exhibits a maximum force plateau prior to fracture with no significant prior pop-ins (see 6.3.1), values of F_m and V_m shall be obtained from the test record at the point corresponding to the first attainment of the maximum force [see Figure 2, test record type (6)].

6.3.3 Determination of V_p

The plastic component of notch-opening displacement V_p corresponding to the notch-opening displacement V_c, V_u, V_{uc}, or V_m (determined in 6.3.1 and 6.3.2, see Figure 17) is determined and recorded either manually from the test record, or automatically using a computer technique.



Key

a See Figure 2.

b V_c, V_u or V_m corresponding to F_c, F_u or F_m.

c Parallel to 0A.

Figure 17 — Definition of V_p (for determination of CTOD)

An analytical procedure based on compliance relationships may also be used by which the theoretical elastic notch-opening displacement, V_e, is deducted from total notch-opening displacement, V_g, as described in G.1.

Determination of V_p corresponds to $F \leq F_m$ (see Figure 2), and ignores the effects of stable or pop-in crack extension over this range of force.

6.3.4 Calculation of δ_0

δ_0 is calculated from the following relationships using B, B_N, W and z from 5.5.1, a_0 from 5.8.2, F from 6.3.1 or 6.3.2, and V_p from 6.4.3:

NOTE 1 Values of δ_0 are not corrected for crack extension Δa.

NOTE 2 For plain-sided specimens, $B_N = B$.

NOTE 3 When V_p is measured at a position beyond the notched edge of the specimen [see Figure 8 b)], z is positive; when V_p is measured at a position before the notched edge, z is negative.

δ_0 is calculated for the three-point bend specimen as:

$$\delta_0 = \left[\frac{S}{W} \cdot \frac{F}{(BB_N W)^{0,5}} \cdot g_1\left(\frac{a_0}{W}\right)\right]^2 \cdot \frac{1-\nu^2}{2R_{p0,2}E} + \frac{0,4(W-a_0)}{0,6a_0 + 0,4W + z} \cdot V_p \quad (21)$$

where S is the bending span established in 5.7.1.1 (see Figure 10).

NOTE 4 The relationship for $g_1(a_0/W)$ is given in Annex D.

δ_0 is calculated for the straight-notch compact specimen as:

$$\delta_0 = \left[\frac{F}{(BB_N W)^{0,5}} g_2\left(\frac{a_0}{W}\right)\right]^2 \cdot \frac{1-\nu^2}{2R_{p0,2}E} + \frac{0,46(W-a_0)}{0,54a_0 + 0,71W + z} \cdot V_p \quad (22)$$

NOTE 5 The relationship for $g_2(a_0/W)$ is given in Annex D.

δ_0 is calculated for the stepped-notch compact specimen as:

$$\delta_0 = \left[\frac{F}{(BB_N W)^{0,5}} g_2\left(\frac{a_0}{W}\right)\right]^2 \cdot \frac{1-\nu^2}{2R_{p0,2}E} + \frac{0,46(W-a_0)}{0,54a_0 + 0,46W + z} \cdot V_p \quad (23)$$

NOTE 6 The relationship for $g_2(a_0/W)$ is the same as in Formula (22) for straight-notched compact specimens.

6.3.5 Qualification of δ_0 fracture toughness value

Values of δ_0 fracture toughness conforming to 6.3 shall be regarded as size sensitive, qualified only for the thickness tested. The thickness shall be noted in millimetre units in parentheses as a subscript to the symbol for the fracture toughness, as follows:

— $\delta_{c(B)}$, for δ_0 calculated using values of F_c and V_c;

— $\delta_{u(B)}$, for δ_0 calculated using values of F_u and V_u;

— $\delta_{uc(B)}$, for δ_0 calculated using values of F_{uc} and V_{uc};

— $\delta_{m(B)}$, for δ_0 calculated using values of F_m and V_m.

For example, for δ_0 calculated from values of F_c and V_c for a test specimen of thickness B = 25 mm, the $\delta_{c(B)}$ fracture toughness shall be symbolized $\delta_{c(25)}$.

6.4 Determination of fracture toughness in terms of J

6.4.1 Determination of F_c and q_c, F_u and q_u, or F_{uc} and q_{uc}

J_0 is calculated in accordance with 6.4.4 using values of F and q determined by the same procedure used to determine F and V in 6.3.1.

When values of F and q correspond to small amounts of measured stable crack extension (see 5.8.2), i.e.

$$\Delta a < 0,2 \text{ mm} + \left(\frac{J}{3,75R_m}\right) \quad (24)$$

they shall be recorded as F_c and q_c.

When F and q correspond to larger amounts of measured stable crack extensions, (see 5.8.3), i.e.

$$\Delta a \geq 0,2\ \text{mm} + \left(\frac{J}{3,75 R_m}\right) \tag{25}$$

they shall be recorded as F_u and q_u.

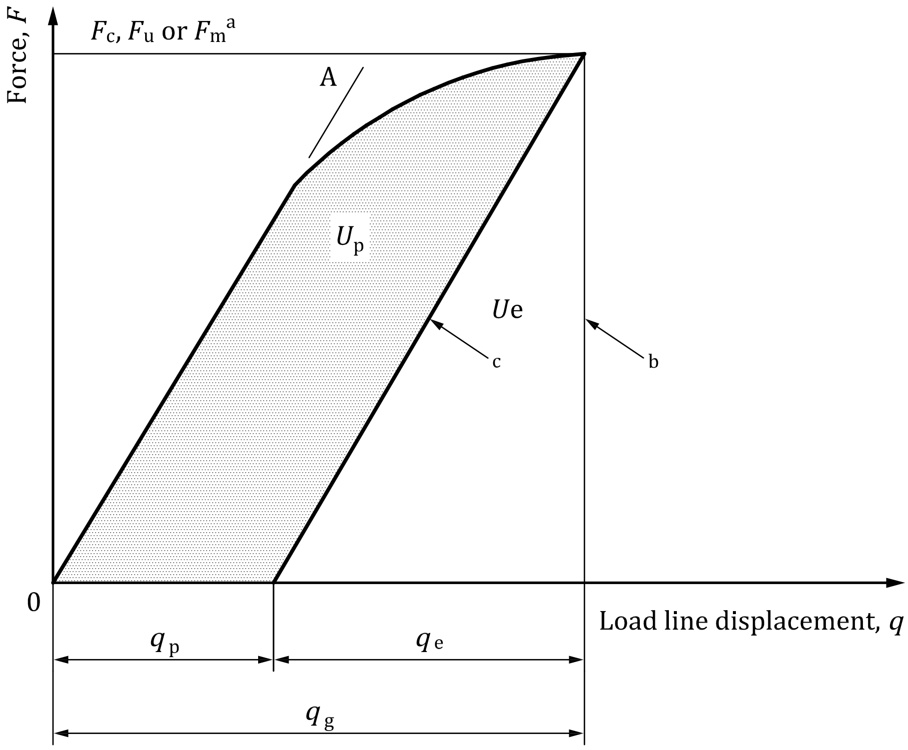
When it is not possible to determine Δa (see 5.8.3), F and q shall be recorded as F_{uc} and q_{uc}.

6.4.2 Determination of F_m and q_m

When the test record exhibits a maximum force plateau prior to fracture with no significant prior pop-ins (see 6.3.2), the values F_m and q_m shall be obtained from the test record at the point corresponding to the first attainment of the maximum force [see Figure 2, test record type (6)].

6.4.3 Determination of U_p

The plastic component of the work (U_p) done up to the appropriate load-line displacement q_c, q_u or q_m (determined in 6.4.1 and 6.4.2) is determined and recorded directly from the test record (e.g. using a polar planimeter), or by numerical integration using computer techniques, or by a combination of the latter and an analytical procedure based on elastic compliance (see Figure 18). The plastic component is obtained by subtraction of the theoretical elastic area (U_e) from the total area as described in G.3.



Key

a See Figure 2.

b q_c, q_u or q_m corresponding to F_c, F_u or F_m.

c Parallel to 0A.

Figure 18 — Definition of U_p (for determination of J)

NOTE This determination of U_p corresponds to $F \leq F_m$ (see Figure 2), and ignores the effects of stable and pop-in crack extension over this range of force.

6.4.4 Calculation of J_o

J_o is calculated from the following relationships for bend and compact specimens, using B, B_N and W from 5.5.1, a_o from 5.8.2, and the appropriate force from the test record (determined in 6.4.1 or 6.4.2) along with the corresponding value of U_p (determined in 6.4.3).

NOTE 1 Values of J_o are not corrected for crack extension Δa.

NOTE 2 For plain-sided specimens, $B_N = B$.

NOTE 3 When V_p is measured at a position beyond the notched edge of the specimen [see Figure 8 b)], z is positive; when V_p is measured at a position before the notched edge, z is negative.

J_o is calculated for the three-point bend specimen as:

$$J_o = \left[\frac{FS}{\left(BB_N\right)^{0,5} W^{1,5}} g_1 \left(\frac{a_o}{W} \right) \right]^2 \cdot \frac{1-\nu^2}{E} + \frac{1,9\, U_p}{B_N \left(W - a_o\right)} \quad (26)$$

where S is the bending span established in 5.7.1.1 (see Figure 10).

NOTE 4 The relationship for $g_1(a_o/W)$ is given in Annex D.

J_o is calculated for the stepped-notch compact specimen as:

$$J_o = \left[\frac{F}{\left(BB_N W\right)^{0,5}} g_2 \left(\frac{a_o}{W} \right) \right]^2 \cdot \frac{1-\nu^2}{E} + \frac{\eta_p U_p}{B_N \left(W - a_o\right)} \quad (27)$$

where

$$\eta_p = 2 + 0,522\left(1 - a_p / W\right) \quad (28)$$

NOTE 5 The relationship for $g_2(a_o/W)$ is given in Annex D.

U_p may be derived for straight-notch compact specimens from A_p (see Figure 17) provided that a relationship is established between U_p and A_p. J_o is calculated for straight-notch compact specimens in the same way as for the stepped-notch compact specimen using Formula (27).

6.4.5 Qualification of J_o fracture toughness value

Values of J_o fracture toughness conforming to 6.4 shall be regarded as size sensitive, and qualified only for the thickness tested. The tested thickness shall be noted in millimetre units in parentheses as a subscript to the symbol for the fracture toughness, as follows:

— $J_{c(B)}$, for J_o calculated using values of F_c and q_c;

— $J_{u(B)}$, for J_o calculated using values of F_u and q_u;

— $J_{uc(B)}$, for J_o calculated using values of F_{uc} and q_{uc};

— $J_{m(B)}$,for J_o calculated using values of F_m and q_m.

For example, for J_o calculated from values of F_c and q_c for a test specimen of thickness B = 25 mm, the $J_{c(B)}$ fracture toughness shall be symbolized $J_{c(25)}$.

7 Determination of resistance curves δ_J-Δa and J-Δa and initiation toughness $\delta_{J0,2BL}$ and $J_{0,2BL}$ and δ_{Ji} and J_i for stable crack extension

7.1 General

This clause describes the evaluation of fracture behaviour of specimens that exhibit stable crack extension and nonlinear force-displacement records corresponding to the right branch of Figure 1. Fracture behaviour is characterized in terms of the variation of either δ_J or J with crack extension Δa. δ_J is an estimate of CTOD obtained from J. Its variation with crack extension Δa is geometry- and size-insensitive. δ_J is corrected for stable crack extension. Methods are given for interpreting the δ_J-Δa and J-Δa crack resistance curves in terms of the single-point engineering initiation toughness parameters $\delta_{J0,2BL}$ or $J_{0,2BL}$.

Analysis procedures are given for determining either δ_J or J from tests of multiple or single specimens.

7.2 Test procedure

7.2.1 General

Specimens are loaded in accordance with 5.7 and the resulting amount of crack extension evaluated in accordance with 5.8.

NOTE Values of δ_J and J are corrected for stable crack extension Δa.

7.2.2 Multiple-specimen procedure

A series of nominally identical specimens is loaded to selected displacement levels and the corresponding amounts of crack extension are determined. Each specimen tested provides one point on the δ_J-Δa or J-Δa 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 (see 7.4) and to determine fracture toughness $\delta_{J0,2BL}$ or $J_{0,2BL}$ near the onset of stable crack extension (see 7.6). Loading the first specimen to a point just past maximum force and measuring the resulting stable crack extension helps to determine the displacement levels needed to favourably position data points in additional tests.

7.2.3 Single-specimen procedure

The single-specimen procedure makes use of elastic compliance or other techniques to obtain multiple points on the resistance curve from the test of a single specimen. Single-specimen testing procedures are described in Annex H.

Using a direct method, estimated final crack extension Δa shall be within 15 % of the measured crack extension or 0,15 mm, whichever is greater, for $\Delta a \leq 0{,}2\,(W - a_0)$, and within $0{,}03(W - a_0)$ for $\Delta a > 0{,}2\,(W - a_0)$. 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, the first specimen tested shall be used to establish a correlation between experimental output and measured crack extension to beyond Δa_{max} as defined in 7.4.1.2. At least one additional test shall be conducted to estimate crack extension using the results from the first test.

Agreement between estimated and actual crack extension Δa shall be within 15 % or 0,15 mm, whichever is greater; otherwise, the procedure is not acceptable.

7.2.4 Final crack front straightness

Final crack length shall be determined as the sum of initial crack length plus stable crack extension measured using the nine-point average methods described in 5.8.2 and 5.8.3. None of the seven interior final crack length measurements shall differ from the nine-point average value by more than 0,1 a_o; otherwise, the result is not acceptable.

7.3 Calculation of J and δ_J

7.3.1 Calculation of J

J is calculated for the three-point bend specimen as follows:

$$J = \left[\frac{FS}{\left(BB_N\right)^{0,5} W^{1,5}} g_1 \left(\frac{a_0}{W} \right) \right]^2 \cdot \frac{1-\nu^2}{E} + \frac{1,9\,U_p}{B_N\left(W-a_0\right)} \cdot \left[1 - \frac{\Delta a}{2\left(W-a_0\right)} \right] \tag{29}$$

where S is the bending span established in 5.7.1.1 (see Figure 10).

NOTE 1 The relationship for $g_1(a_o/W)$ is given in Annex D.

J is calculated for the stepped-notch compact specimen as follows:

$$J = \left[\frac{F}{\left(BB_N W\right)^{0,5}} g_2 \left(\frac{a_0}{W} \right) \right]^2 \cdot \frac{1-\nu^2}{E} + \frac{\eta_p U_p}{B_N\left(W-a_0\right)} \cdot \left[1 - \frac{\left(0,75\,\eta_p - 1\right)\Delta a}{W-a_0} \right] \tag{30}$$

where η_p is given by Formula (28).

NOTE 2 The relationship for $g_2(a_o/W)$ is given in Annex D.

NOTE 3 For plain-sided specimens, $B_N = B$ in Formulae (29) and (30).

NOTE 4 Direct measurement of the load-line displacement (q) is not possible with the straight-notch compact specimen, but q can be derived from the notch-opening displacement (V) provided that it can be demonstrated that the q so derived would be equivalent to the directly measured q to within 1 %. J is calculated using Formula (30).

7.3.2 Calculation of δ_J

δ_J is calculated for three-point bend specimen as follows:

$$\delta_J = \frac{J}{m \dfrac{R_{p0,2} + R_m}{2}} \tag{31}$$

where J is defined in Formula (29) and:

$$m = A_0 - A_1 \frac{R_{p0,2}}{R_m} + A_2 \left(\frac{R_{p0,2}}{R_m} \right)^2 - A_3 \left(\frac{R_{p0,2}}{R_m} \right)^3 \tag{32}$$

with:

$$A_0 = 3,18 - 0,22 \frac{a_i}{W} \tag{33}$$

$$A_1 = 4,32 - 2,23 \frac{a_i}{W} \tag{34}$$

$$A_2 = 4{,}44 - 2{,}29\frac{a_i}{W} \tag{35}$$

$$A_3 = 2{,}05 - 1{,}06\frac{a_i}{W} \tag{36}$$

NOTE 1 Calculation of δ_J requires $\frac{R_{p0,2}}{R_m} \geq 0{,}5$.

δ_J is calculated for the stepped-notch compact specimen as follows:

$$\delta_J = \frac{J}{m\,\frac{R_{p0,2} + R_m}{2}} \tag{37}$$

where J is defined in Formula (29) and:

$$m = 3{,}62 - 4{,}21\frac{R_{p0,2}}{R_m} + 4{,}33\left(\frac{R_{p0,2}}{R_m}\right)^2 - 2{,}00\left(\frac{R_{p0,2}}{R_m}\right)^3 \tag{38}$$

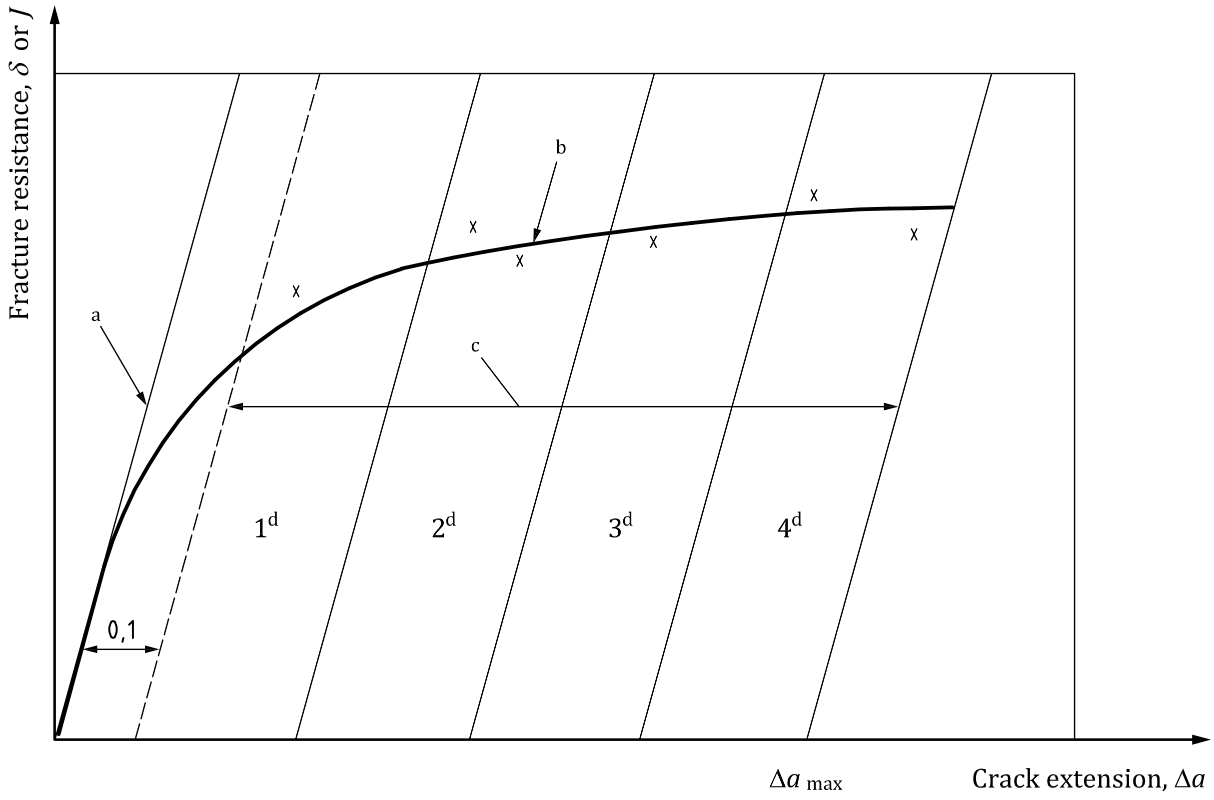
NOTE 2 Calculation of δ_J requires $\frac{R_{p0,2}}{R_m} \geq 0{,}5$.

7.4 *R*-curve plot

The points of δ_J or J versus crack extension Δa form the *R*-curve (e.g. Figure H.1). The data may be used in tabular form or as a plotted graph. A formula may be fitted to the graph for analysis, or the plot itself may be used for analysis.

7.4.1 Plot construction

7.4.1.1 A plot of fracture resistance δ_J or J versus crack extension Δa is constructed from the data obtained in 7.2 and 7.3 (see Figure 19).



Key

a Construction line.

b Fitted curve.

c Exclusion lines.

d Crack sector.

x test data.

At least six data points are required. Each crack sector shall contain at least one data point. If a formula is required, the offset power law of 7.4.2.2 shall be used.

Figure 19 — Data spacing for *R*-curve determination

7.4.1.2 For each specimen tested, Δa_{max} is calculated from:

$$\Delta a_{max} = 0{,}25(W - a_0), \text{ for both } \delta_J \text{ and } J \quad (39)$$

7.4.1.3 A construction line is drawn on the plot described in 7.4.1.1 using either:

$$\delta_J = 1{,}87 \cdot \frac{R_m}{R_{p0,2}} \cdot \Delta a \qquad (40)$$

or

$$J = 3{,}75 R_m \Delta a \qquad (41)$$

where R_m and $R_{p0,2}$ are determined at the temperature of the test.

NOTE Formula (40) is derived from Formula (41) by assuming that the δ_J construction line can be approximated by $\delta_J = \frac{J}{2R_{p0,2}}$.

7.4.1.4 The valid crack-extension limit exclusion line is drawn parallel to the construction line at an offset equal to the value of Δa_{max} calculated in 7.4.1.2 (see Figure 19).

7.4.1.5 Another valid crack-extension exclusion line is drawn parallel to the construction line at an offset of 0,10 mm (see Figure 19).

7.4.1.6 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, that datum point is included 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 C).

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

7.4.2 Data spacing and curve fitting

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

7.4.2.2 When a formula is to be fitted to the *R*-curve, at least one datum point shall reside in each of the four equal crack-extension regions (crack sectors) shown in Figure 19. The curve shall be best-fitted through the data points lying between the 0,1 mm and Δa_{max} exclusion lines (see Figure 19) using the power-law Formula (42):

$$\delta_J \left(\text{or } J\right) = \alpha + \beta\, \Delta a^{\gamma} \qquad (42)$$

where α and $\beta \geq 0$, and $0 \leq \gamma \leq 1$.

NOTE 1 A method for evaluating the constants α, β and γ is given in Annex I.

NOTE 2 If α or β is less than zero from the linearized regression of Annex I, then the result is unacceptable and the fitted formula is not representative of the *R*-curve. In such cases, additional tests or the use of a single-specimen test procedure (Annex H) are suggested.

If a single-specimen procedure is used, all data with Δa greater than 0,1 mm offset to the construction line may be used in the curve fitting. The *R*-curve is valid, however, only up to Δ_g or J_g; see Figure 20.

7.5 Qualification of resistance curves

7.5.1 Qualification of J-Δa resistance curves

7.5.1.1 J_{max} is calculated for each specimen as the smallest of:

$$J_{max} = B \cdot \frac{R_{p0,2} + R_m}{20} \qquad (43)$$

$$J_{max} = a_0 \cdot \frac{R_{p0,2} + R_m}{20} \qquad (44)$$

$$J_{max} = \left(W - a_0\right)\frac{R_{p0,2} + R_m}{20} \qquad (45)$$

7.5.1.2 An exclusion line is constructed to the J-Δa data at the minimum J_{max} value calculated above (see Figure 20).

7.5.1.3 J at the intersection of the best-fit curve with either the J_{max} or Δa_{max} [from Formula (39)] exclusion line defines J_g (see Figure 20). J_g shall be the upper limit to J-controlled crack extension behaviour for the test specimen size used.

7.5.2 Qualification of δ_J–Δa resistance curves

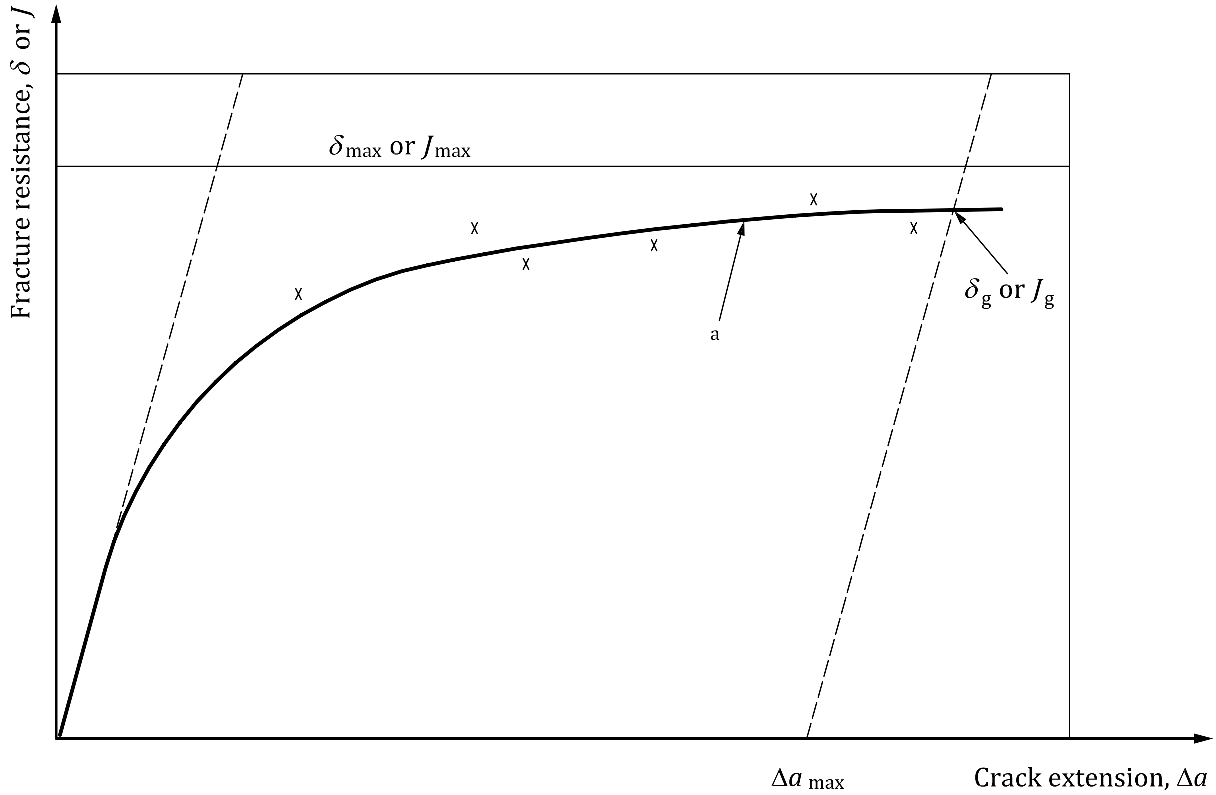
7.5.2.1 $\delta_{J,max}$ is calculated for each specimen as the smallest of:

$$\delta_{J,max} = \frac{B}{15} \qquad (46)$$

$$\delta_{J,max} = \frac{a_0}{15} \qquad (47)$$

$$\delta_{J,max} = \frac{W - a_0}{15} \qquad (48)$$

7.5.2.2 An exclusion line is constructed on the δ_J–Δa data at the minimum $\delta_{J,max}$ value calculated from 7.5.2.1 (see Figure 20).



Key

a Fitted curve.

x test data.

NOTE If the *R*-curve intersects the $\delta_{J,max}$ or J_{max} limit within the Δa_{max} limit, then $\delta_{J,g}$ or J_g equals $\delta_{J,max}$ or J_{max}.

Figure 20 — Qualification limits and definitions of J_g or δ_g

7.5.2.3 δ_J at the intersection of the best-fit curve with either the $\delta_{J,max}$ or Δa_{max} [from Formula (39)] exclusion lines defines $\delta_{J,g}$ (see Figure 20). $\delta_{J,g}$ shall be the upper limit to δ_J-controlled crack extension behaviour for the test specimen size used.

7.6 Determination and qualification of $J_{0,2BL}$ and $\delta_{J0,2BL}$

7.6.1 Determination of $J_{0,2BL}$

7.6.1.1 The *R*-curve is plotted and fitted in accordance with 7.4, but with the requirement that one datum point lie between the 0,10 mm and 0,30 mm crack extension offset lines and at least two data points lie between the 0,10 mm and 0,50 mm offset lines (see Figure 21). The best-fit curve [Formula (42)] shall pass through a minimum of six J-Δa data points.

7.6.1.2 A line is drawn parallel to the construction line at 0,2 mm crack extension offset as shown in Figure 21. The intersection of the best-fit curve with the offset line defines $J_{0,2BL}$.

7.6.1.3 If $J_{0,2BL}$ exceeds J_{max} (determined in 7.5.1.1), then it does not qualify.

7.6.1.4 If the slope $(\mathrm{d}J/\mathrm{d}a)_{0,2\mathrm{BL}}$ of the J-Δa curve at its intersection with the 0,2 mm offset construction line fails to meet the following criterion:

$$3{,}75R_\mathrm{m} > \left[2\left(\frac{\mathrm{d}J}{\mathrm{d}a}\right)\right]_{0,2\mathrm{BL}} \tag{49}$$

then the $J_{0,2\mathrm{BL}}$ determined in 7.6.1.2 does not qualify.

7.6.1.5 If $J_{0,2\mathrm{BL}}$ conforms to 7.6, as well as 8.8, then $J_{0,2\mathrm{BL}}$ determined in 7.6.1.2 is considered size-insensitive. If not, the value shall be reported as size-sensitive $J_{0,2\mathrm{BL}(B)}$, where B is specimen thickness.

7.6.1.6 In cases when the application is predominantly elastic but specimen tests do not yield valid K_Ic results, a value of linear elastic, plane strain fracture toughness at the onset of stable crack growth can be evaluated from:

$$K_{J0,2\mathrm{BL}} = \sqrt{\frac{EJ_{0,2\mathrm{BL}}}{1-\nu^2}} \tag{50}$$

7.6.2 Determination of $\delta_{J0,2\mathrm{BL}}$

7.6.2.1 The R-curve is plotted and fitted in accordance with 7.4, but with the requirement that one datum point lie between the 0,10 mm and 0,30 mm crack extension offset lines and at least two data points lie between the 0,10 mm and 0,50 mm offset lines (see Figure 21). The best-fit curve [Formula (42)] shall pass through a minimum of six δ_J–Δa data points.

7.6.2.2 A line is drawn parallel to the construction line at 0,2 mm crack extension offset as shown in Figure 21. The intersection of the best-fit curve with the 0,2 mm offset line defines $\delta_{J0,2\mathrm{BL}}$.

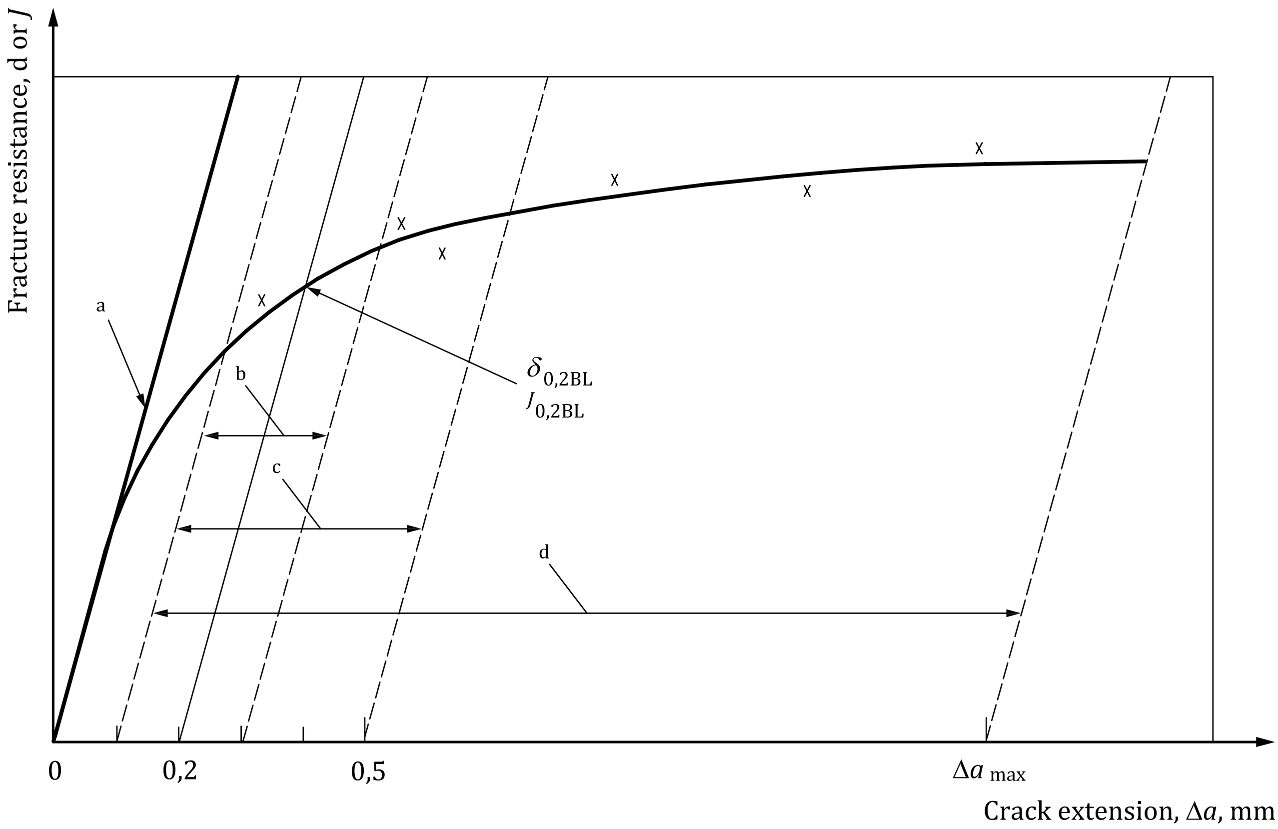
7.6.2.3 If $\delta_{J0,2\mathrm{BL}}$ exceeds $\delta_{J,\max}$ (see 7.5.2.1), then it does not qualify.

7.6.2.4 If the slope $(\mathrm{d}\delta_J/\mathrm{d}a)_{0,2\mathrm{BL}}$ of the δ_J-Δa curve at its intersection with the 0,2 mm offset construction line fails to meet the following criterion:

$$1{,}87 \cdot \frac{R_\mathrm{m}}{R_{\mathrm{p}0,2}} > \left[2\left(\frac{d\delta_\mathrm{J}}{da}\right)\right]_{0,2\mathrm{BL}} \tag{51}$$

then the $\delta_{J0,2\mathrm{BL}}$ determined in 7.6.2.2 does not qualify.

7.6.2.5 If $\delta_{J0,2BL}$ conforms to 7.6, as well as 8.7, then $\delta_{J0,2BL}$ determined in 7.6.2.2 is considered size-insensitive. If not, the value shall be reported as size-sensitive $\delta_{J0,2BL(B)}$, where B is the specimen thickness.



Key

a Construction line.

b At least one point.

c At least two points.

d Region of data dispersion in accordance with Figure 19.

x test data.

NOTE At least six data points are required.

Figure 21 — Data spacing for $J_{0,2BL}$ or $\delta_{J0,2BL}$

7.7 Determination of initiation toughness J_i and δ_{Ji} by scanning electron microscopy (SEM)

Values of initiation toughness J_i and δ_{Ji} may be determined from stretch zone width (SZW) measurements by the procedure given in Annex A. *It is essential* that the scanning electron microscope operator be experienced in the interpretation of SEM fractographs. If the SZW cannot be distinguished from stable crack extension, then neither J_i nor δ_{Ji} can be determined.

8 Test report

8.1 Organization

The test report shall make reference to this document, and shall be comprised of seven parts (see 8.2 to 8.8). Details regarding test material, test specimen and test conditions, including test environment, shall be reported as in 8.2. Machining, fatigue cracking, crack front straightness and crack length data shall conform to 8.3. Derived fracture parameters shall be qualified in accordance with 8.4 to 8.8.

8.2 Specimen, material and test environment

See C.1.

8.2.1 Specimen description

— identification;

— type;

— crack-plane orientation;

— location within product form.

8.2.2 Specimen dimensions

— thicknesses B and B_N, (mm);

— width W, (mm);

— initial relative crack length, a_0/W.

8.2.3 Material description

— composition and standardized designation code;

— product form (plate, forging, casting, etc.) and condition;

— tensile properties at precracking temperature, referenced or measured;

— tensile properties at the test temperature, referenced, or measured.

8.2.4 Additional dimensions

— force span S, (mm);

— knife edge “stand-off” z (see 5.5.1).

8.2.5 Test environment

— temperature (°C);

— loading displacement rate (mm/min);

— type of displacement control.

8.2.6 Fatigue precracking conditions

— K_f (MPam^{0,5});

— F_f (kN);

— precracking temperature (°C).

8.3 Test data qualification

8.3.1 Limitations

All data shall meet certain requirements in order to be qualified in accordance with this method. Only qualified data shall be used to define fracture resistance in accordance with this method. The data described in 8.3.2 to 8.3.4 shall be assembled in the suggested format of Table C.2.

The force versus displacement record shall meet the requirements of 5.7.4.

8.3.2 Crack length measurements

Measurements shall be made at nine evenly-spaced locations across the specimen thickness as shown in Figures 13 and 14. The following values shall be reported:

— the initial machined notch length (a_m);

— the initial crack length to the fatigued notch tip (a_o);

— the fatigue precrack length ($a_o - a_m$);

— the final crack length (a_f);

— the average crack extension ($\Delta a = a_f - a_o$).

8.3.3 Fracture surface appearance

— a record of unusual features on the fracture surface;

— a record of the occurrence of unstable crack extension such as cleavage.

8.3.4 Pop-in

— quantities *F*, *x*, *y* and *Q* for each pop-in from the force versus displacement record;

— the number of significant pop-ins;

— the location of first significant pop-in and information indicated in Table C.2.

8.3.5 Resistance curves

— include data for resistance curves from single-specimen tests in Table C.3.

8.3.6 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 in 5.4.1;

b) the test apparatus conforms to the tolerance and alignment requirements in 5.7;

c) the test machine and displacement gauge(s) conform to the accuracy requirements in 5.6;

d) the average initial crack length a_o is within the range 0,45 *W* to 0,7 *W*, or within the range 0,45 *W* to 0,55 *W* for K_{Ic} determination;

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

f) the fatigue precrack is within the appropriate envelope (see Figure 6) on both surfaces of the specimen;

g) the fatigue precrack stress intensity factor satisfies the requirements of 5.4.2.4;

h) none of the seven interior initial crack length measurements differs by more than 0,10 a_0 from the nine-point average initial crack length;

i) none of the seven interior final crack length measurements differs by more than 0,10 (a_0 + Δa) from the nine-point average final crack length;

j) the initial slope of force versus displacement record lies between 0,85 and 1,5 (for purposes of manual record analysis);

k) for a single-specimen *direct* crack length measurement method used to estimate crack extension, the final estimated crack length is within 15 % of the nine-point average measured crack length, or 0,15 mm, whichever is greater, up to a crack extension of 0,2 b_0, and to within 0,03 b_0 thereafter;

l) the estimated initial a_0/W from single-specimen tests is within 2 % of the measured initial a_0/W;

m) for a single-specimen *indirect* crack length prediction, 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, to be within 15 % of the nine point average of measured final crack length or 0,15 mm, whichever is greater, to a crack extension of 0,2 b_0 and to within 0,03 b_0 thereafter;

n) the data number and spacing requirements of 7.4.2 and 7.6.1 are satisfied for δ_J-Δa curve and $\delta_{J0,2BL}$ determinations;

o) the data number and spacing requirements of 7.4.2 and 7.6.2 are satisfied for J-Δa curve and $J_{0,2BL}$ determinations.

8.4 Qualification of K_{Ic}

The following requirements shall be met for K_Q (calculated in accordance with 6.2.3) to qualify as K_{Ic} in accordance with this method and are to be reported in the suggested format of C.4:

a) All requirements of 8.3, including 0,45 $W \le a_0 \le$ 0,55 W, are satisfied;

b) $2{,}5\left(\dfrac{K_Q}{R_{p0,2}}\right)^2 \le a_0$;

c) $2{,}5\left(\dfrac{K_Q}{R_{p0,2}}\right)^2 \le B$;

d) $2{,}5\left(\dfrac{K_Q}{R_{p0,2}}\right)^2 \le \left(W - a_0\right)$;

e) $\dfrac{F_{max}}{F_Q} \le 1{,}10$, where F_{max} is the maximum force sustained by the specimen.

8.5 Qualification of the δ_J-R Curve

The δ_J-R curve of this method is the power law regression line fit to the data of 7.4.2. The following requirements shall be met in defining that portion of the offset regression line that qualifies as a δ_J-R curve in accordance with this method:

a) the data are qualified in 8.3;

b) the limit of applicability of the δ_J-R curve is set by $\delta_{J,g}$ as defined in 7.5.1.3.

8.6 Qualification of the J-R Curve

The J-R curve of this method is the power law regression line fit to the data of 7.4.2. The following requirements shall be met in defining that portion of the offset regression line that qualifies as a J-R curve in accordance with this method:

a) the data are qualified in accordance with 8.2;

b) the limit of applicability of the J-R curve is set by J_g as defined in 7.5.1.3.

8.7 Qualification of $\delta_{J0,2BL(B)}$ as $\delta_{J0,2BL}$

If the following requirements are not met for $\delta_{J0,2BL}$ calculated according to 7.6.1, it shall be qualified as size-dependent and denominated $\delta_{J0,2BL(B)}$ in accordance with this method:

a) all requirements of 8.3 are satisfied;

b) the slope $d\delta_J/da$ of the power law regression line, evaluated at the 0,2 mm offset construction line, is <0,935 $(R_m/R_{p0,2})$;

c) $15\,\delta_{J0,2BL} \le a_0$;

d) $15\,\delta_{J0,2BL} \le B$;

e) $15\,\delta_{J0,2BL} \le (W - a_0)$.

8.8 Qualification of $J_{0,2BL(B)}$ as $J_{0,2BL}$

If the following requirements are not met for $J_{0,2BL}$ calculated in accordance with 7.6.2, it shall be qualified as size-dependent and denominated $J_{0,2BL(B)}$ in accordance with this method:

a) all requirements of 8.3 are satisfied;

b) the slope dJ/da of the power law regression line, evaluated at the 0,2 mm offset construction line, is <1,875 R_m;

c) $20\,\dfrac{J_{0,2BL}}{R_{p0,2} + R_m} \le a_0$;

d) $20\,\dfrac{J_{0,2BL}}{R_{p0,2} + R_m} \le B$;

e) $20\,\dfrac{J_{0,2BL}}{R_{p0,2} + R_m} \le (W - a_0)$.

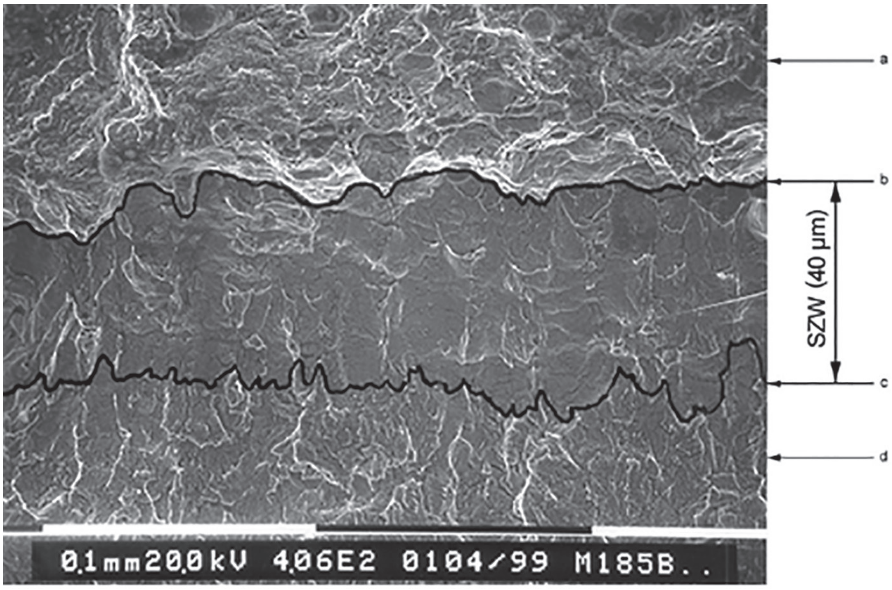
Annex A
(informative)

Determination of $\delta_{J\mathrm{i}}$ and J_i

NOTE The determination of $\delta_{J\mathrm{i}}$ and J_i requires the use of a scanning electron microscope (SEM) to measure the stretch zone width SZW on the fracture surfaces of failed specimens (see References [8] and [9]). A large scatter in the values of δ_{iJ} and J_i is inherent in the method due to the subjective nature of interpretation and measurement of the stretch zone width. To minimize scatter, it is suggested that only personnel with extensive experience in the interpretation of SEM fractographs be employed for this procedure. If the stretch zone cannot be distinguished from ductile crack extension, $\delta_{J\mathrm{i}}$ and J_i cannot be determined.

A.1 Critical stretch zone width (SZW) measurement

A.1.1 The local critical stretch zone width SZW_L is measured at the nine positions shown in Figures 13 and 14 using calibrated photographs taken in a SEM. An example of SEM photograph is shown in Figure A.1.



Key

a Fracture.

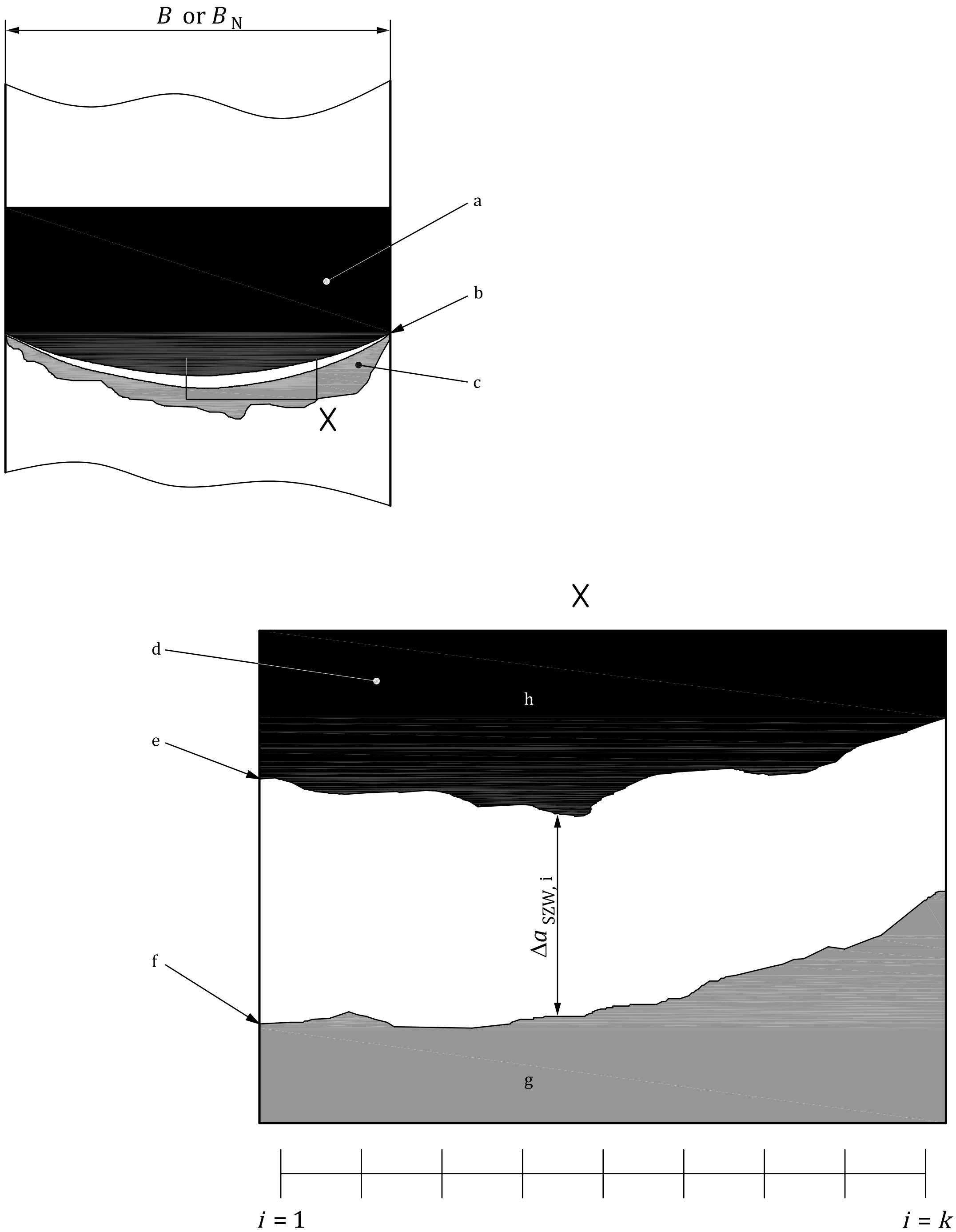
b End of stretch zone.

c Start of stretch zone.

d Fatigue.

Figure A.1 — Typical stretch zone width

The SEM magnification shall be adjusted so that both the beginning and end of the stretch zone are visible in a single field of view (see Figure A.2).



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

Key

a Fatigue precrack.

b Stretch zone.

c Stable crack extension.

d Image plane parallel to fatigue surface.

e Beginning of stretch zone.

f End of stretch zone.

g SEM photograph.

h Crack plane.

Figure A.2 — Determination of Δa_{SZW}

At least five measurements shall be made at each of the nine local stretch zone width measurement positions; thus,

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

A.1.2 The critical stretch zone width is established as the average of nine local measurements; thus,

$$\Delta a_{\mathrm{SZW}} = \frac{1}{9}\sum_{L=1}^{9}\Delta a_{\mathrm{SZW},L} \tag{A.2}$$

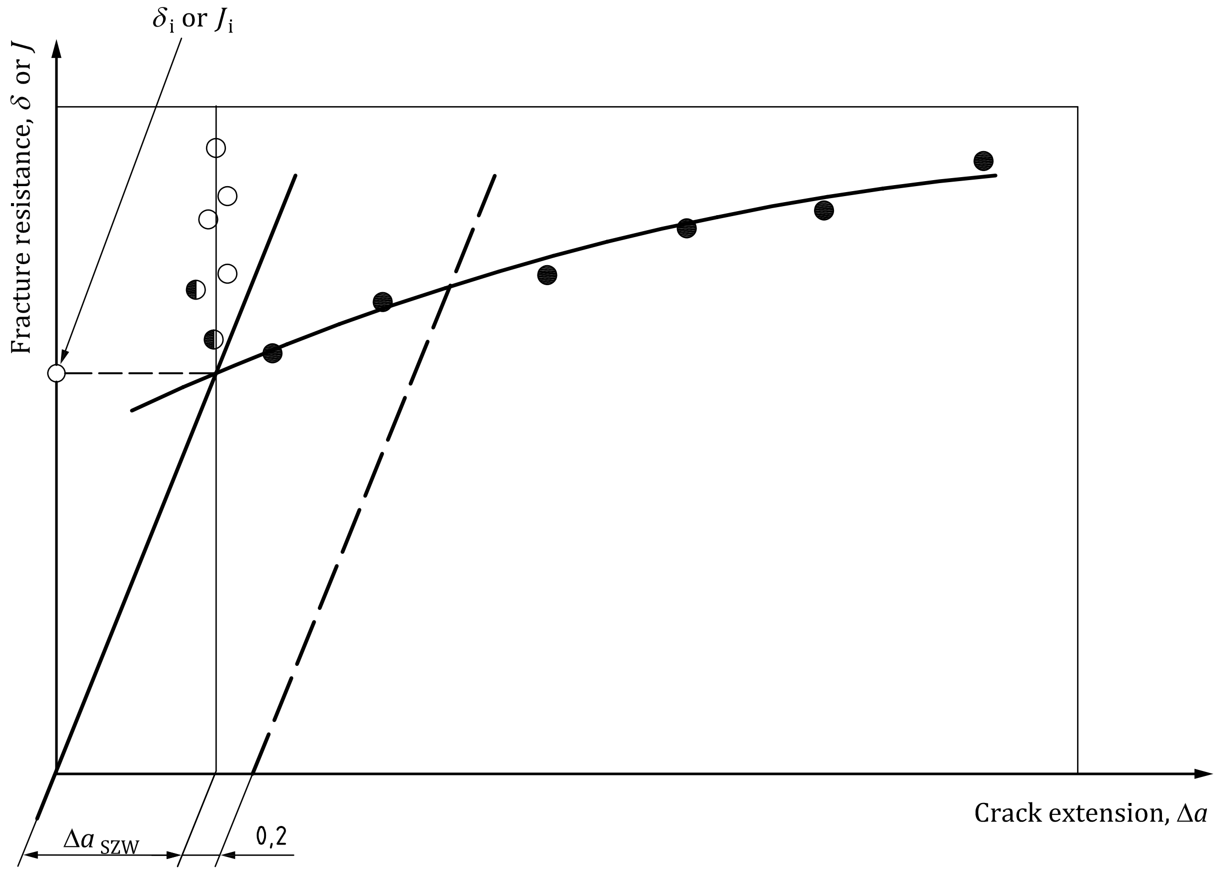
A.1.3 Crack extension Δa measured in accordance with 5.8.3 shall be greater than (Δa_{SZW} + 0,2 mm). Data points failing to conform to this requirement shall not be used to establish the mean critical stretch zone width Δa_{SZW}. A minimum of three data points shall be obtained to establish Δa_{SZW}; thus,

$$\Delta a_{\mathrm{SZW}} = \frac{1}{j}\sum_{N=1}^{j}\Delta a_{\mathrm{SZW},N}\text{, provided that } j \geq 3. \tag{A.3}$$

A.2 Determination of δ_{Ji}

A.2.1 The critical stretch zone width Δa_{SZW} shall be superimposed on a plot of δ_J-Δa data (obtained in accordance with 7.4.1 and 5.8.3) as shown in Figure A.3.

Dimensions in millimetres



Key

●	δ_J - Δa or J - Δa data
○	valid stretch zone width data
◐	invalid stretch zone width data

Figure A.3 — Determination of $\delta_{J\text{i}}$ and J_i

A.2.2 A line shall be drawn parallel to the δ_J-axis through the mean of the critical stretch zone width data Δa_{SZW} as illustrated in Figure A.3. Using the procedure described in 7.4.2.2, a best-fit curve shall be fitted through all δ_J-Δa data that exceed Δa_{SZW}. The intercept of the best-fit curve with the drawn parallel line defines $\delta_{J\text{i}}$.

A.2.3 A line shall be drawn from the origin through $\delta_{J\text{i}}$ (see Figure A.3). At least one δ_J-Δa datum point shall reside within 0,2 mm of this line. If $\delta_{J\text{i}}$ exceeds $\delta_{J,\text{max}}$ determined in accordance with 7.5.1.1, $\delta_{J\text{i}}$ is not qualified in accordance with this method.

A.2.4 The slope of the δ_J-Δa plot shall be evaluated at the intersection point ($\delta_{J\text{i}}$) using the formula determined in Annex I. If the slope of the line constructed in A.2.2 is such that

$$\left(\frac{d\delta_J}{da}\right)_L \geq 2\left(\frac{d\delta_J}{da}\right)_i$$

$\delta_{J\text{i}}$ is qualified in accordance with this method.

A.3 Determination of J_i

A.3.1 The critical stretch zone width Δa_{SZW} shall be superimposed on a plot of J-Δa data (obtained in accordance with 7.4.1 and 5.8.3) as shown in Figure A.3.

A.3.2 A line shall be drawn parallel to the J-axis through the mean of the critical stretch zone width data Δa_{SZW} as illustrated in Figure A.3. Using the procedure described in 7.4.2.2, a best-fit curve shall be fitted through all J-Δa data that exceed Δa_{SZW}. The intercept of the best-fit curve with the drawn parallel line defines J_i.

A.3.3 A line shall be drawn from the origin through J_i (Figure A.3). At least one J-Δa datum point shall reside within 0,2 mm of this line. If J_i exceeds J_{max} determined in accordance with 7.5.2.1, J_i is not qualified in accordance with this method.

A.3.4 The slope of the J-Δa shall be evaluated at the intersection point (J_i) using the formula determined in Annex I. If the slope of the line constructed in A.3.2 is such that

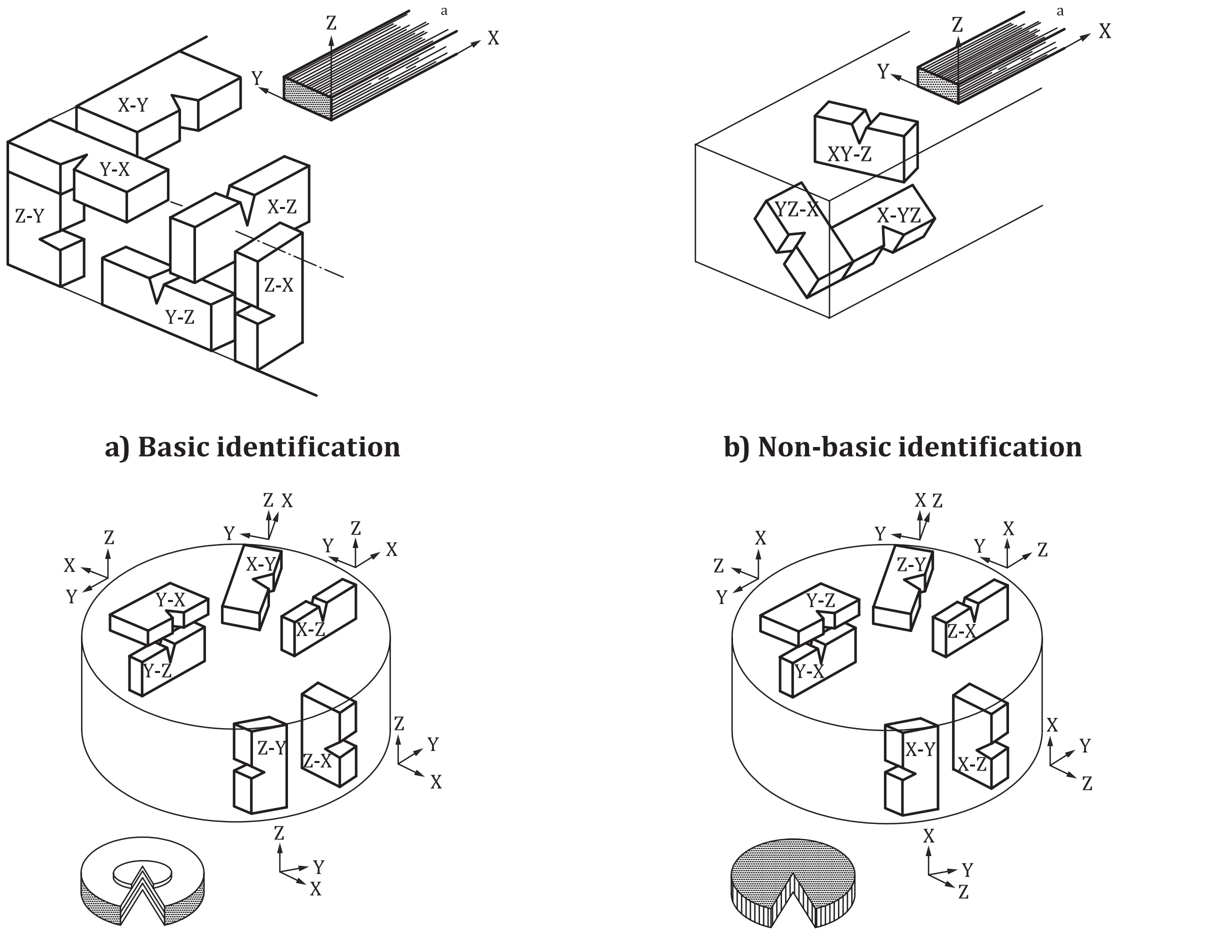
$$\left(\frac{dJ}{da}\right)_L \geq 2\left(\frac{dJ}{da}\right)_i$$

J_i is qualified in accordance with this method.

Annex B
(normative)

Crack plane orientation

The following notation shall be used to relate the plane and direction of crack extension to the characteristic directions of the product (see ISO 3785). A hyphenated code shall be used where the letter(s) preceding the hyphen represent(s) the direction normal to the crack plane and the letter(s) following the hyphen represent(s) the expected direction of crack extension (see Figure B.1). For wrought metals, the letter X shall always denote the direction of principal deformation (maximum grain flow); Z the direction of least deformation; Y the direction normal to the X-Z plane. If the specimen directions do not coincide with the product's characteristic directions, then two letters shall be used to denote the normal to the crack plane and/or the expected direction of crack extension [see Figure B.1 b)]. If there is no grain flow direction (as in a casting), reference axes may be arbitrarily assigned but shall be clearly identified.



a) Basic identification **b) Non-basic identification**

c) Radial grain flow, axial working direction **d) Axial grain flow, radial working direction**

Key

a Grain flow.

Figure B.1 — Fracture plane identification

Annex C
(informative)

Example test reports

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

C.1 Specimen, material and test environment

Specimen identifier: **Operator:** **Date:**

Specimen ______________

Type (compact/bend) ______________

Identification number ______________

Orientation ______________

Location within product ______________

Material

Material designation ______________

Material form/condition ______________

Specimen dimensions

B = ______________ (mm)

B_N = ______________ (mm)

W = ______________ (mm)

a_0/W (nominal) = ______________

Additional dimensions

Bend span: S = ______________ (mm)

Knife edge stand-off z = ______________ (mm)

Tensile properties — fatigue precracking temperature

Temperature = ______________ (°C)

		Referenced (R)	Measured (M)
E (modulus of elasticity)	= ______________ (GPa)		______________
ν (Poisson's ratio)	= ______________		______________
$R_{p0,2}$ (tensile yield strength)	= ______________ (MPa)		______________
R_m (ultimate tensile strength)	= ______________ (MPa)		______________

Tensile properties – test temperature

Temperature = ______________ (°C)

	Referenced (R)	Measured (M)
E (modulus of elasticity)	= ______________ (GPa)	______________
ν (Poisson's ratio)	= ______________	______________
$R_{p0,2}$ (tensile yield strength) = (MPa)	= ______________ (MPa)	______________
R_m (ultimate tensile strength)	= ______________ (MPa)	______________

Precracking

Fatigue temperature = ______________ (°C)

Final K_f = ______________ (MPa $\sqrt{m}$)

Final F_f = ______________ (kN)

Final K_f/E = ______________ ($\sqrt{m}$)

Test information

Type of displacement control ______________ (Stroke/crack mouth opening)

Displacement rate ______________ (mm/minute)

Test temperature ______________ (°C)

C.2 Data qualification

Measured crack length information Specimen identifier ______________________

Table C.1 — Crack measurement table

Point	**Position** mm	**Precrack length** mm	**Δ*a*** mm
1			
2			
3			
4			
5			
6			
7			
8			
9			

a_o Average initial crack length[a] ________________ (mm)

$a_o - a_m$ Average fatigue precrack length[a] ________________ (mm)

Δa Average crack extension[a] ________________ (mm)

$a_o + \Delta a$ Average final crack length[a] ________________ (mm)

[a] See 5.8.

Estimated crack lengths

$a_{o,est}$ Estimated fatigue crack length ________________ (mm)

$a_{f,est}$ Estimated final crack length ________________ (mm)

Fracture surface appearance

Record occurrence of cleavage _____________________ (yes/no)

Record any unusual features on the fracture surface below:

Pop-in information

Specimen type ____________________

$\Delta F/F$ __________________

Q_1 __________________

F_1 __________________

C_1 __________________

Table C.2 — Pop-in information table

Pop-in number, n	F_n	x_n	y_n	Q_n	P	Significant? (y/n)
1						
2						
3						
4						
5						
6						
7						
8						
9						

Number of significant pop-ins ___________________

Number of the first significant pop-in ____________________

C.3 Resistance curve data

Table C.3 — Resistance curve data

Specimen identifier:						Date:	
R-curve method:							
(Single/Multiple): (Direct/Indirect): (UC/ACPD/DCPD/Other)[a]							
Test record information:						Operator:	
Event	F kN	q mm	v mm	a mm	Δa mm	δ_J mm	J MJm^{-2}

[a] UC = unloading compliance; ACPD = alternating current potential drop; DCPD = direct current potential drop.

C.4 Qualification of K_Q as K_{Ic}

F_{max} =________________________ (kN)

$R_{p0,2}$ = (MPa) =________________________ (MPa)

F_Q = (kN) =________________________ (kN)

K_Q = (MPa $\sqrt{m}$) =________________________ (MPa $\sqrt{m}$)

a_o = (mm) =________________________ (mm)

B = (mm) =________________________ (mm)

$W - a_o$ = (mm) =________________________ (kN)

$2{,}5\left(\frac{K_Q}{R_{p0,2}}\right)^2$ =________________________(kN)

Requirements (see 8.4):

a) The data shall be qualified in accordance with 8.3;

b) $2{,}5\left(\frac{K_Q}{R_{p0,2}}\right)^2 \leq a_0$;

c) $2{,}5\left(\frac{K_Q}{R_{p0,2}}\right)^2 \leq B$;

d) $2{,}5\left(\frac{K_Q}{R_{p0,2}}\right)^2 \leq \left(W - a_0\right)$;

e) $\frac{F_{max}}{F_Q} \leq 1{,}10$, where F_{max} is the maximum force sustained by the specimen;

f) $K_f < 0{,}6\, K_Q \cdot \frac{\left(R_{p0,2}\right)_P}{\left(R_{p0,2}\right)_t}$.

If all requirements are met: K_{Ic} = (MPa√m)

C.5 Qualification of δ_J-R curve

a_0	=______________________ (mm)
B	=______________________ (mm)
$W - a_0$	=______________________ (mm)

Coefficients of power law fit to data $\delta_J = \alpha + \beta\, \Delta a^\gamma$:

α = ______________

β = ______________

γ = ______________

$\delta_{J,max}$ = smallest of: $\frac{B}{15}$, $\frac{a_0}{15}$ or $\frac{W - a_0}{15}$	______________________ (mm)
$\Delta a_{max} = 0{,}25(W - a_0)$	______________________ (mm)
$\delta_{J,g}$ (intersection of power law curve and limits set by $\delta_{J,max}$, Δa_{max} bounds)	______________________ (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 prediction	______________________ (%)

Requirements (see 8.5):

a) The data shall be qualified in accordance with 8.3;

b) The limit of applicability of the δ_J-R curve is set by $\delta_{J,g}$.

If all requirements are met, this power law represents a δ_J-R curve to $\delta_{J,g}$ in accordance with this method.

C.6 Qualification of J-R curve

a_0	=_________________ (mm)
B	=_________________ (mm)
$W - a_0$	=_________________ (mm)

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

α = _______________

β = _______________

γ = _______________

J_{max} = smallest of: $a_0 \dfrac{R_{p0,2} + R_m}{20}$, $B \dfrac{R_{p0,2} + R_m}{20}$ or $\left(W - a_0\right) \dfrac{R_{p0,2} + R_m}{20}$	=_________________ (kJ/m^2)
$\Delta a_{max} = 0{,}25(W - a_0)$	=_________________ (mm)
J_g (intersection of power law curve and limits set by J_{max}, Δa_{max} bounds)	=_________________ (kJ/m^2)
Measured final crack extension (if single-specimen method)	=_________________ (mm)
Estimated final crack extension (if single-specimen method)	=_________________ [mm]
Percentage error in final crack length prediction	=_________________ [%]

Requirements (see 8.6):

a) The data shall be qualified in accordance with 8.3;

b) The limit of applicability of the J-R curve is set by J_g.

If all requirements are met, this power law represents a J-R curve to J_g in accordance with this method.

C.7 Qualification of $\delta_{JQ0,2BL(B)}$ as $\delta_{J0,2BL}$

$R_{p0,2}$	=_________________ (MPa)
R_m	=_________________ (MPa)
$\delta_{JQ0,2BL}$	=_________________ (mm)
$15\delta_{JQ0,2BL}$	=_________________ (mm)
$d\delta_J/da$ in Δa_Q	=_________________ (MPa)

$(W - a_o)$ =__________________ (mm)

Measured final crack extension (if single-specimen method) =__________________ (mm)

Estimated final crack extension (if single-specimen method) =__________________ (mm)

Number specimens used, data points (if single-specimen method) ______________________

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

α = ______________

β = ______________

γ = ______________

Requirements (see 7.6.1):

a) The data shall be qualified in accordance with 8.3;

b) The slope $d\delta_J/da$ of the power law regression line evaluated at the 0,2 mm offset construction line, shall be less than 0,935 $(R_m/R_{p0,2})$;

c) $15\ \delta_{J0,2BL} \le a_0$;

d) $15\ \delta_{J0,2BL} \le B$;

e) $15\ \delta_{J0,2BL} \le \left(W - a_0\right)$.

If all requirements are met: $\delta_{J0,2BL}$ = ______ (mm)

C.8 Qualification of $J_{Q0,2BL}$ as $J_{0,2BL}$

a_o =__________________ (mm)

B =__________________ (mm)

$(W - a_o)$ =__________________ (mm)

$R_{p0,2}$ =__________________ (MPa)

R_m =__________________ (MPa)

$J_{Q0,2BL}$ =__________________ (MJ/m²)

$\dfrac{R_{p0,2} + R_m}{2}$ =__________________ (MPa)

dJ/da in Δa_Q =__________________ (MPa)

20 $J_Q(R_{p0,2} + R_m)$ =__________________ (mm)

Measured final crack extension (if single-specimen method) =__________________ (mm)

Estimated final crack extension (if single-specimen method) =__________________ (mm)

Number specimens used, data points (if single-specimen method) ______________________

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

α = ______________

β = ______________

γ = ______________

Requirements (see 7.6.2):

a) The data shall be qualified in accordance with 8.3;

b) The slope of the power law regression line, dJ/da, evaluated at the 0,2 mm offset construction line, shall be less than 1,875 R_m;

c) $20\,\dfrac{J_{0,2BL}}{R_{p0,2}+R_m} \le a_0\,;$

d) $20\,\dfrac{J_{0,2BL}}{R_{p0,2}+R_m} \le B\,;$

e) $20\,\dfrac{J_{0,2BL}}{R_{p0,2}+R_m} \le \left(W - a_0\right).$

If all requirements are met: $J_{0,2BL}$ = ______________ (MJ/m^2)

Annex D
(normative)

Stress intensity factor coefficients and compliance relationships

D.1 Stress intensity factor coefficients

D.1.1 Three-point bend specimens

For three-point bend specimens, the stress intensity factor coefficient $g_1(a_o/W)$ is given in Reference [10].

$$g_1\left(\frac{a_o}{W}\right)=\frac{3\left(\frac{a_o}{W}\right)^{0,5}\left[1,99-\frac{a_o}{W}\left(1-\frac{a_o}{W}\right)\left(2,15-\frac{3,93a_o}{W}+\frac{2,7a_o^2}{W^2}\right)\right]}{2\left(1+\frac{2a_o}{W}\right)\left(1-\frac{a_o}{W}\right)^{1,5}} \tag{D.1}$$

NOTE To facilitate the calculation of K, values of $g_1(a_o/W)$ are given in Table D.1 for specific values of a_o/W.

D.1.2 Compact specimens

For compact specimens, the stress intensity factor coefficient $g_2(a_o/W)$ is given in Reference [10].

$$g2\left(\frac{a_o}{W}\right)=\frac{\left(2+\frac{a_o}{W}\right)\left[0,886+4,64\frac{a_o}{W}-13,32\left(\frac{a_o}{W}\right)^2+14,72\left(\frac{a_o}{W}\right)^3-5,6\left(\frac{a_o}{W}\right)^4\right]}{\left(1-\frac{a_o}{W}\right)^{1,5}} \tag{D.2}$$

NOTE To facilitate the calculation of K, values of $g_2(a_o/W)$ are given in Table D.2 for specific values of a_o/W.

Table D.1 — Values of $g_1(a_0/W)$ for three-point bend specimens

a/W	$g_1(a_0/W)$	a/W	$g_1(a_0/W)$
0,450	2,29	0,575	3,43
0,455	2,32	0,580	3,50
0,460	2,35	0,585	3,56
0,465	2,39	0,590	3,63
0,470	2,43	0,595	3,70
0,475	2,46	0,600	3,77
0,480	2,50	0,605	3,85
0,485	2,54	0,610	3,92
0,490	2,58	0,615	4,00
0,495	2,62	0,620	4,08
0,500	2,66	0,625	4,16
0,505	2,70	0,630	4,25
0,510	2,75	0,635	4,34
0,515	2,79	0,640	4,43
0,520	2,84	0,645	4,53
0,525	2,89	0,650	4,63
0,530	2,94	0,655	4,73
0,535	2,99	0,660	4,84
0,540	3,04	0,665	4,95
0,545	3,09	0,670	5,06
0,550	3,14	0,675	5,18
0,555	3,20	0,680	5,30
0,560	3,25	0,685	5,43
0,565	3,31	0,690	5,57
0,570	3,37	0,695	5,71
		0,700	5,85

Table D.2 — Values of $g_2(a_o/W)$ for compact specimens

a/W	$g_2(a_o/W)$	a/W	$g_2(a_o/W)$
0,450	8,34	0,575	12,42
0,455	8,46	0,580	12,65
0,460	8,58	0,585	12,89
0,465	8,70	0,590	13,14
0,470	8,83	0,595	13,39
0,475	8,96	0,600	13,65
0,480	9,09	0,605	13,93
0,485	9,23	0,610	14,21
0,490	9,37	0,615	14,50
0,495	9,51	0,620	14,80
0,500	9,66	0,625	15,11
0,505	9,81	0,630	15,44
0,510	9,96	0,635	15,77
0,515	10,12	0,640	16,12
0,520	10,29	0,645	16,48
0,525	10,45	0,650	16,86
0,530	10,63	0,655	17,25
0,535	10,80	0,660	17,65
0,540	10,98	0,665	18,07
0,545	11,17	0,670	18,52
0,550	11,36	0,675	18,97
0,555	11,56	0,680	19,44
0,560	11,77	0,685	19,94
0,565	11,98	0,690	20,45
0,570	12,20	0,695	20,99
		0,700	21,55

D.2 Elastic compliance relationship

D.2.1 Three-point bend specimens instrumented for measurement of force *F* versus crack-mouth opening displacement V_{M1}

For three-point bend specimens instrumented for measurement of force *F* versus crack-mouth opening displacement V_{M1}, the elastic compliance V_{M1}/F is given in Reference [11].

$$\frac{V_{M1}}{F} = \frac{S\left(1-\nu^2\right)}{EB_eW} \cdot g_3\left(\frac{a}{W}\right) \tag{D.3}$$

where

$$B_e = B - \frac{\left(B-B_N\right)^2}{B};$$

$$g_3\left(\frac{a}{W}\right) = 6\ \frac{a}{W}\left[0{,}76 - 2{,}28\ \frac{a}{W} + 3{,}87\left(\frac{a}{W}\right)^2 - 2{,}04\left(\frac{a}{W}\right)^3 + \frac{0{,}66}{\left(1-\frac{a}{W}\right)^2}\right].$$

D.2.2 Straight-notch compact specimens instrumented for measurement of *F* versus crack-mouth opening displacement V_{M2}

For straight-notch compact specimens instrumented for measurement of *F* versus crack-mouth opening displacement V_{M2}, the elastic compliance V_{M2}/F is given in Reference [12].

$$\frac{V_{M2}}{F} = \frac{1-\nu^2}{EB_e} \cdot g_4\left(\frac{a}{W}\right) \tag{D.4}$$

where

$$B_e = B - \frac{\left(B-B_N\right)^2}{B};$$

$$g_4\left(\frac{a}{W}\right) = \frac{19{,}75}{\left[1-\left(\frac{a}{W}\right)\right]^2}\left[0{,}5 + 0{,}192\ \frac{a}{W} + 1{,}385\left(\frac{a}{W}\right)^2 - 2{,}919\left(\frac{a}{W}\right)^3 + 1{,}842\left(\frac{a}{W}\right)^4\right].$$

D.2.3 Three-point bend specimens instrumented for measurement of *F* versus load-line displacement q_{e1}

For three-point bend specimens instrumented for measurement of *F* versus load-line displacement q_{e1}, the elastic compliance q_{e1}/F is given in Reference [13].

$$\frac{q_{e1}}{F} = \frac{1-\nu^2}{EB_e}\left(\frac{S}{W-a}\right)^2 \cdot g_5\left(\frac{a}{W}\right) \qquad \text{(D.5)}$$

where

$$B_e = B - \frac{(B-B_N)^2}{B};$$

$$g_5\left(\frac{a}{W}\right) = 1,193 - 1,980\ \frac{a}{W} + 4,478\left(\frac{a}{W}\right)^2 - 4,443\left(\frac{a}{W}\right)^3 + 1,739\left(\frac{a}{W}\right)^4.$$

D.2.4 Stepped-notch compact specimens instrumented for measurement of *F* versus load-line displacement q_{e2}

For stepped-notch compact specimens instrumented for measurement of *F* versus load-line displacement q_{e2} the elastic compliance q_{e2}/F is given in Reference [14].

$$\frac{q_{e2}}{F} = \frac{1-\nu^2}{EB_e} \cdot g_6\left(\frac{a}{W}\right) \qquad \text{(D.6)}$$

where

$$B_e = B - \frac{(B-B_N)^2}{B};$$

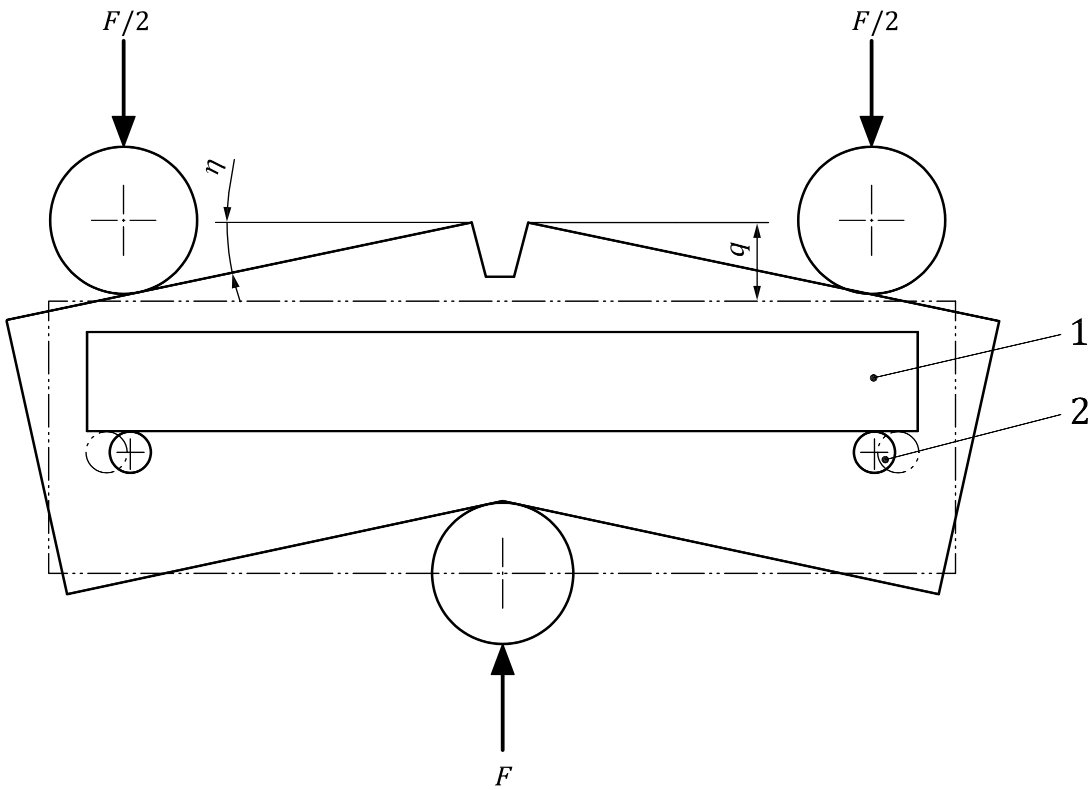
$$g_6\left(\frac{a}{W}\right) = \left(\frac{W+a}{W-a}\right)^2\left[2,163 + 12,219\frac{a}{W} - 20,065\left(\frac{a}{W}\right)^2 - 0,9925\left(\frac{a}{W}\right)^3 + 20,609\left(\frac{a}{W}\right)^4 - 9,9314\left(\frac{a}{W}\right)^5\right].$$

Annex E
(informative)

Measurement of load-line displacement *q* in the three-point bend test

One method for determining K_{Ic} values (see 6.2), and the general method for determining J values (see 6.4), require measurement of load-line displacement q; however, it is difficult to obtain direct measurements of load-line displacement for the three-point bend specimen. The difficulty lies in separating the true load-line displacement of the specimen from elastic-plastic displacement attributed to deformation of the specimen under the three points of loading and elastic displacements in the loading fixtures and testing machine components. These extraneous displacements are additive, so that measurements of machine ram or crosshead displacement, or relative displacements between the specimen and testing machine, all overestimate the true load-line displacement. The extent of such overestimates varies with specimen material, condition and temperature, the loading rate, and the dimensions of the specimen, loading fixtures and testing machine.

The only way to obtain load-line displacement directly is to measure the relative movement of appropriate points on the specimen. This can be done by measuring the vertical displacement of the notch tip relative to fixed points on the specimen's "neutral axis" above the outer load points. In practice this is done in converse. Use is made of a horizontal "comparator" (see Reference [15]) bar whereby vertical displacement of the bar is measured relative to the notch tip, or notch mouth, as shown schematically in Figure E.1.



Key

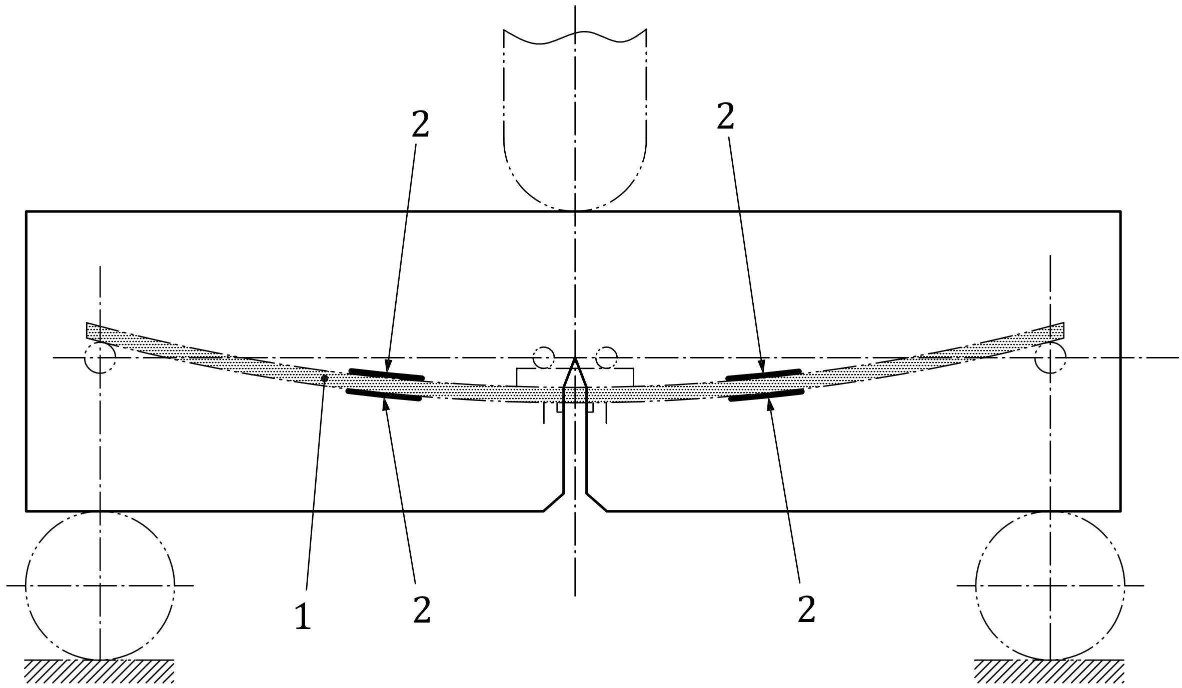
1 comparator bar

2 pin

Figure E.1 — Principle of the "comparator" bar measurement

NOTE 1 Measurements made relative to the notch mouth (see Figure E.1) represent the load-line displacement q to an accuracy of better than ±2 % for q equal to or less than 0,14W, which corresponds to a total notch opening angle θ of 8°.

An alternative device (see Reference [16]) for direct load-line displacement measurement is the “flex bar” shown in Figure E.2. A four-arm strain gauge bridge installed on the 0,50 mm to 0,75 mm-thick flex bar provides a transducer accurate to ±2 % for q values up to 0,14W.

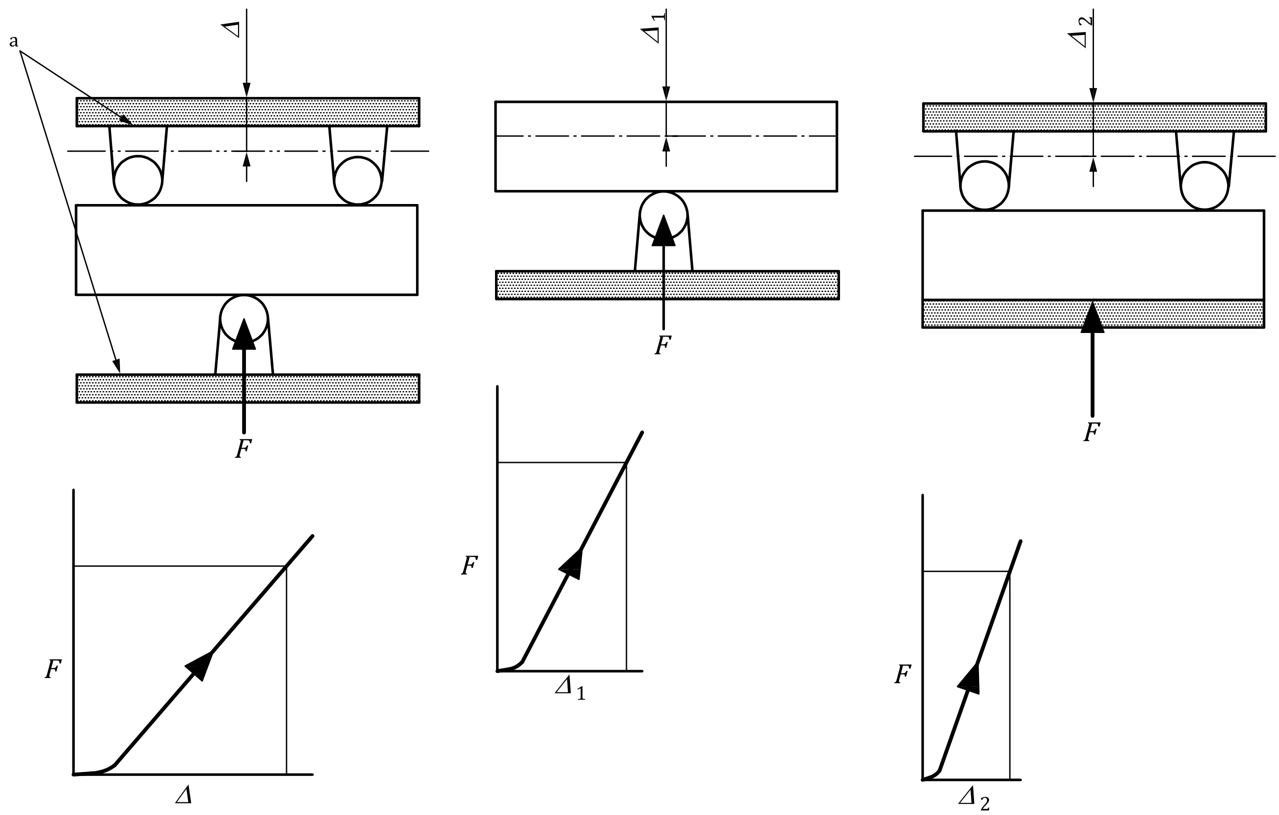


Key

1 flex bar

2 strain gauges

Figure E.2 — Diagram of three-point bend static test arrangement showing details of flex bar and specimen supports



a) Crosshead displacement, Δ

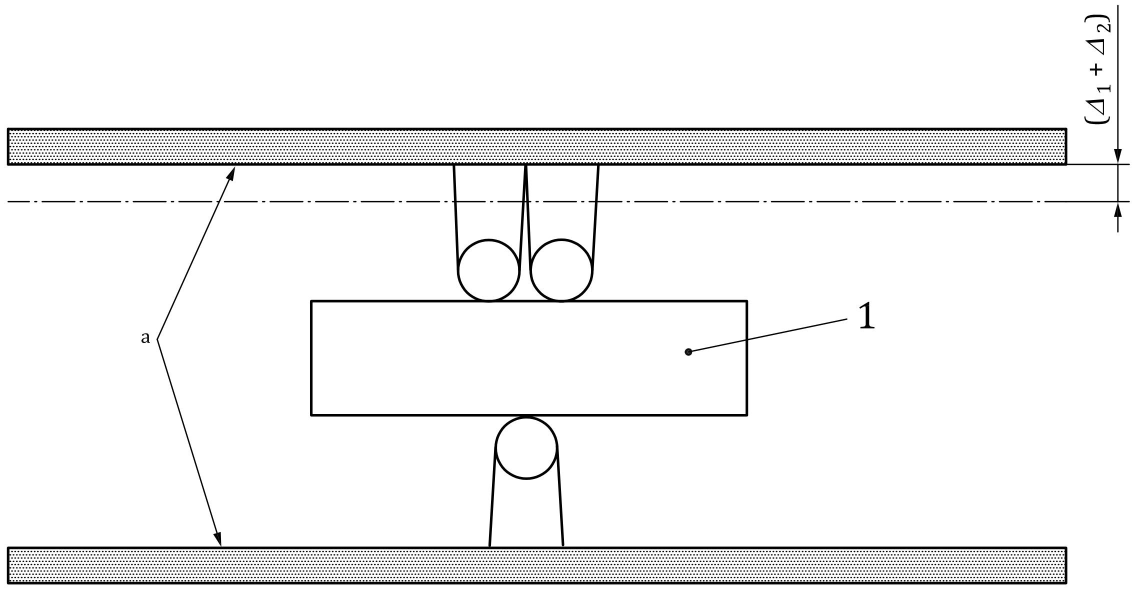
b) Elastic plastic indentation of specimen and compression of central roller and anvil, Δ_1

c) Elastic plastic indentation of specimen and compression of outer roller and anvils, Δ_2

Key

a Reference faces.

Figure E.3 — Displacements associated with three-point bend specimens



Key

1 unnotched specimen

a Reference faces.

Figure E.4 — Simultaneous determination of extraneous displacements ($\Delta_1 + \Delta_2$)

For tests terminating at or before maximum force, indirect measurements of load-line displacement may be made by

a) measuring extraneous displacements separately, and then subtracting them from total machine crosshead displacement. Thus, referring to Figure E.3, load-line displacement q at any force F is $q = \Delta - \Delta_1 - \Delta_2$. The extraneous displacement $\Delta_1 + \Delta_2$ is measured with the loading points close together as shown in Figure E.4, and

b) loading an unnotched specimen of the same geometry, size and material as the precracked test specimen, to determine system compliance from remote load-line displacement measurements over the range of forces anticipated in the fracture test. Unnotched specimen compliance, calculated using elastic beam formulae, is subtracted from the remote load-line compliance to yield machine/fixture compliance. The machine/fixture compliance is, in turn, subtracted from the remote load-line compliance for the subsequent fracture test to obtain the fracture test load-line compliance q/F, and hence load-line displacement.

NOTE 1 The above indirect methods need to be modified for q measurements beyond maximum force (see Reference [17]).

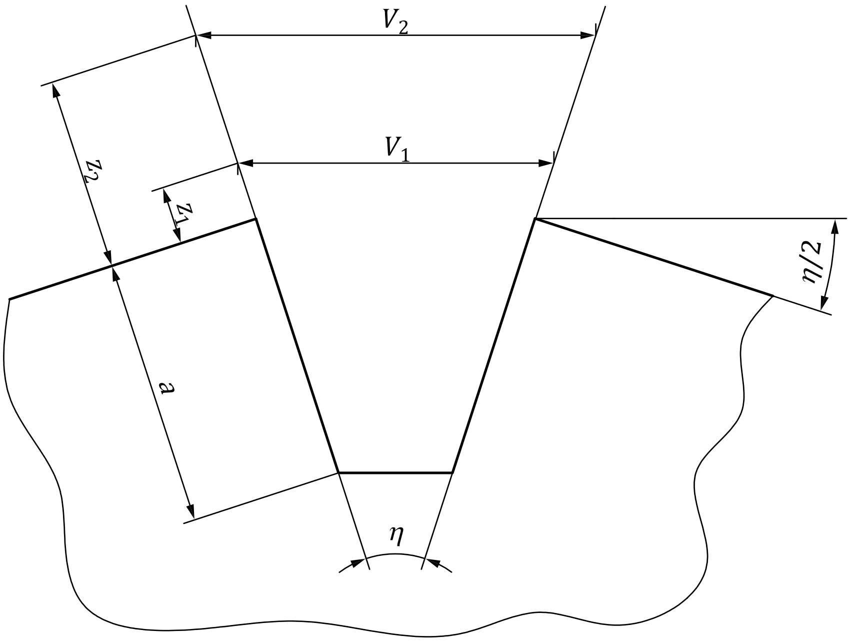


Figure E.5 — Location of two notch-opening displacements measurements (V_1 and V_2) for the determination of load-line displacement

An alternative indirect measurement of load-line displacement, equally suitable before or after maximum force, is made using two separate, simultaneous measurements of notch-opening displacement. Using one notch-opening displacement gauge located near the notch mouth, and a second located above the notch mouth (see Figure E.5), the load-line displacement (see Reference [18]) is determined from:

$$q = \frac{S\left(V_2 - V_1\right)}{4\left(z_2 - z_1\right)} \tag{E.1}$$

NOTE 2 Formula (E.1) assumes that the bend specimen deforms as two rigid halves about a centre of rotation, and that S is the actual span (though it may vary during the test). Under these conditions, Formula (E.1) underestimates q by less than 1 % for a total notch opening angle θ < 8°. For $\theta \geq$ 8°, the load-line displacement may be estimated with similar accuracy from:

$$q = \frac{S}{2}\tan\left\{\arcsin\left[\frac{V_2 - V_1}{2\left(z_2 - z_1\right)}\right]\right\} \tag{E.2}$$

Annex F
(informative)

Derivation of pop-in formulae

Referring to Figure F.1, and the similar triangles OAD and OBC, it can be seen that:

$$\mathrm{AD} = \mathrm{BC} \times \frac{\mathrm{OD}}{\mathrm{OC}} = \frac{Q_1\left(F_n - y_n\right)}{Q_n + x_n} \tag{F.1}$$

and

$$\Delta F_n = F_1 - \mathrm{AD} = F_1 - \frac{Q_1\left(F_n - y_n\right)}{Q_n + x_n} \tag{F.2}$$

Hence,

$$\frac{\Delta F_n}{F_1} = 1 - \frac{Q_1}{F_1}\left(\frac{F_n - y_n}{Q_n + x_n}\right) \tag{F.3}$$

For simplicity, if

$$\frac{\Delta F_n}{F_1} = P \tag{F.4}$$

then

$$P = 1 - \frac{Q_1}{F_1}\left(\frac{F_n - y_n}{Q_n + x_n}\right) \tag{F.5}$$

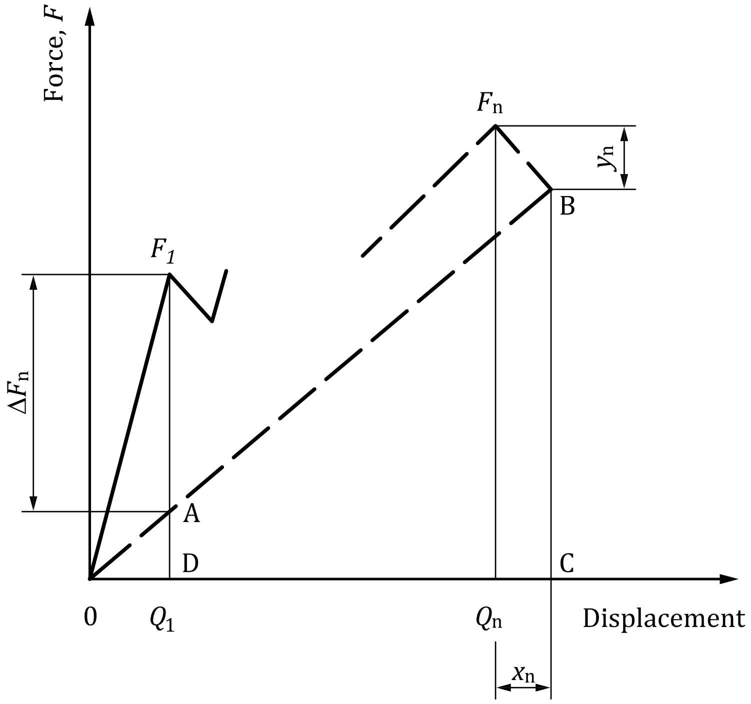


Figure F.1 — Forces and elastic displacements associated with multiple pop-ins

Annex G
(informative)

Analytical methods for the determination of V_p and U_p

G.1 General

These analytical methods are based on elastic compliance relationships.

G.2 Plastic displacement, V_p

The plastic displacement, V_p, (Figure 17) is determined from total notch-opening displacement, V_g, at the force, F, of interest using the relationship:

$$V_p = V_g - V_e \tag{G.1}$$

where V_e is given by the following:

a) Three-point single-edge-notched bend specimens, having $S = 4\,W$ (see References [19] to [21]).

$$V_e = V_{M1}\left(1 + \frac{z}{0,8a + 0,2W}\right) \text{for } \frac{z}{a} \le 0,2 \tag{G.2}$$

where V_{M1} is given by Formula (D.3).

b) Straight-notch compact specimen (see References [19] to [21]).

$$V_e = V_{M2}\left(1 + \frac{z}{0,8a + 0,2W}\right) \text{for } \frac{z}{a} \le 0,2 \tag{G.3}$$

where V_{M2} is given by Formula (D.4).

c) Stepped-notch compact specimen (see References [19] to [21]).

$$V_e = q_{e2}\left(1 + \frac{z}{0,8a + 0,2W}\right) \text{for } \frac{z}{a} \le 0,2 \tag{G.4}$$

where q_{e2} is given by Formula (D.6).

G.3 Plastic area, U_p

The plastic area, U_p, (see Figure 18) is determined from the total area U at the force of interest using:

$$U_p = U - U_e \tag{G.5}$$

where U_e is given by the following:

a) Three-point bend specimen;

$$U_e = \frac{Fq_{e1}}{2} \tag{G.6}$$

where q_{e1} is given by Formula (D.5).

b) Stepped-notch compact specimen;

$$U_e = \frac{Fq_{e2}}{2} \tag{G.7}$$

where q_{e2} is given by Formula (D.6).

Annex H
(informative)

Guidelines for single-specimen methods

H.1 General

Guidance is given in this Annex for measuring crack extension in a specimen based on the unloading compliance and potential drop techniques (see Reference [22]).

By the unloading compliance technique (see References [23] to [29]) a specimen is partially unloaded and then reloaded at specified intervals during the test. The unloading slopes, which tend to be linear and independent of prior plastic deformation, are used to estimate the crack length at each unloading from analytical elastic compliance relationships. The specimen compliance is determined from either mouth-opening or load-point compliance, and the crack length is estimated using formulae given below. If the displacement is measured at an alternative point, then the appropriate compliance function should be developed and utilized. For bend specimens, compliance can be measured from the load-point displacement transducer used for J determination. However, it is recommended that an additional transducer, situated at the mouth opening, be used for crack length estimation. Errors may occur in the compliance measurement as a result of transducer nonlinearity. Significant improvement in accuracy can be achieved by curve-fitting the lowest-order polynomial function possible through the calibration data.

The electrical potential technique (see References [30] to [41]) relies on the fact that the distribution of electrical potential in the vicinity of a crack changes with crack extension. With suitable instrumentation, the changes in potential can be detected and calibrated to provide an estimate of increase in crack length. The applied potential is either direct or alternating and the procedure referred to as either the DC or the AC potential technique respectively.

Both techniques are ideally suited to computer control and subsequent analysis of the test data. However, it should be noted that both require careful experimentation and sophisticated test equipment in order to realize their full capability.

The data points from qualified tests used to demonstrate the accuracy of the test equipment can be combined to generate a single crack extension resistance curve. The distribution of the points is described in 7.4.2.

H.2 Unloading compliance technique

Several procedures have been written for the unloading compliance technique of crack length estimation (see References [23] to [29]).

The elastic compliance, C, is determined at each (k^{th}) unloading/reloading event performed during the test from

$$C_k = \left(\frac{\Delta q}{\Delta F} \right)_k \tag{H.1}$$

where q is the appropriate displacement.

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

$$\left(\frac{a}{W}\right)_k = f\left(C_k\right) \quad \text{(H.2)}$$

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

H.3 Test recommendations

NOTE The following additional items have been found helpful in generating high quality single-specimen data.

H.3.1 Compliance measurement

Errors may occur in compliance measurements as a result of transducer nonlinearity. Significant improvement in accuracy is possible by curve-fitting the lowest-order possible polynomial function through the calibration data.

H.3.2 Digital signal resolution

For unloading compliance measurement, the digitized displacement resolution Δq shall be better than

$$\Delta q = \frac{W' R_{p0,2}}{500E} \quad \text{(H.3)}$$

where W' is the lesser of 50 mm or the specimen width.

The corresponding digital force resolution ΔF shall be better than

$$\Delta F = \frac{BW' R_{p0,2}}{15\ 000} \quad \text{(H.4)}$$

A 16-bit analogue-to-digital converter should meet the requirements for most applications. It is permissible to amplify the force and displacement signals to attain a satisfactory level for digitization.

For the duration of test, the stability of the digitized force and displacement signals shall be less within $4\Delta F$ or $4\Delta q$, whichever is appropriate. The maximum signal noise shall be less than $\pm 2\Delta F$ or $\pm 2\Delta q$, whichever is appropriate.

H.3.3 Autographic signal resolution

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

H.4 Procedure

H.4.1 Precycling

Before commencing the test, it is recommended that the specimen be cycled several times in the elastic regime at test temperature to allow the specimen to “bed-in”. During this operation, the maximum applied force shall not exceed the final fatigue force (see Reference [25]).

At least three unloading compliance measurements shall be made at a force less than the maximum permissible final fatigue force defined in 5.4.2.4.3. No value of the estimated crack length shall differ from the mean by more than 0,002 W. The maximum range of the unload/reload cycles shall not exceed 50 % of the actual maximum force used to measure the three initial unloadings.

Nonlinear parts of the force displacement record that may occur at low forces from crack closure effects shall be excluded from the compliance measurement.

H.4.2 Loading rate

The loading rate during unload/reload cycles shall be as rapid as possible to minimize time-dependent effects, but slow enough to ensure that sufficient data are recorded to enable the compliance of the specimen to be measured accurately. If possible, the loading rate during the unload/reload cycles shall not be less than that used between the unloadings. It is recommended that prior to each unloading, the displacement be held constant until force relaxation caused by time-dependent plasticity effects ceases.

H.4.3 Crack length measurements

Specimens are partially unloaded and reloaded during test at displacement intervals selected to ensure that evenly-spaced data points are obtained. Typically 30 unloadings are sufficient to define crack extension fracture resistance behaviour and to meet the data spacing requirement given in 7.4.2. It is recommended that the unloading range be as small as practicable but not exceed 25 % of the maximum force F_L evaluated from 5.6.2, or 50 % of the current force value, whichever is smaller.

At each unloading, the crack length a, δ, or J, shall be evaluated, as appropriate, using the formulae given in H.5 and 7.3 of the procedure. In the case of computerized test systems, compliance is generally determined by performing a regression analysis of the recorded data.

H.4.4 Termination of test

After final unloading, the force shall be reduced to zero, ensuring no further increase in displacement. The extent of stable crack extension is determined as described in 5.8.

The specimen is broken open at or below room temperature to reveal the fracture surfaces. Initial crack length a_0 is measured and the total crack extension marked using the procedure described in 5.8.

H.5 Crack length calculation

H.5.1 Bend specimen: Crack-mouth opening displacement (CMOD) measured at the specimen surface

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

$$\frac{a}{W} = 0,999\,748 - 3,950\,4\mu + 2,982\,1\mu^2 - 3,214\,08\mu^3 + 51,515\,6\mu^4 - 113,031\mu^5 \qquad \text{(H.5)}$$

where

$$\mu = \frac{1}{\left(\frac{4W}{S} B_e \lambda EC\right)^{1/2} + 1}; \qquad \text{(H.6)}$$

$$B_e = B - \frac{\left(B - B_N\right)^2}{B};$$

$$\text{coefficient } \lambda = \frac{g_3\left(\dfrac{a_0}{W}\right)}{g_3\left(\dfrac{a_{0,\text{est}}}{W}\right)}; \tag{H.7}$$

in which

a_0 is the original crack size as optically measured in 5.8.2;

$a_{0,\text{est}}$ is the original crack size as estimated from Formula (H.5);

the function $g_3\left(\dfrac{a}{W}\right)$ is obtained from Annex D.

The coefficient λ is intended to correct for experimental uncertainties that often occur in the unloading compliance test. λ shall not deviate from one by more than 10 % of the specimen unloading compliance. If it does, then the test is invalid.

H.5.2 Bend specimen: Compliance based on load-point displacement

The crack length corresponding to specimen compliance, C, determined from load-point displacement for $S/W = 4$ is given by

$$\frac{a}{W} = 0,987\ 4 - 3,625\mu - 13,98\mu^2 + 94,52\mu^3 - 327,8\mu^4 \tag{H.8}$$

where

$$\mu = \frac{1}{\left(B_\text{e}\lambda EC\right)^{1/2} + 1};$$

$$B_\text{e} = B - \frac{\left(B - B_\text{N}\right)^2}{B};$$

$$\text{coefficient } \lambda = \frac{g_5\left(\dfrac{a_\text{o}}{W}\right)}{g_5\left(\dfrac{a_{\text{o,est}}}{W}\right)}; \tag{H.9}$$

in which

a_0 is the original crack size as optically measured in 5.8.2;

$a_{0,\text{est}}$ is the original crack size as estimated from Formula (H.8);

the function $g_5\left(\dfrac{a}{W}\right)$ is obtained from Annex D.

The coefficient λ is intended to correct for experimental uncertainties that often occur in the unloading compliance test. λ shall not deviate from one by more than 10 % of the single-specimen unloading compliance, otherwise the test is not valid.

H.5.3 Compact specimens

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

$$\frac{a}{W} = 1{,}000\ 196 - 4{,}063\ 19\mu + 11{,}242\mu^2 - 106{,}043\mu^3 + 464{,}335\mu^4 - 650{,}677\mu^5 \qquad \text{(H.10)}$$

where

$$\mu = \frac{1}{\left(B_e \lambda E C\right)^{1/2} + 1}; \qquad \text{(H.11)}$$

$$B_e = B - \frac{\left(B - B_N\right)^2}{B};$$

$$\text{coefficient } \lambda = \frac{g_6\left(\dfrac{a_o}{W}\right)}{g_6\left(\dfrac{a_{o,est}}{W}\right)}; \qquad \text{(H.12)}$$

in which

a_o is the initial crack length as measured in 5.8.2;

$a_{o,est}$ is the estimated initial crack length as estimated from Formula (H.10);

the function $g_6\left(\dfrac{a}{W}\right)$ is obtained from Annex D.

This λ coefficient is intended to correct for experimental uncertainties that often occur in the unloading compliance test. λ shall not deviate from one by more than 10 % of the specimen unloading compliance. If it does, then the test is invalid.

H.5.4 Rotation correction for compact specimens

To account for the change in specimen geometry that occurs on loading, the measured load-line compliance is corrected for rotation as follows:

$$C_c = \frac{C}{\left(\frac{h}{r}\sin\theta - \cos\theta\right)\left(\frac{D}{r}\sin\theta - \cos\theta\right)} \quad \text{(H.13)}$$

where

C_c is the compliance corrected for rotation;

C is the measured compliance;

h is one half of the initial distance between the centres of the loading holes (see Figures 4 and 5);

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

θ is the angle of rotation given by $\theta = \arcsin\left[\frac{\frac{q}{2} + D}{\left(D^2 + r^2\right)^{1/2}}\right] - \arctan\left(\frac{D}{r}\right)$;

D is one half of the initial distance between the displacement measurement points;

q is the total measured load line displacement.

H.6 Resistance to crack extension

H.6.1 General

Ideally, resistance to crack extension is characterized as a monotonically increasing function of crack length (see Figure H.1). However, the unloading compliance technique does not always give this idealized behaviour. Discrepancies may include positive or negative offset from the original estimate of initial crack length, scatter in the data and apparent negative crack extension. These effects are made worse by problems in the testing fixture, transducer gauge seating, electronic noise and signal nonlinearity.

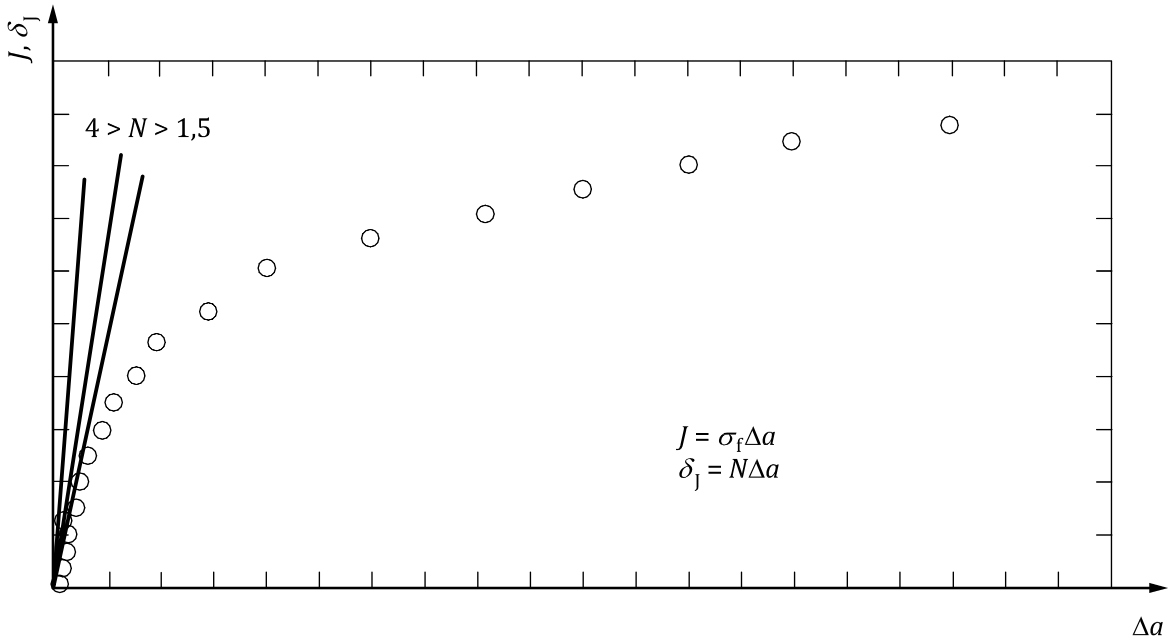


Figure H.1 — Ideal behaviour of crack-growth–fracture-resistance curve

H.6.2 Estimated initial crack length

A graph of estimated crack length, a, versus either δ_J or J is plotted as shown in Figure H.2.

Formula (H.14) or (H.15) shall be fitted from the minimum a_k estimated to the minimum a_k plus 2 mm, using the method of least squares. The estimated, best-fit, initial crack length is then $a_{o,est} = \Lambda$. If this $a_{o,est}$ differs from that used to calculate δ_J or J by more than 2 %, then all δ_J or J values shall be recalculated using the new $a_{o,est}$ and the formulae in 7.3.

$$a_k = \Lambda + \theta \delta_k^2 + \Psi \delta_k^3 \qquad \text{(H.14)}$$

$$a_k = \Lambda + \theta J_k^2 + \Psi \delta_k^3 \qquad \text{(H.15)}$$

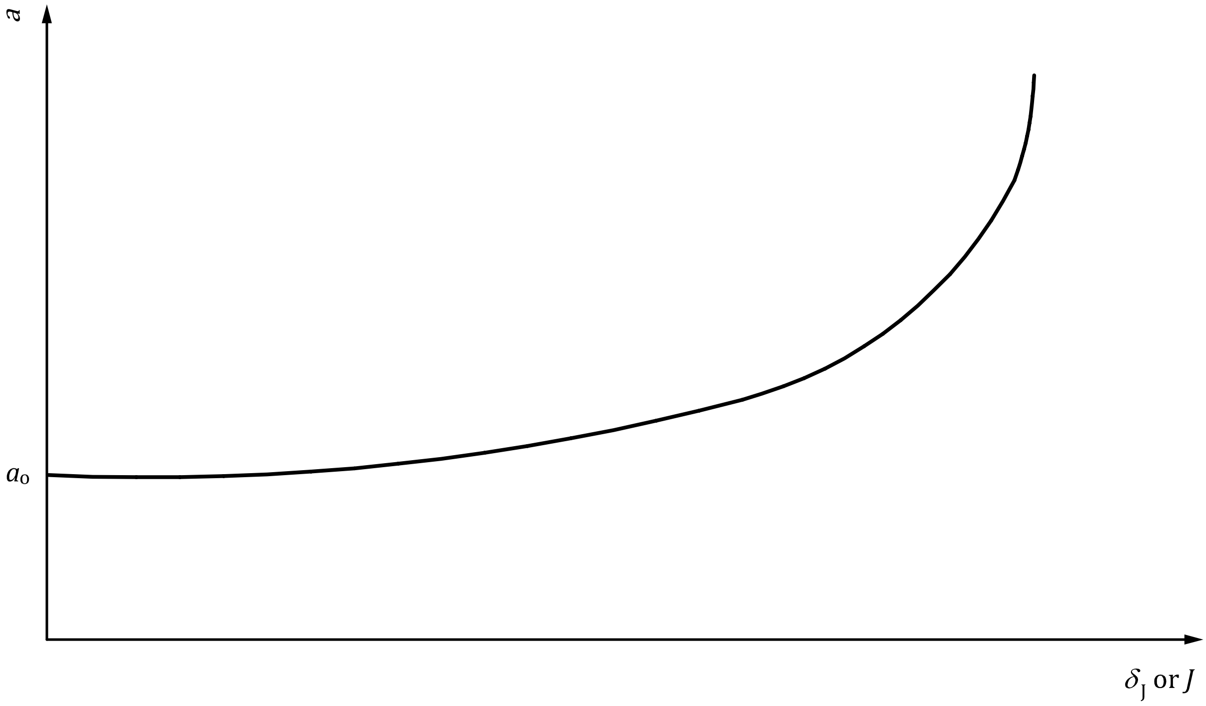


Figure H.2 — Typical plot of estimated crack length *a* versus δ_J or *J* from single specimen fracture test [using **Formulae (H.14)** and **(H.15)**]

H.6.3 Estimated crack extension

The estimated crack extension Δa_k at the k^{th} unloading shall be calculated from

$$\Delta a_k = a_k - a_{\text{o,est}} \tag{H.16}$$

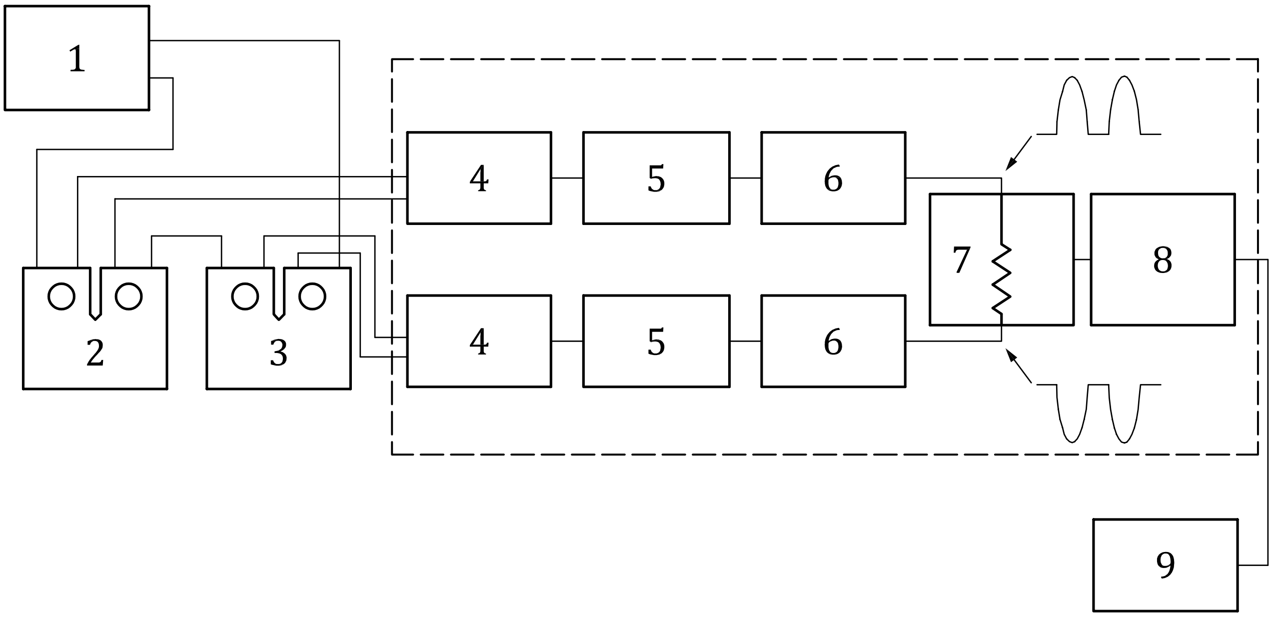
H.6.4 Resistance curves

Plots of δ_J or *J* against estimated crack extension Δa_k shall be constructed.

H.7 Electrical potential techniques

H.7.1 AC potential method

A typical AC potential test system is shown in Figure H.3. It is an indirect technique. In this system, the potential drop measured in the test specimen shall be compared with that produced by a reference specimen of identical geometry.



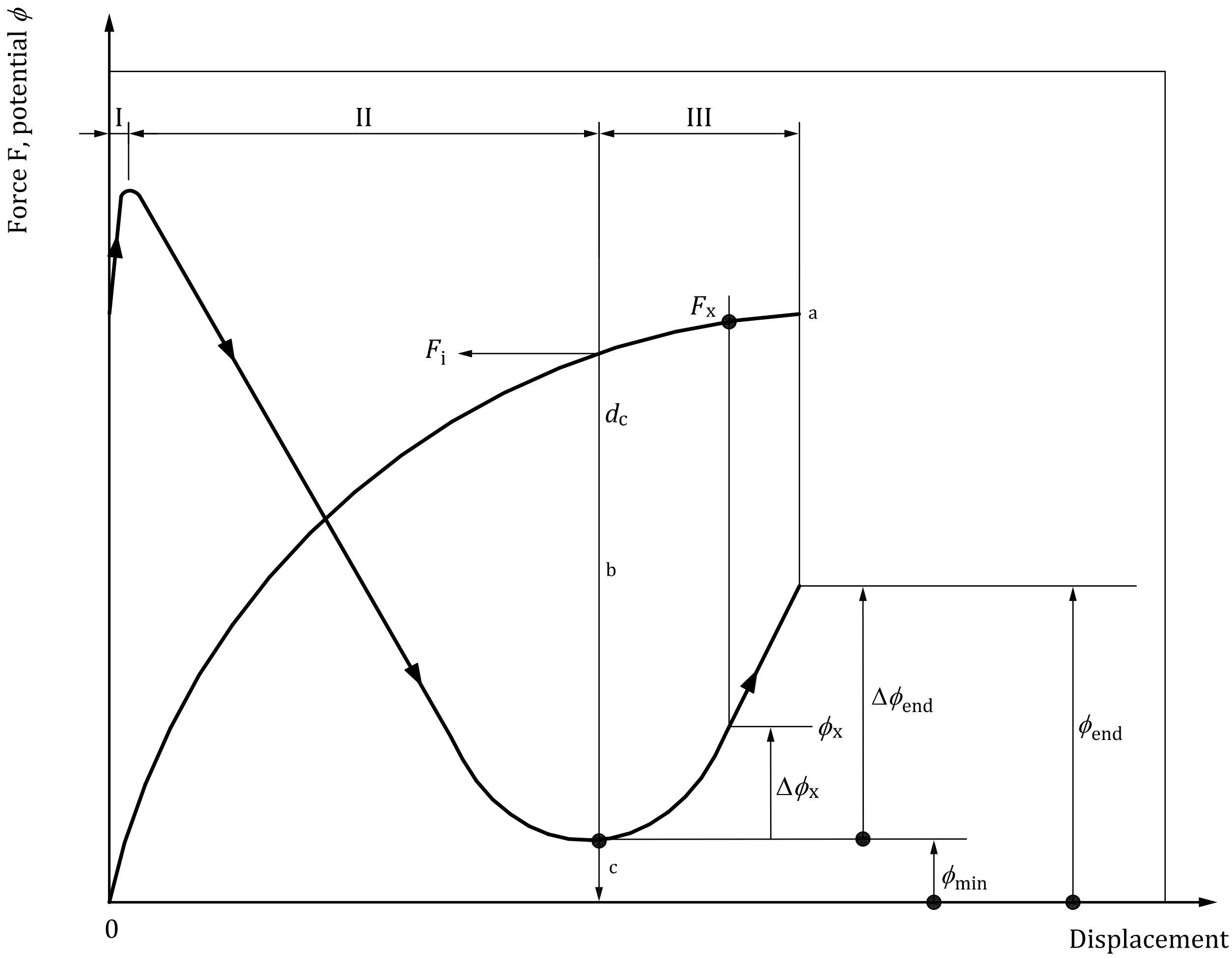
Key

1 regulated current source; F = 50 Hz, I = 20 A
2 reference specimen
3 test specimen
4 differential amplifier
5 two-stage selected amplifier band filter
6 linear detection
7 summation
8 DC amplifier with output adaptation
9 analogue recorder

Figure H.3 — Typical AC potential drop test system

The method described can only be used if a potential minimum is observed (see Figure H.4). This minimum shall be interpreted as the point of crack initiation.

The test specimen shall be loaded as described in 5.7, and test records of both force and potential obtained against either load-point or mouth-opening displacement. The general form of the test records is illustrated in Figure H.4.



Key

a End of loading.

b Estimate of initiation.

c Crack growth.

Figure H.4 — Typical AC potential drop test record

On completion of the test, the extent of stable crack extension shall be marked as described in 5.8 prior to breaking open the specimen.

The initial crack length a_0 and the total crack extension Δa shall be measured as described in 5.8.

Values for δ_{Ji} or J_i shall be determined at the point marked as F_i in Figure H.4, in accordance with 7.3.

The critical stretch zone width, Δa_{SZW}, shall be determined. See Annex A.

Alternatively, the critical stretch zone width, Δa_{SZW}, is determined using a scanning electron microscope (SEM).

H.7.2 Interpretation of test records

The minimum potential ϕ_{min} shall be identified on the potential versus displacement record.

The potential difference $\Delta\phi_{end}$ between ϕ_{min} and the potential at the end of the test ϕ_{end} shall be measured.

A graph of total crack extension versus potential difference as shown in Figure H.5 shall be constructed.

The points Δa_{SZW}, $\Delta\phi$ = 0 and Δa, $\Delta\phi_{end}$ shall be plotted and a straight line drawn between them, (see Figure H.5). This represents the calibration line for the specimen.

To determine the amount of total crack extension corresponding to the point F_x on the force–displacement record, the potential difference between ϕ_{min} and ϕ_x shall be recorded as indicated in Figure H.4. The amount of total crack extension corresponding to $\Delta\phi_x$ shall be estimated from the calibrated line similar to that in Figure H.5.

Values of δ_J or J for the force F_x shall be determined using the formulae given in 7.3. Plots of either δ_J or J versus estimated crack extension shall be constructed.

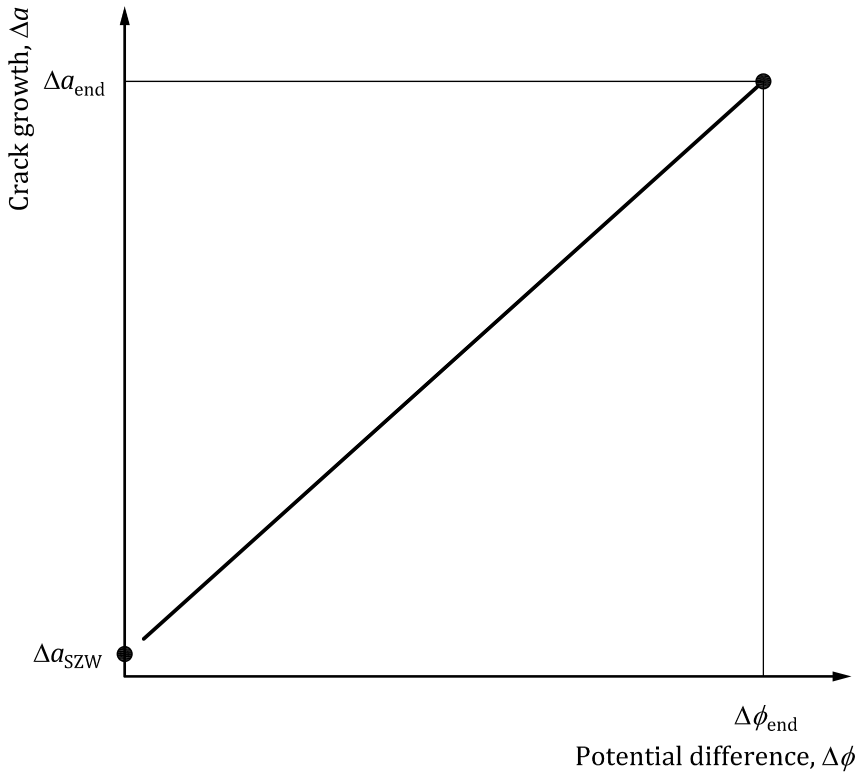


Figure H.5 — Plot of crack growth against potential difference

H.8 DC potential methods

H.8.1 Method 1

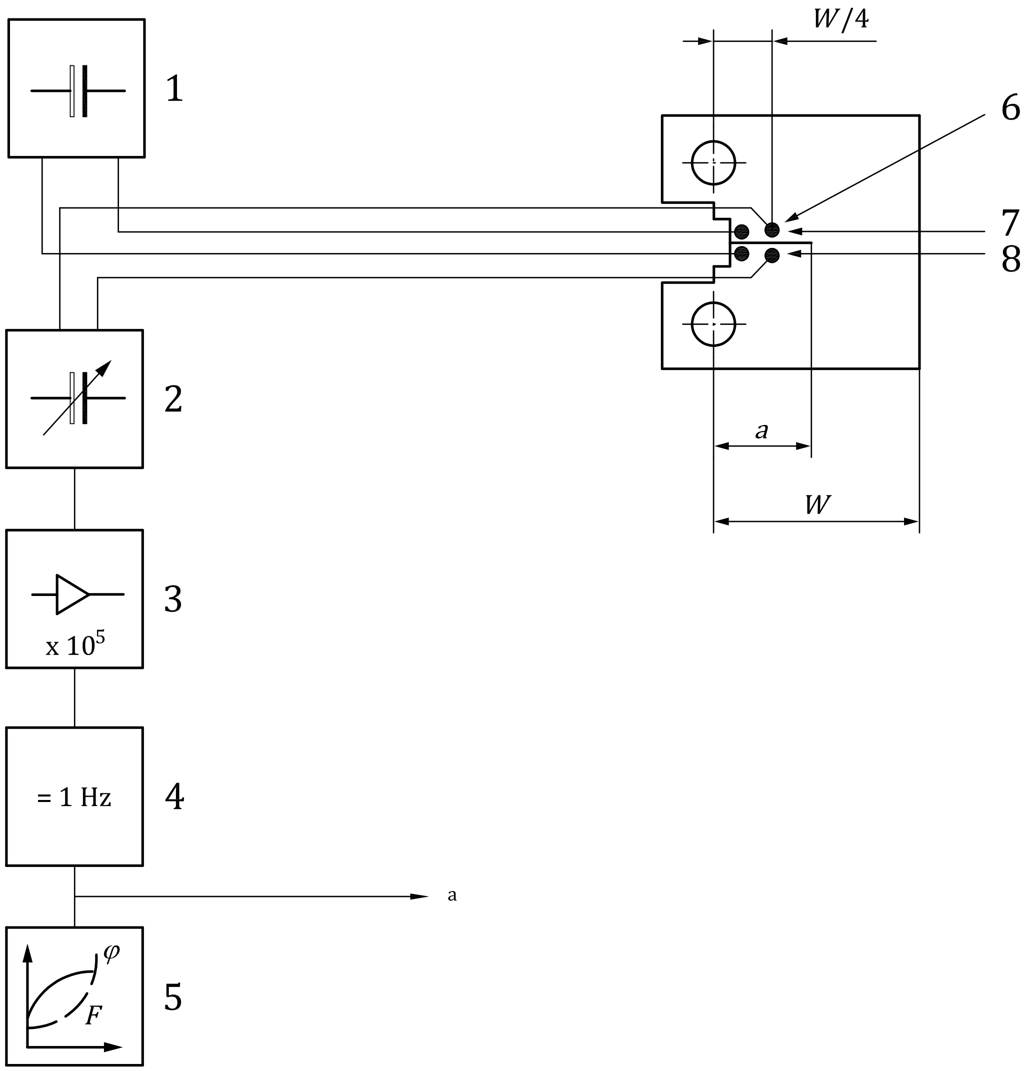
H.8.1.1 Procedure

A typical DC potential difference test system for method 1 is shown in Figure H.6. It is an indirect correlation technique.

The test specimen is loaded as described in 5.7, and test records of both force and potential against either load point or notch opening displacement obtained. The general form of the test records is illustrated in Figure H.7.

On completion of the test, the extent of stable crack extension shall be marked, as described in 5.8, prior to breaking open the specimen.

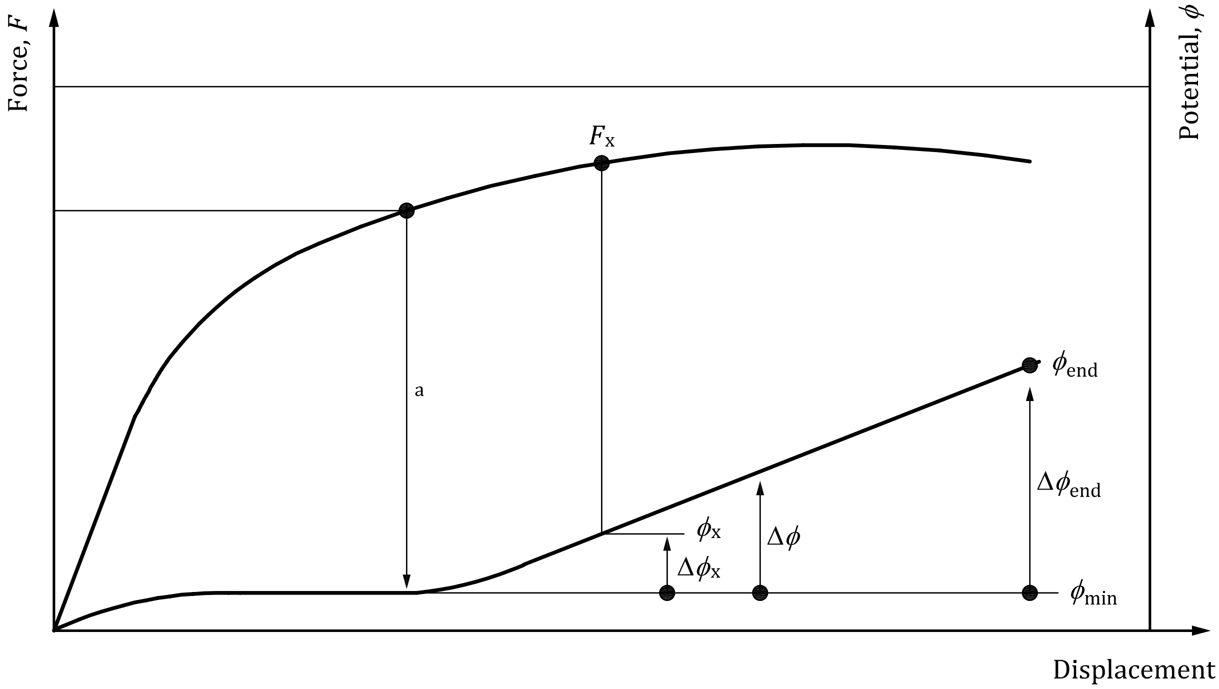
The initial crack length a_0 and the total crack extension Δa shall be measured as described in 5.8.



Key

1 DC constant current supply
2 variable zero suppression
3 nanovolt amplifier
4 filter
5 pen recorder
6 potential pick-up
7 front
8 rear
a To data acquisition.

Figure H.6 — Typical DC potential drop test system



Key

a Onset of stable crack growth.

Figure H.7 — Typical DC potential drop test record for system shown in Figure H.6

H.8.1.2 Interpretation of test records

The abrupt increase in slope of the potential versus displacement record shall be used as an estimate of the initiation of crack extension.

A value for Δa_{SZW} shall be determined as described in H.7.2.

The potential difference ($\Delta\phi_{end}$) between estimated initiation of crack extension and the potential at the end of the test shall be measured.

A graph of total crack extension against potential difference shall be plotted as shown in Figure H.5.

The points Δa_{SZW}, $\Delta\phi = 0$ and Δa_{end}, $\Delta\phi_{end}$ shall be plotted and a straight line drawn between them, (see Figure H.5). This straight line represents the calibration line for the specimen.

To determine the amount of total crack extension corresponding to a point F_x on the force-displacement record, the potential difference between ϕ_{min} and ϕ_x shall be recorded as indicated in Figure H.7. The amount of total crack extension corresponding to $\Delta\phi_x$ can be estimated from the calibrated line similar to that in Figure H.5.

Values of δ or J shall be determined for the force F_x using the formulae given in 7.3. Plots of either δ or J versus estimated crack extension shall be constructed.

H.8.2 Method 2

H.8.2.1 Procedure

A typical DC potential test system for method 2 is shown in Figure H.8. It represents a direct crack length prediction technique.

The specimen shall be loaded as described in 5.7 and records of force against displacement and potential obtained. The general form of the force potential test record is illustrated in Figure H.9.

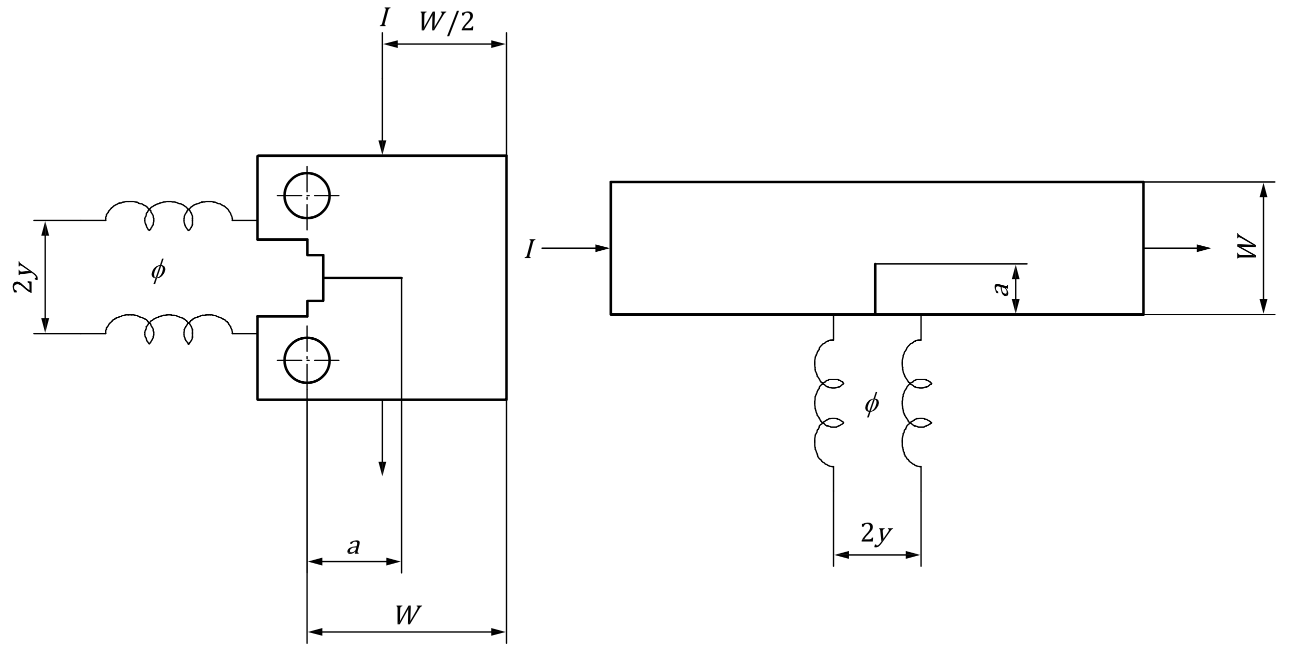
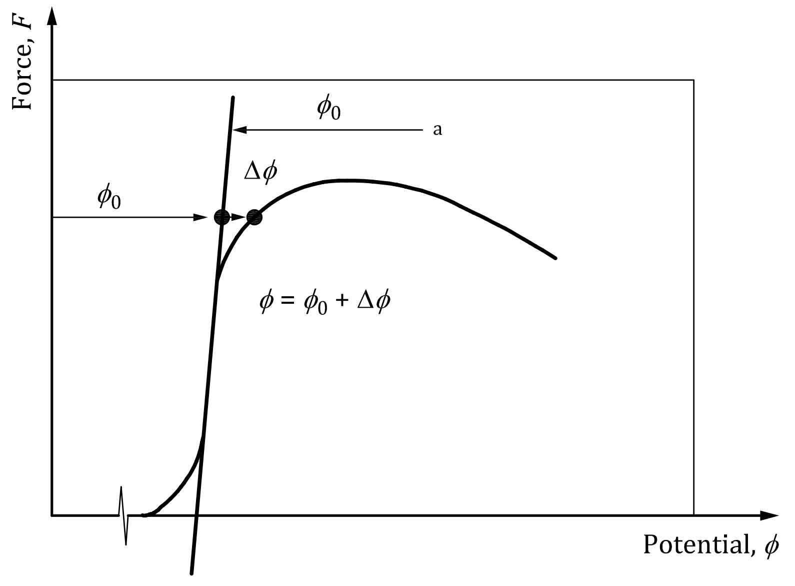


Figure H.8 — Alternative DC potential drop test system



Key

a Base line.

Figure H.9 — Typical DC potential drop test record for the system in Figure H.8

On completion of the test, the extent of stable crack extension is marked as described in 5.8 before breaking open the specimen.

The initial crack length a_0 and the total crack extension Δa shall be measured as described in 5.8.

H.8.2.2 Interpretation of test records

A straight line shall be constructed through the steeply rising part of the force versus potential record as shown in Figure H.9.

For any force of interest, ϕ_0 and $\Delta\phi$ shall be measured as shown in Figure H.9 and the following evaluated:

$$\phi = \phi_0 + \Delta\phi \tag{H.17}$$

The crack length corresponding to the selected force shall be calculated using the following expression:

$$a = \frac{2W}{\pi}\cos^{-1}\frac{\cosh\left(\dfrac{\pi y}{2W}\right)}{\cosh\left\{\dfrac{\phi}{\phi_0}\cdot\cosh^{-1}\left[\dfrac{\cosh\left(\dfrac{\pi y}{2W}\right)}{\cos\left(\dfrac{\pi a_0}{2W}\right)}\right]\right\}} \tag{H.18}$$

where y is defined in Figure H.8.

The corresponding crack extension Δa is given by

$$\Delta a = a - a_0 \tag{H.19}$$

Values of δ_J or J shall be determined for the force of interest using the formulae given in 7.3. Plots of either δ_J or J against estimated crack extension Δa shall be constructed.

Annex I
(normative)

Power-law fits to crack extension data (see Reference [42])

The form of Formula (I.1) shall be fitted to the crack extension data y_i versus Δa_i

$$y = c + m\,\Delta a^n \tag{I.1}$$

and is equivalent to the form given in the main text, i.e.

$$\delta_J \text{ or } J = \alpha + \beta\left(\Delta a\right)^\gamma \tag{I.2}$$

where y is either δ_J or J, Δa is the crack extension, and the constants $m = \beta$, $n = \gamma$ and $c = \alpha$.

$x = \Delta a^n$ is substituted into the formula to enable m and c to be evaluated using linear regression in statistical analysis packages or hand calculators.

The value of n is chosen that will maximize the correlation coefficient.

A detailed approach for doing this follows.

Values of n are taken from 0 to 1 in steps of 0,01. For each value of n, $x = \Delta a^n$ is calculated, as well as the correlation coefficient r from

$$r = \frac{S_{xy}}{\sqrt{S_{xx} S_{yy}}} \tag{I.3}$$

where

$$S_{xx} = \sum x^2 - \frac{\left(\sum x\right)^2}{N}; \tag{I.4}$$

$$S_{yy} = \sum y^2 - \frac{\left(\sum y\right)^2}{N}; \tag{I.5}$$

$$S_{xy} = \sum xy - \frac{\sum x \sum y}{N}. \tag{I.6}$$

A value of n that maximizes r is selected. The corresponding m and c are evaluated, if appropriate, from

$$m = \frac{S_{xy}}{S_{xx}} \text{ and } c = \bar{y} - m\bar{x} \tag{I.7}$$

where

$$\bar{x} = \frac{\sum x}{N} \text{ and } \bar{y} = \frac{\sum y}{N} \tag{I.8}$$

Power law fit formulae shall not be extrapolated beyond the available data.

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