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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

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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 of the voluntary nature of standards, 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 www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 164, *Mechanical testing of metals*, Subcommittee SC 4, *Fatigue, fracture and toughness testing*.

This third edition cancels and replaces the second edition (ISO 12135:2016), which has been technically revised.

The main changes compared to the previous edition are as follows:

— formulae to calculate CTOD have been replaced with those based on rigid rotation assumption throughout; replacing the previous *R*-curve formulae based on CTOD from *J*. CTOD formulae for SENBs are now those based on recent research to include the material yield to tensile strength ratio in the CTOD formulae;

— the determination of *J* directly from displacement defined in terms of CMOD has been included, in addition to the methods based on load line displacement;

— where fatigue precrack straightness requirements cannot be met due to internal residual stresses, the application of modification techniques, originally developed for weld specimens, is now permitted;

— the rotation correction factor for compact specimens has been revised with a new formula;

— editorial changes have been made to improve consistency of terms and definitions used throughout the document.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

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 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 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. Special testing requirements and analysis procedures are necessary when testing weldments, and these are described in ISO 15653 which is complementary to this document.

Statistical variability of the results strongly depends on the fracture type, for instance, fracture toughness associated with cleavage fracture in ferritic steels can show large variation. For applications that require high reliability, a statistical approach can be used to quantify the variability in fracture toughness in the ductile-to-brittle transition region, such as that given in ASTM E1921. However, it is not the purpose of this document to specify the number of tests to be carried out nor how the results of the tests are to be applied or interpreted.

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:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

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
relative opening 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
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

3.4
J
loading parameter, equivalent to the *J-integral* (3.3), the specific values of which, experimentally determined by this method of test (J_c, J_i, J_u,...), characterize fracture toughness under elastic-plastic conditions

3.5
stable crack extension
crack extension which stops or would stop when the applied displacement is held constant as a test progresses under displacement control

3.6
unstable crack extension
abrupt crack extension occurring with or without prior *stable crack extension* (3.5)

3.7
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 can result from *unstable crack extension* (3.6) 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.

3.8
crack extension resistance curves
R-**curves**
variation in *δ* (3.2) or *J* (3.4) with *stable crack extension* (3.5)

4 Symbols and abbreviated terms

Symbol	Unit	Designation
a	mm	Nominal crack length (for the purposes of fatigue precracking, an assigned value less than a_0)
a_f	mm	Final crack length ($a_0 + \Delta a$)
a_i	mm	Instantaneous crack length
a_m	mm	Length of machined notch
a_0	mm	Initial crack length
NOTE 1 This is not a complete list of parameters. Only the main parameters are given, 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.			

Symbol	Unit	Designation
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
CMOD	mm	Crack-mouth opening displacement, V
CTOD	mm	Crack tip opening displacement, δ
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 18)
F_f	kN	Maximum fatigue precracking force
F_L	kN	Limiting collapse load estimated for a given specimen type
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 the 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_0	MJ/m^2	J unclassified, and 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)
K	MPa m^{0,5}	Stress intensity factor
K_f	MPa m^{0,5}	Maximum value of K during the final stage of fatigue precracking
K_{lc}	MPa m^{0,5}	Plane strain linear elastic fracture toughness
$K_{J0,2BL}$	MPa m^{0,5}	Plane strain linear elastic fracture toughness equivalent to $J_{0,2BL}$
K_Q	MPa m^{0,5}	A provisional value of K_{lc}

NOTE 1   This is not a complete list of parameters. Only the main parameters are given, 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.

Symbol	Unit	Designation
M	—	Where M appears as a superscript designation (such as J^M or δ^M), it indicates that residual stress modification techniques have been applied to the specimen prior to test.
q	mm	Load-line displacement. q equals V in compact specimens (Figure 14).
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 crack-mouth opening displacement V, or load-line displacement q
U_e	J	Elastic component of U
U_p	J	Plastic component of U (Figure 20)
V	mm	In bend specimens, V is the crack-mouth opening displacement (CMOD), which is the opening displacement at the notch edges (Figure 13). In compact specimens, the opening displacement, V, is determined at the load-line. V equals q in compact specimens (Figure 14).
V_e	mm	Elastic component of V
V_g	mm	Displacement measured by clip gauges mounted on knife edges at a distance z from the crack -mouth. Where integral knife edges are used, $V_g=V$ (Figure 13).
V_p	mm	Plastic component of V
W	mm	Width of the test specimen
z	mm	For bend and straight-notch compact specimens, z is the initial distance of the crack-mouth 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, z is the initial distance of the crack-mouth opening gauge measurement position either beyond ($+z$) or before ($-z$) the initial load-line.
δ	mm	Crack-tip opening displacement (CTOD)
$\delta_{c(B)}$	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_i	mm	Fracture resistance δ 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)
δ_{max}	mm	Limit of δ-R curve 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_0	mm	δ unclassified, and uncorrected for stable crack extension
$\delta_{0,2BL}$	mm	Size insensitive fracture resistance δ at 0,2 mm crack extension offset from construction line
$\delta_{0,2BL(B)}$	mm	Size sensitive fracture resistance δ at 0,2 mm stable crack extension offset from construction line (B = specimen thickness in mm)
η_p	—	Dimensionless function of geometry used to calculate J
ν	—	Poisson's ratio

NOTE 1   This is not a complete list of parameters. Only the main parameters are given, 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.
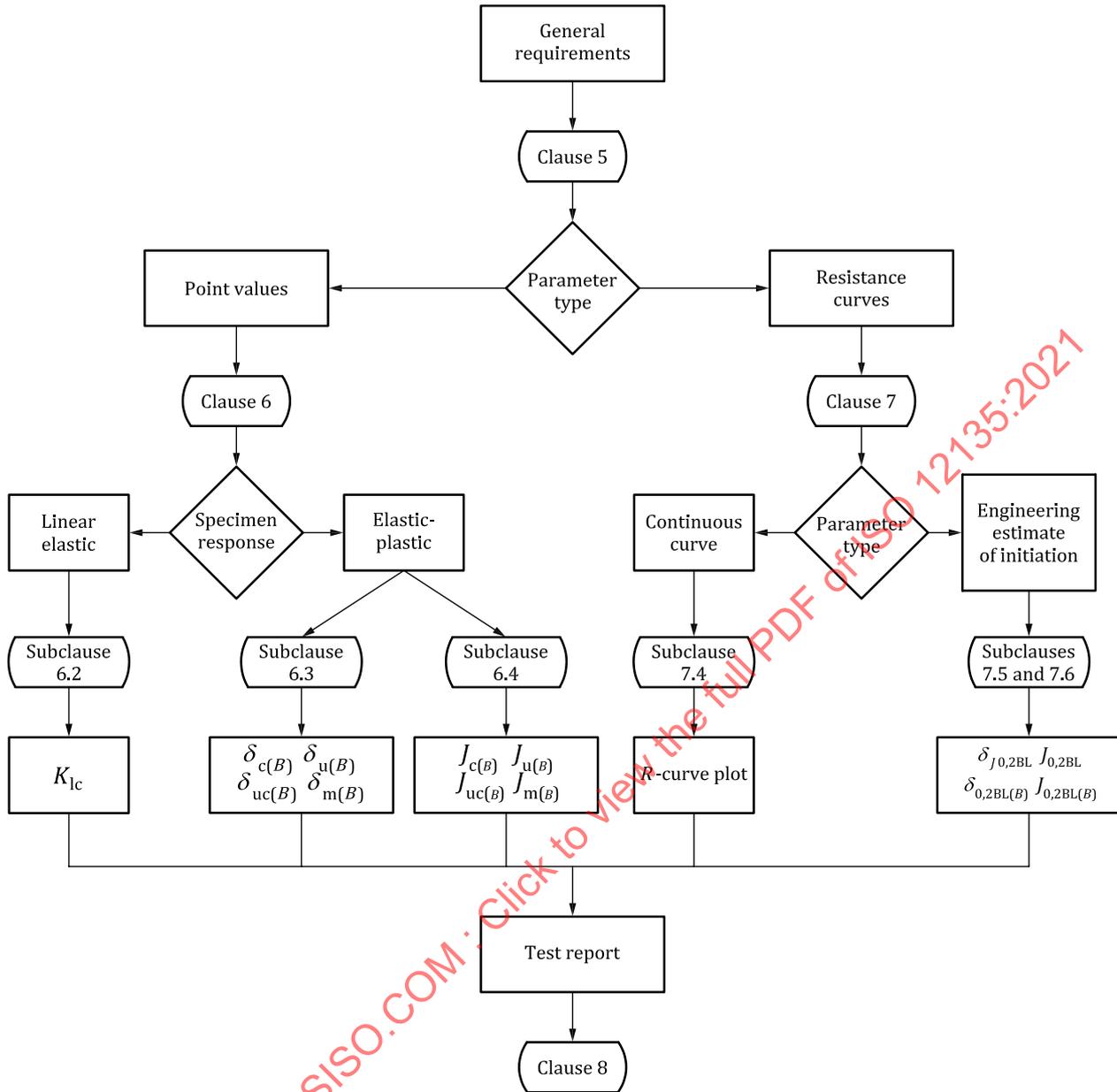
Figure 1 — General flowchart showing how to use the standard method of test

Key
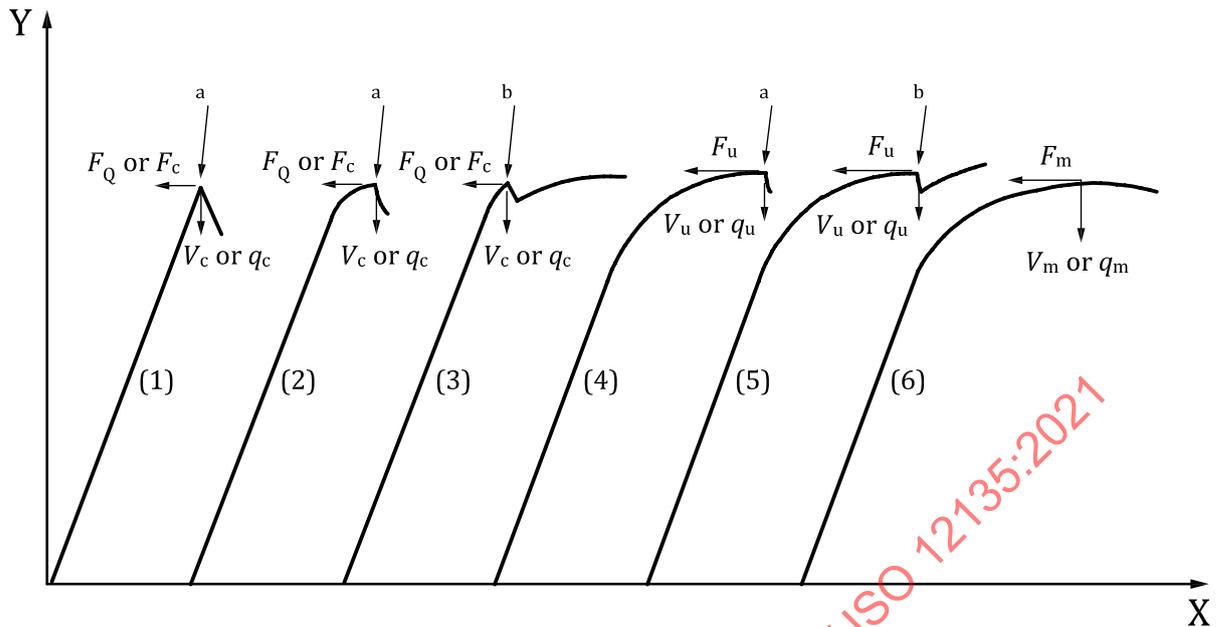
X   crack-mouth opening displacement (V) or load-line displacement (q)

Y   force (F)

NOTE 1 The classifications of F_c, F_u and F_m are described in 6.3.1 and 6.4.1.

NOTE 2 Pop-in behaviour is a function of the material toughness and parameters of the test setup such as the testing machine/specimen compliance and the recorder response rate.

a   Fracture.

b   Pop-in.

Figure 2 — Characteristic 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_{lc} 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_{lc} 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_{lc}.

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, a 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 $\delta_{0,2BL}$ and fracture toughness $J_{0,2BL}$ parameters, or of a continuous δ- and J-resistance curve. The values $\delta_{0,2BL}$ 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_i and J_i. Measurement of δ_i 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 can 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 $\delta_{0,2\text{BL}}$ or $J_{0,2\text{BL}}$ values and δ- 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 1.

Table 1 — Fracture toughness symbols

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

5.4   Test specimens

5.4.1   Specimen configuration and size

Dimensions and tolerances of specimens shall conform to Figures 3 to 5.
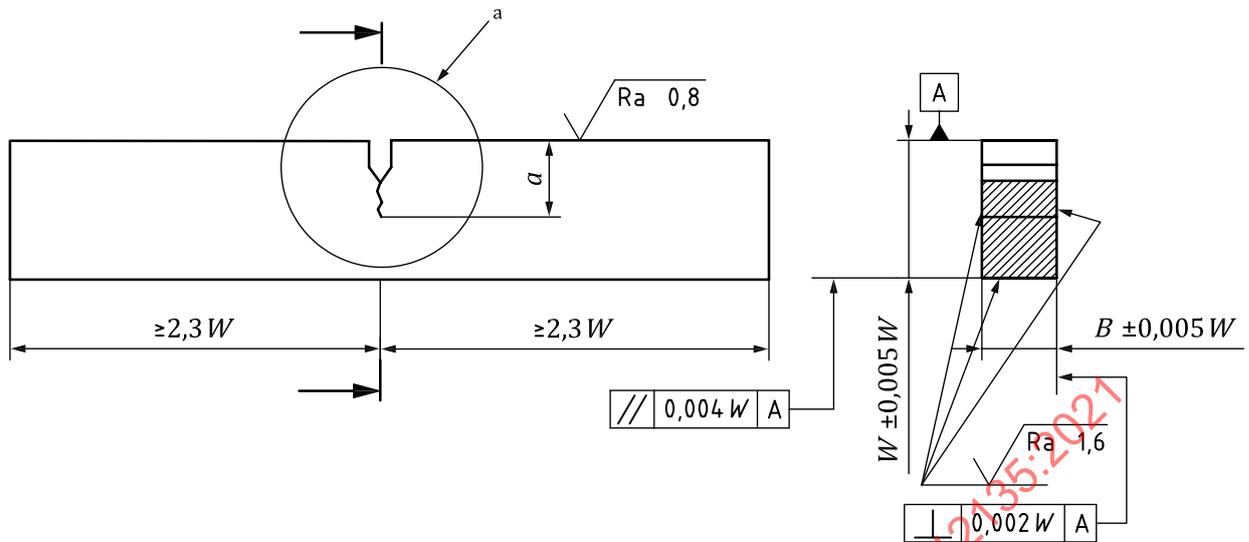
The intersection of the crack starter notch tips with the two specimen surfaces shall be equally distant from the top and bottom edges of the specimen to within 0,005 W.

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

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

NOTE 3 $1,0 \leq W/B \leq 4,0$ ($W/B = 2$ preferred).

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

NOTE 5   Surface roughness Ra in micrometres.

[a]   See Figures 6 to 8 and 5.4.2.3.

Figure 3 — Proportional dimensions and tolerances for bend specimen
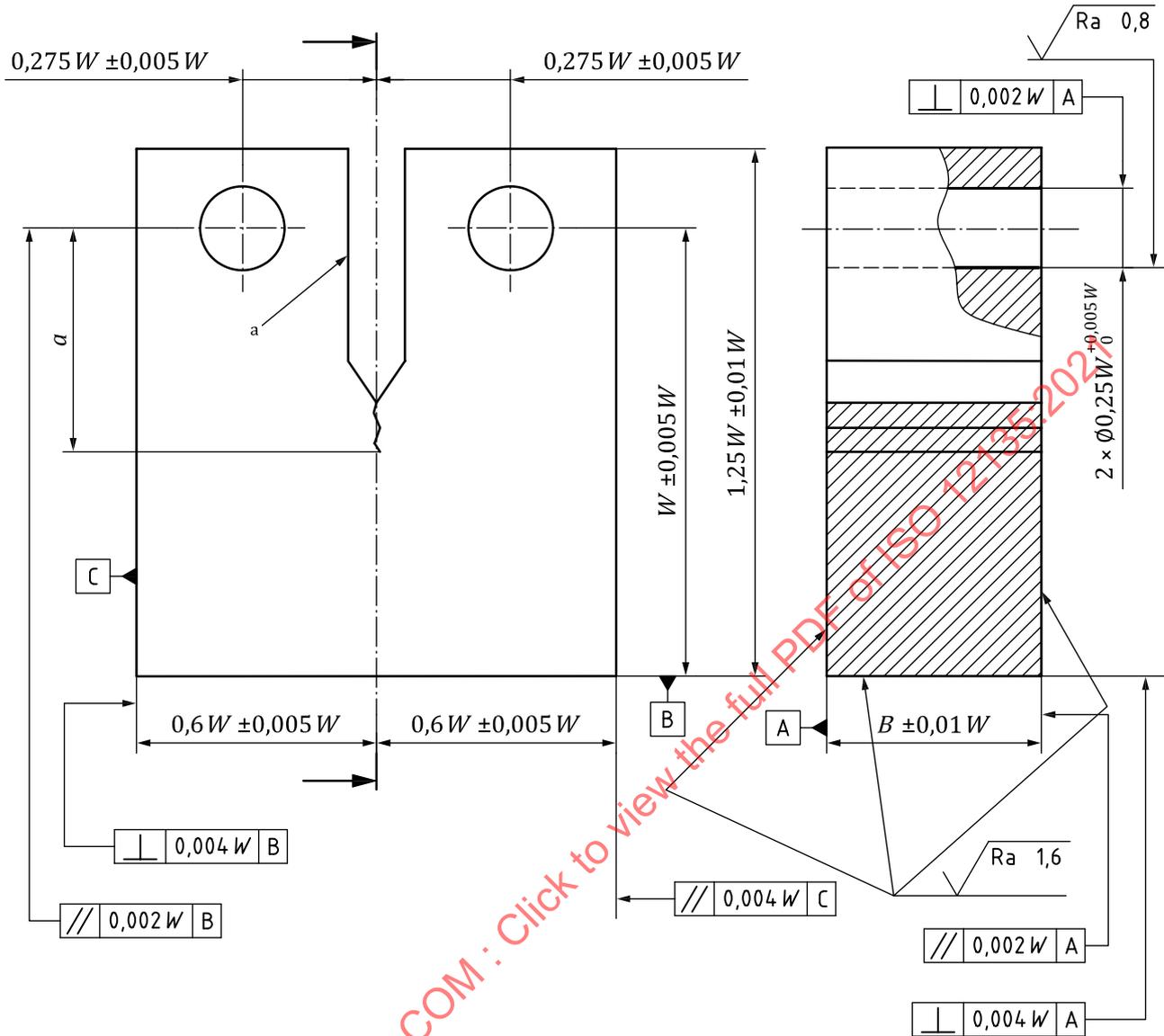
The intersection of the crack starter notch tips with the two specimen surfaces shall be equally distant from the top and bottom edges of the specimen to within 0,005 W.

NOTE 1   Integral or attachable knife edges for clip gauge attachment can 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_{lc} determination, $0,45 \le a/W \le 0,55$.

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

NOTE 6   Surface roughness Ra in micrometres.

a   See Figures 6 to 8 and 5.4.2.3.

Figure 4 — Proportional dimensions and tolerances for straight-notch compact specimen
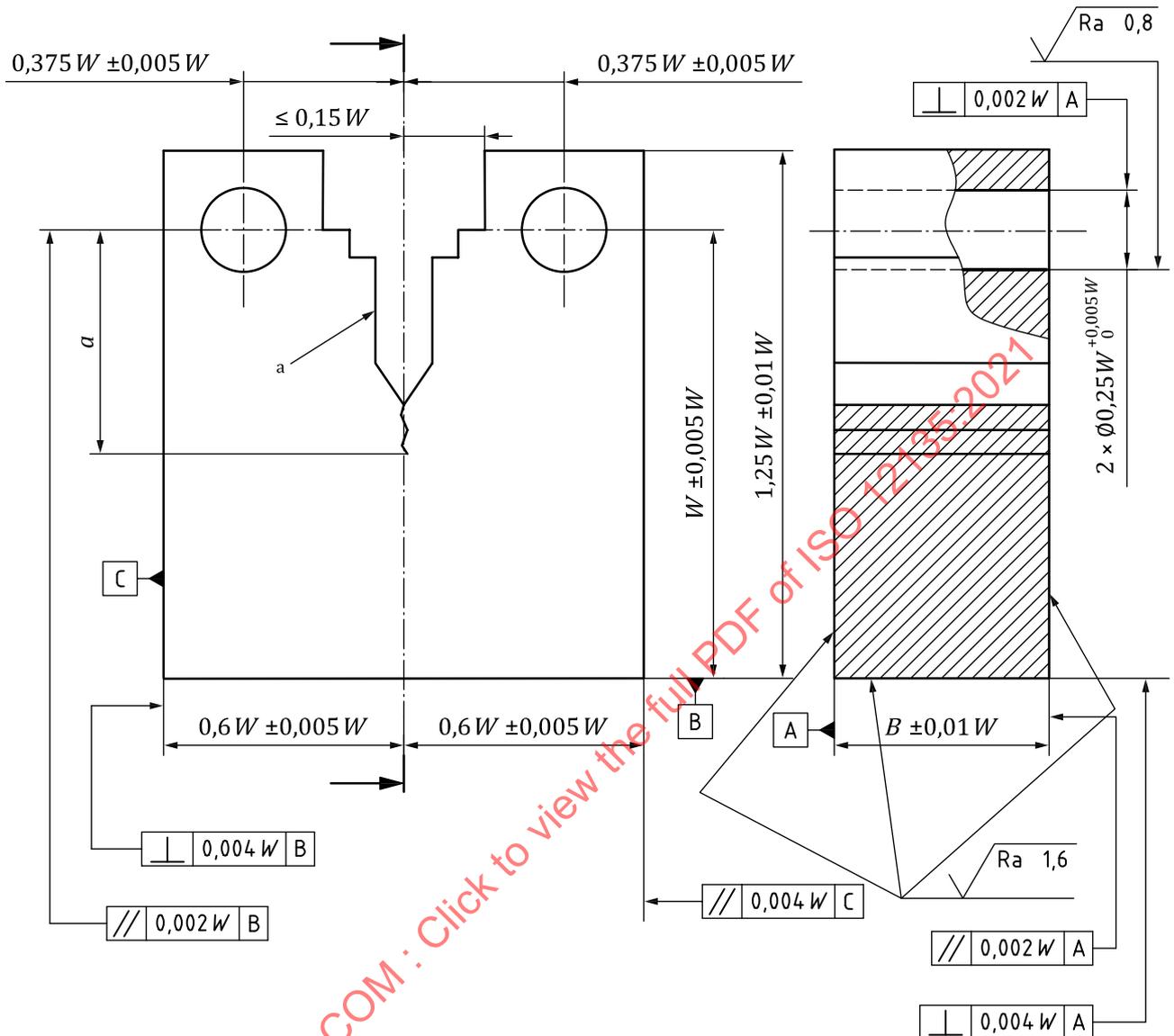
The intersection of the crack starter notch tips with the two specimen surfaces shall be equally distant from the top and bottom edges of the specimen to within 0,005 W.

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

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

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

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

NOTE 5   Alternative pin hole diameter, $\phi\ 0,188\ W^{+0,004W}_{0}$. When this pin size is used, notch opening can be increased to 0,21 W maximum.

NOTE 6   Surface roughness Ra in micrometres.

a   See Figures 6 to 8.

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_{lc}, δ and J values, although there are special procedural requirements for J values calculated from measurements made away from the load line. Table 2 provides guidance on specimen size for K_{lc} measurement.

Table 2 — Minimum recommended thickness for K_{lc} testing

$\dfrac{R_{p0,2}}{E}$			$\begin{array}{c} B \\ \text{mm} \end{array}$
$0{,}005\,0 \leq$	$\dfrac{R_{p0,2}}{E}$	$< 0{,}005\,7$	75
$0{,}005\,7 \leq$	$\dfrac{R_{p0,2}}{E}$	$< 0{,}006\,2$	63
$0{,}006\,2 \leq$	$\dfrac{R_{p0,2}}{E}$	$< 0{,}006\,5$	50
$0{,}006\,5 \leq$	$\dfrac{R_{p0,2}}{E}$	$< 0{,}006\,8$	44
$0{,}006\,8 \leq$	$\dfrac{R_{p0,2}}{E}$	$< 0{,}007\,1$	38
$0{,}007\,1 \leq$	$\dfrac{R_{p0,2}}{E}$	$< 0{,}007\,5$	32
$0{,}007\,5 \leq$	$\dfrac{R_{p0,2}}{E}$	$< 0{,}008\,0$	25
$0{,}008\,0 \leq$	$\dfrac{R_{p0,2}}{E}$	$< 0{,}008\,5$	20
$0{,}008\,5 \leq$	$\dfrac{R_{p0,2}}{E}$	$< 0{,}010\,0$	13
$0{,}010\,0 \leq$	$\dfrac{R_{p0,2}}{E}$		7

NOTE 2   When crack-mouth opening displacement V_g is measured on the load line as shown in Figure 14 b), $V = q = V_g$ for the stepped-notch compact specimen (see Figure 5). The stepped-notch specimen is thus equally useful for the determination of values of K_{lc}, 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 from 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 can be carried out after machining, provided that the specimen's required dimensions and tolerances, shape, and surface finishes are met, and that 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 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) often indicates 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, comprising machined notch and pre-crack, 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°.

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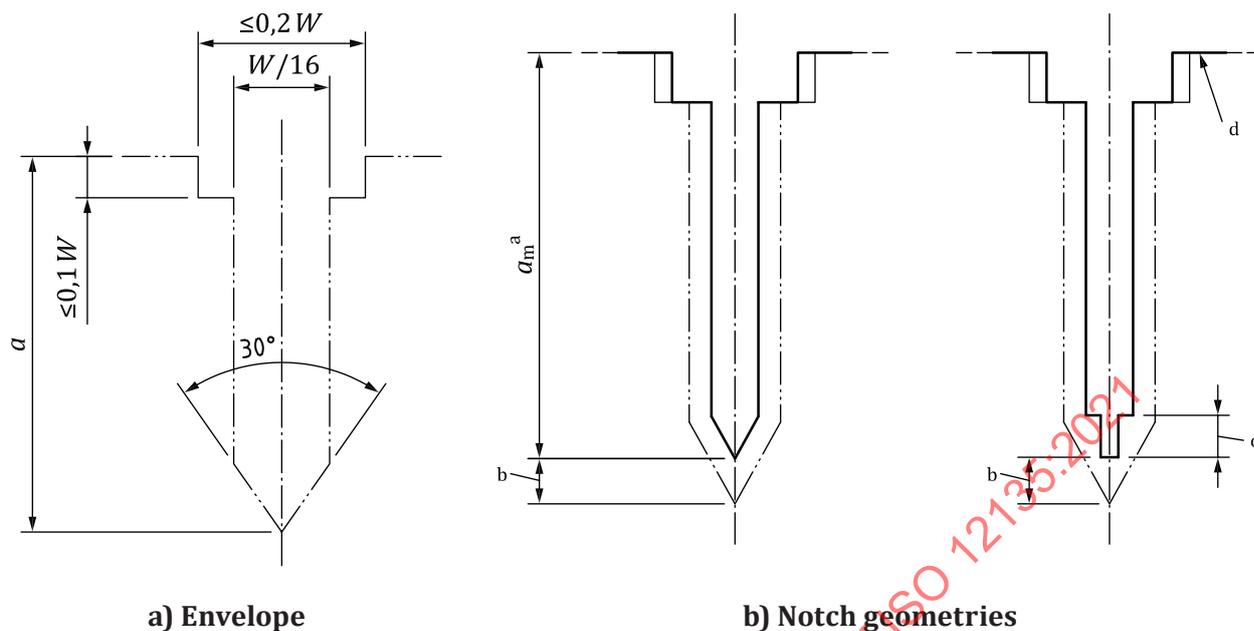
If fatigue crack initiation and/or propagation are a problem, a chevron notch configuration as shown in Figure 7 may be used.

a   Machined notch, a_m.
b   Fatigue precrack.
c   Spark eroded or machined slit.
d   Edge of bend specimen or load-line of compact specimen.

Figure 6 — Acceptable fatigue crack envelope and crack starter notches (see **Figures 7** and **8**)
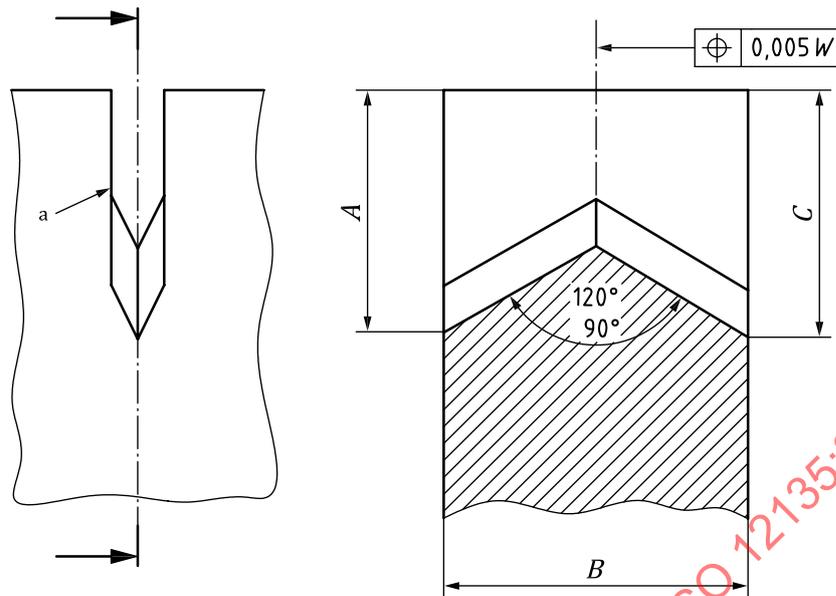
Chevron notch root radii shall not exceed 0,25 mm.

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.

a   See Figure 6.

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 crack-mouth 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 crack-mouth 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 crack-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**

^a See Figure 6.

^b 2*x*, see 5.4.2.3 b).

^c 2*y* + screw thread diameter ≤ *W*/2.

Figure 8 — Outward pointing knife edges and corresponding notch geometries
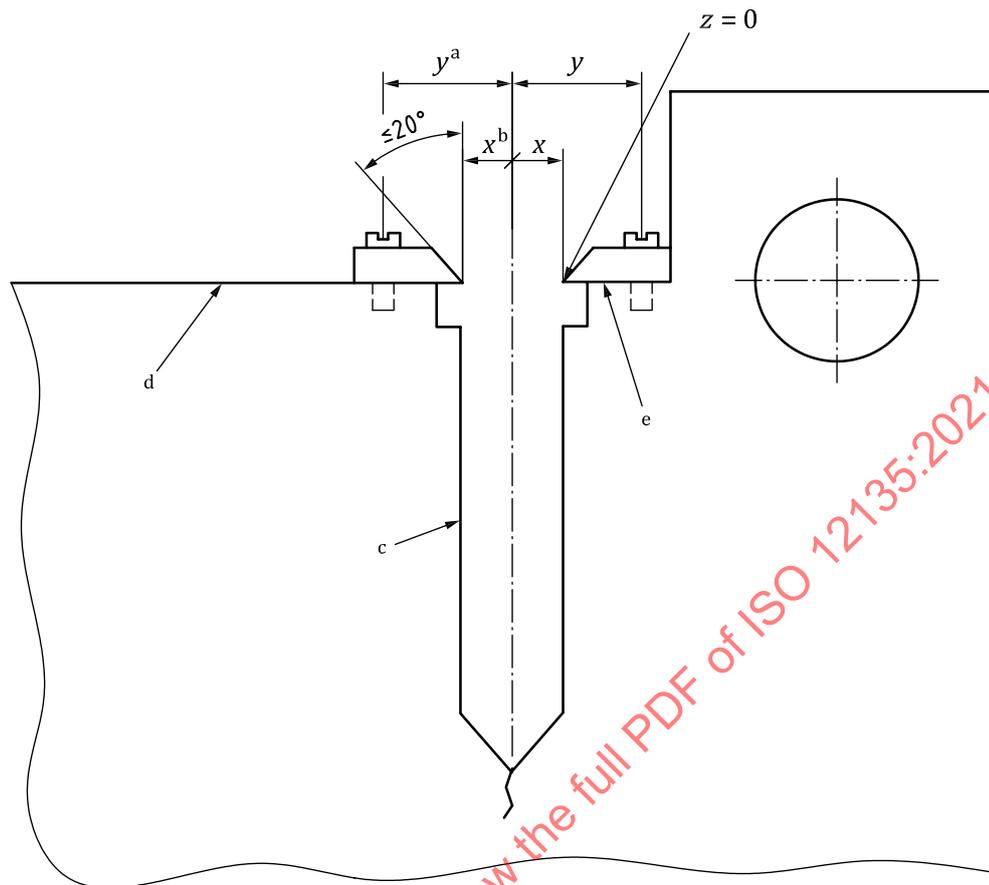
NOTE   If razor blades are used instead of inward-pointing knife edges, the displacement is normally measured at a point half the razor blade thickness above the load line (see 5.5.1).

a $2y$ + screw thread diameter $\leq W/2$.

b $2x$, see 5.4.2.3 b).

c   See Figures 6 and 7.

d   Edge of bend or straight compact, or first step of stepped-notch compact specimen.

e   Load-line stepped compact.

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):

$$F_f = 0,8 \cdot \frac{B(W - a_0)^2}{S} \cdot R_{p0,2} \tag{1}$$

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):

$$F_f = \xi E \cdot \frac{(W \cdot B \cdot B_N)^{0,5}}{g_1\left(a_0/W\right)} \cdot \frac{W}{S} \cdot \frac{(R_{p0,2})_p}{(R_{p0,2})_t} \tag{2}$$

where $\xi = 1,6 \times 10^{-4} m^{0,5}$, $(R_{p0,2})_P$ and $(R_{p0,2})_t$ 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 plane-sided specimens, $B_N = B$.

NOTE 2   Values of $g_1(a_0/W)$ are given in Annex D.

NOTE 3   Additional fatigue precracking requirements are necessary when determining K_{lc}, 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):

$$F_f = 0,6 \cdot \frac{B(W - a_0)^2}{2W + a_0} \cdot R_{p0,2} \tag{3}$$

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

$$F_f = \xi E \cdot \frac{(W \cdot B \cdot B_N)^{0,5}}{g_2\left(a_0/W\right)} \cdot \frac{(R_{p0,2})_p}{(R_{p0,2})_t} \tag{4}$$

where $\xi = 1,6 \times 10^{-4} m^{0,5}$, $(R_{p0,2})_P$ and $(R_{p0,2})_t$ 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 plane-sided specimens, $B_N = B$.

NOTE 2   Values of $g_2(a_0/W)$ are given in Annex D.

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

5.4.2.5   Side grooving

Specimens for the determination of point measurements of fracture toughness (e.g. K_{lc}, δ_c, J_c) may be plane-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 no greater than 0,2B. 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 can lower and flatten the R-curve compared to plane-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

The dimensions of specimens shall conform to Figures 3 to 5. The 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.

The 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_{lc} 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

$$F_L = \frac{4}{3} \cdot \frac{B(W-a_0)^2}{S} \cdot R_m \qquad (5)$$

for bend specimens, and

$$F_L = \frac{B(W-a_0)^2}{2W+a_0} \cdot R_m \qquad (6)$$

for compact specimens.

5.6.3 Displacement measurement

The displacement gauge shall have an electrical output that represents crack-mouth opening displacement V between two precisely located gauge positions spanning the crack-mouth. The design of the 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   The measurement of load-line displacement q (see 5.7.1.3) is described in Annex E.

Displacement gauges for crack-mouth opening displacement and load-line displacement shall be calibrated with reference to 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.

The verification of the displacement gauge shall be performed at the test temperature ± 5 °C, when technically possible, 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. When the clip gauge is well-insulated from the specimen, an ambient temperature calibration is usually adequate; however, it should be demonstrated that the calibration is satisfactory for the test conditions.

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). The roller diameters shall be between W and $W/2$.

The loading fixture bearing surfaces shall have a hardness greater than 40 HRC (400 HV) or a yield strength of at least 1 000 MPa.
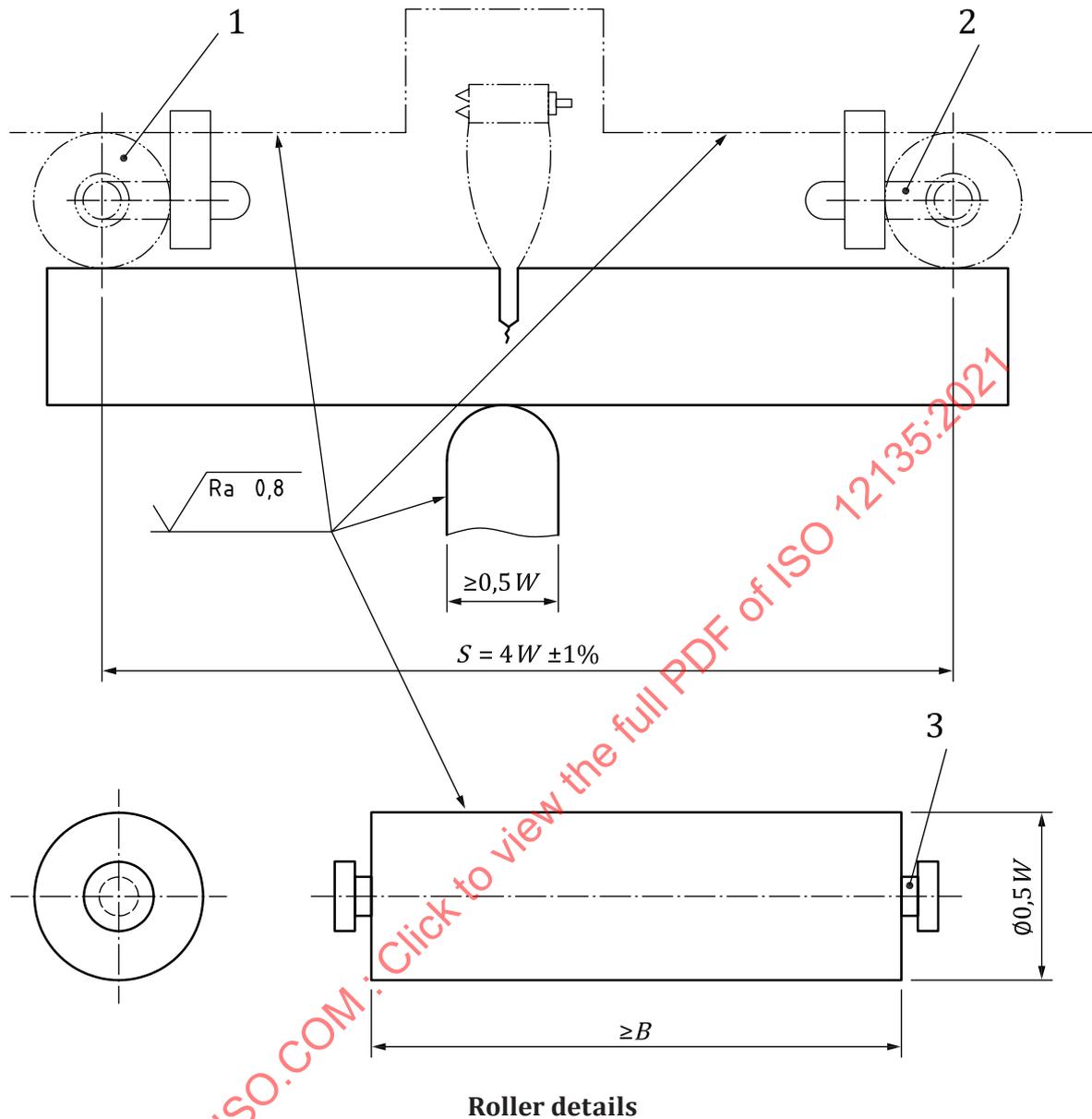
Key
1 roller
2 rubber band or spring
3 bosses for rubber bands or springs

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

NOTE 1 Fixture and roller pin hardness ≥40 HRC.

NOTE 2 Surface roughness Ra in micrometres.

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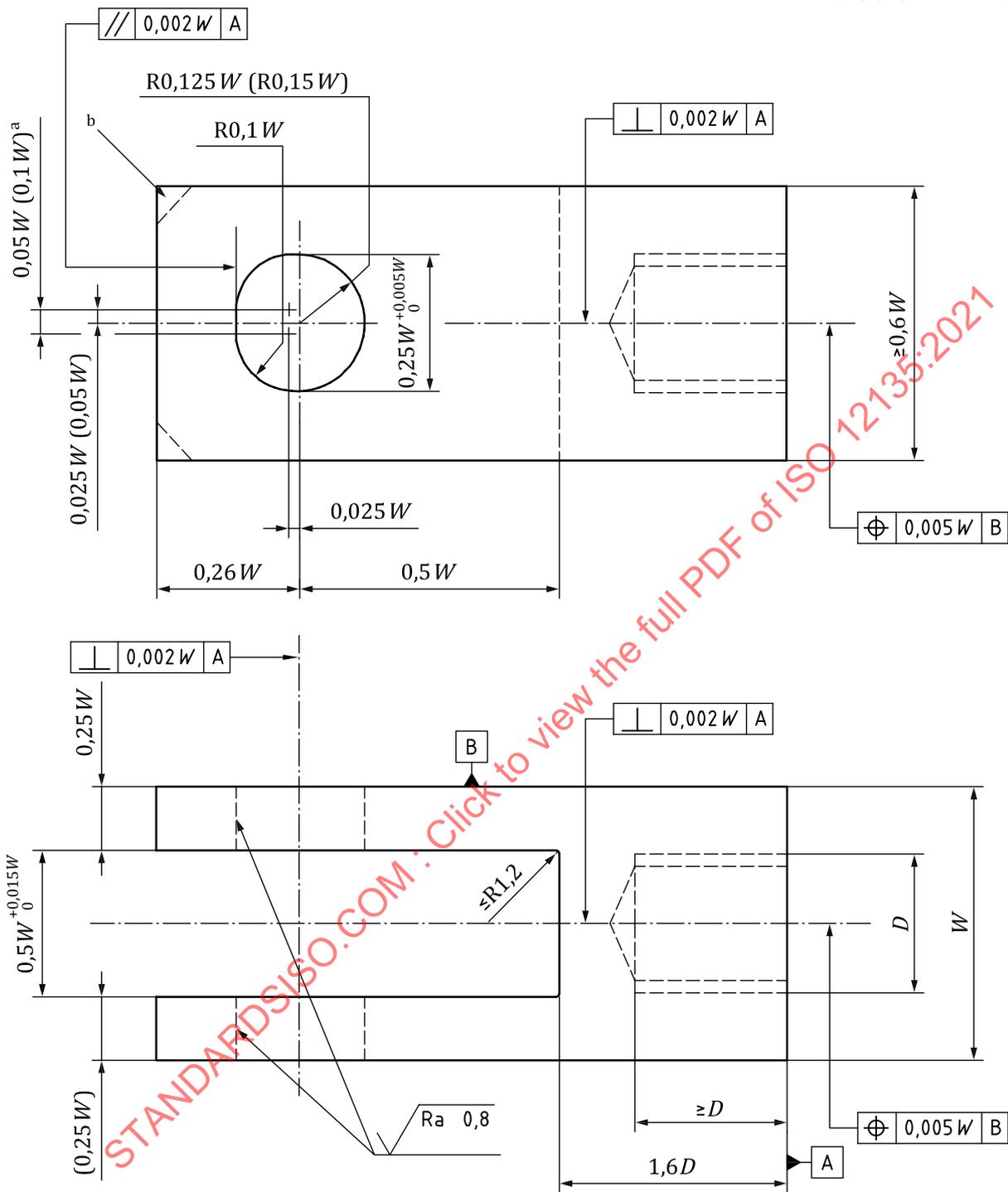
For specimens showing large displacements, clevis hole dimensions shall be enlarged to the values shown in brackets.

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

NOTE 2   Clevis and pin hardness ≥40 HRC.

NOTE 3   Surface roughness Ra in micrometres.

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

**Figure 11 — Typical design of compact specimen clevis employing a flat hole
to accommodate load-pin**
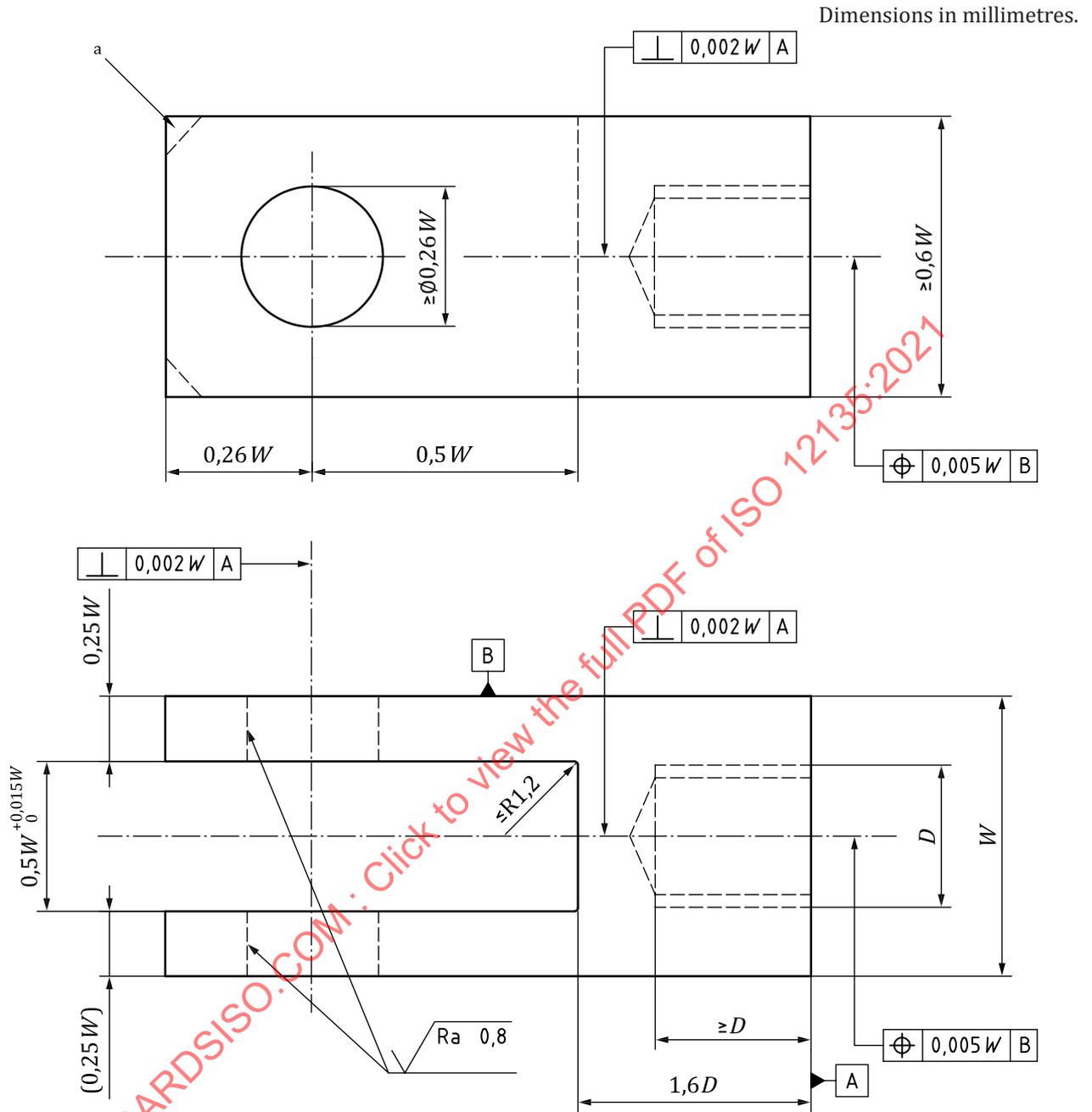
Dimensions in millimetres.

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

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

NOTE 2 Clevis and pin hardness ≥40 HRC.

NOTE 3 Surface roughness Ra in micrometres.

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

**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 %. The 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

The crack-tip opening displacement δ is evaluated from the crack-mouth opening displacement V. When V has not been measured directly, it can be calculated from the clip gauge measurement V_g as given in Formula (25). The positions where V and V_g are defined are shown in Figure 13.

5.7.1.3 *J*-integral

Either the load-line displacement q or the crack-mouth opening displacement V is used for the determination of J. When V has not been measured directly, it can be calculated from the clip gauge measurement V_g as given in Formula (25).

NOTE   Suitable methods for measuring load-line displacement directly or indirectly are described in Annex E, and Reference [6] gives a comparison of different methods to determine q and V.

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

The crack-tip opening displacement δ is evaluated from the crack-mouth opening displacement V. The crack-mouth opening displacement V is defined at the load line in both stepped-notch and straight notch compact specimens (See Figure 14). Since V cannot be measured directly in straight-notch compact specimen, it can be calculated from the clip gauge measurement V_g at the notch edges as given in Formula (27).

5.7.2.3 *J*-integral

The parameter J is evaluated from either crack mouth opening displacement, V, or load-line displacement, q, which are the same for compact specimens. 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 load-line displacement q equals the clip gauge measurement V_g. Since q cannot be measured directly in straight-notch compact specimen, it can be calculated from the clip gauge measurement V_g at the notch edges as given in Formula (27).

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

The 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 crack mouth-opening, load-line or crosshead-displacement control. The load-line displacement rate shall be such that, within the linear elastic region, the stress intensification rate is within the range 0,2 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

The 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 can help to ensure brittle behaviour during specimen opening.

5.8.2 Initial crack length, a_0

The 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 15 and 16. 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:

$$a_0 = \frac{1}{8}\left(\frac{a_1 + a_9}{2} + \sum_{i=2}^{8} a_i \right) \tag{7}$$

a) Integral type knife edges   **b) Attached type knife edges**
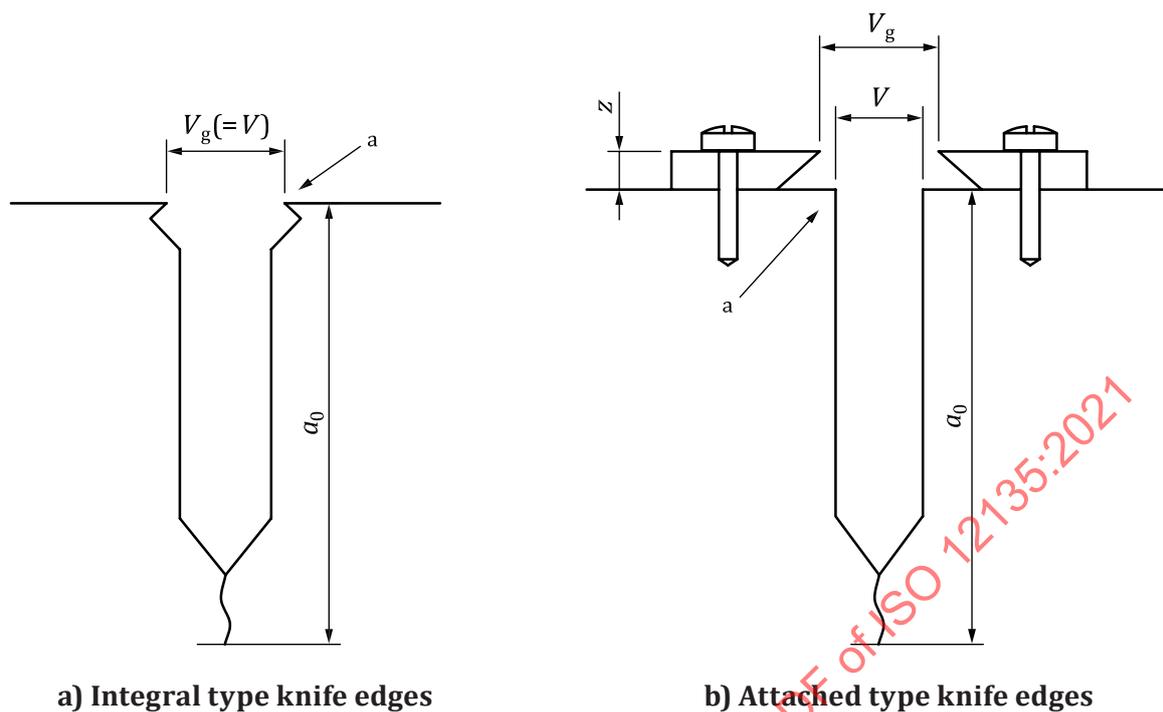
a Crack-mouth.

Figure 13 — Definitions of V and its correspondence with V_g for three point bend specimens

a) Straight-notch compact specimen   b) Stepped-notch compact specimen
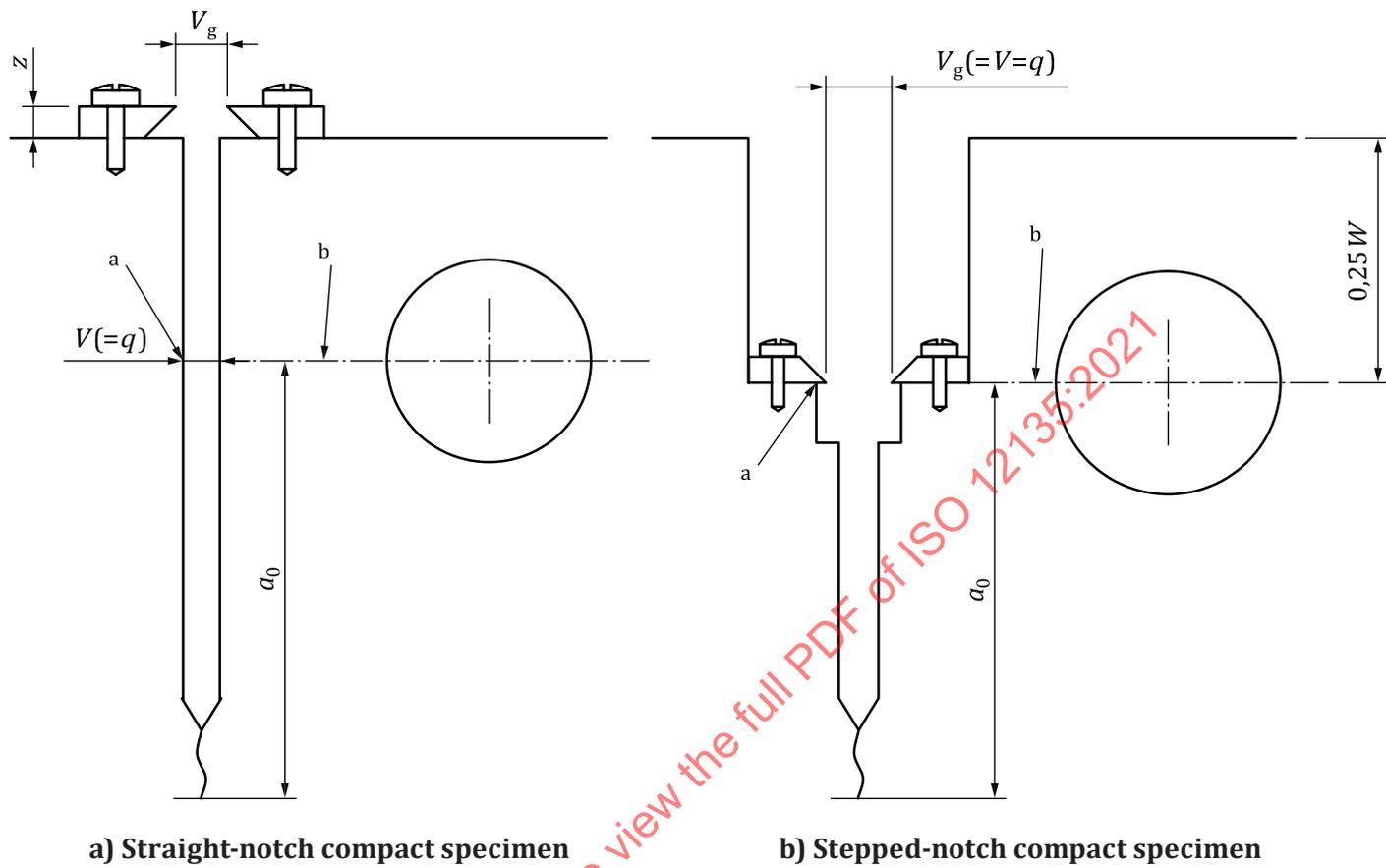
[a] Crack-mouth.

[b] Load-line.

Figure 14 — Definitions of V, q and its correspondence with V_g in compact tension specimens

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

a) Plane sided
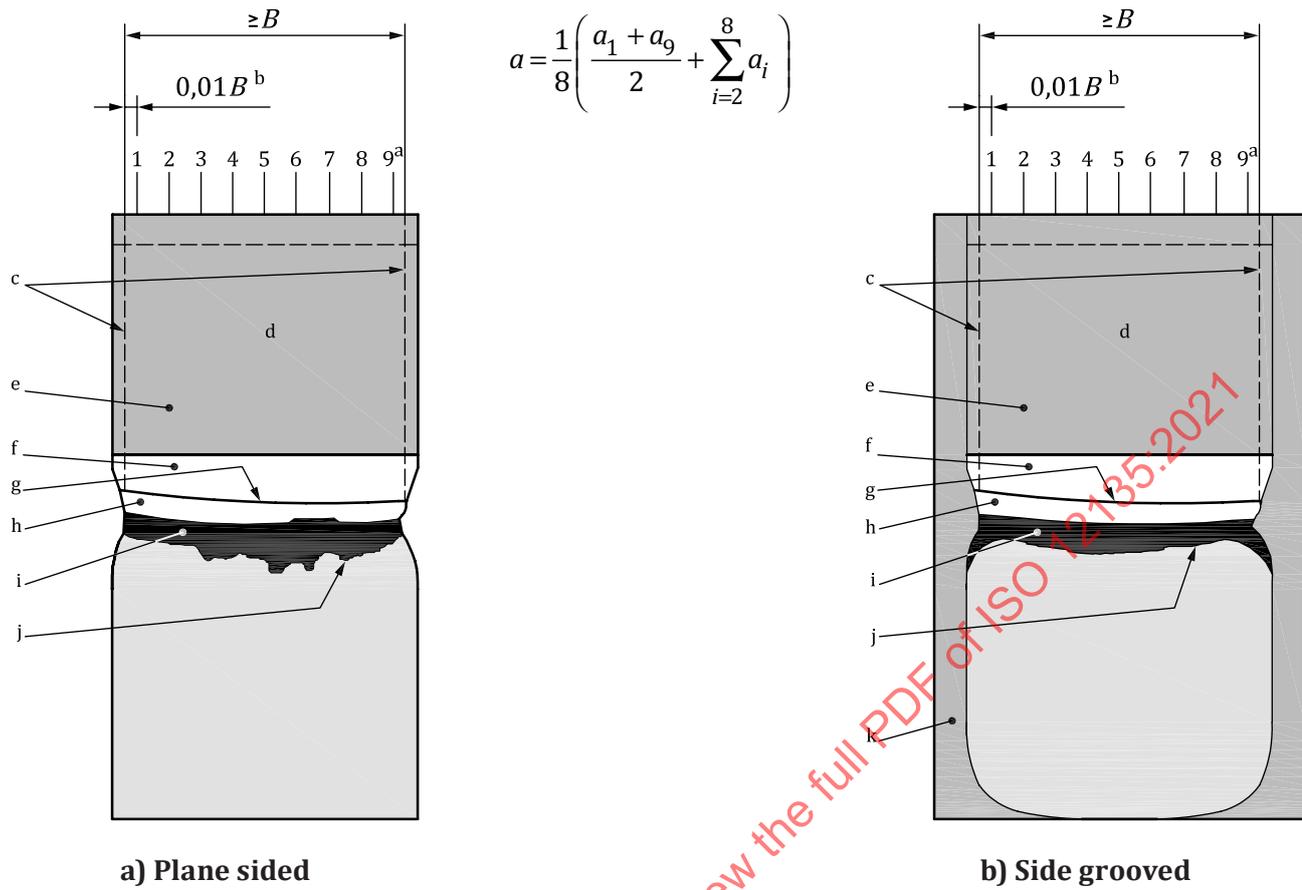
b) Side grooved

[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 15 — 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) Plane sided

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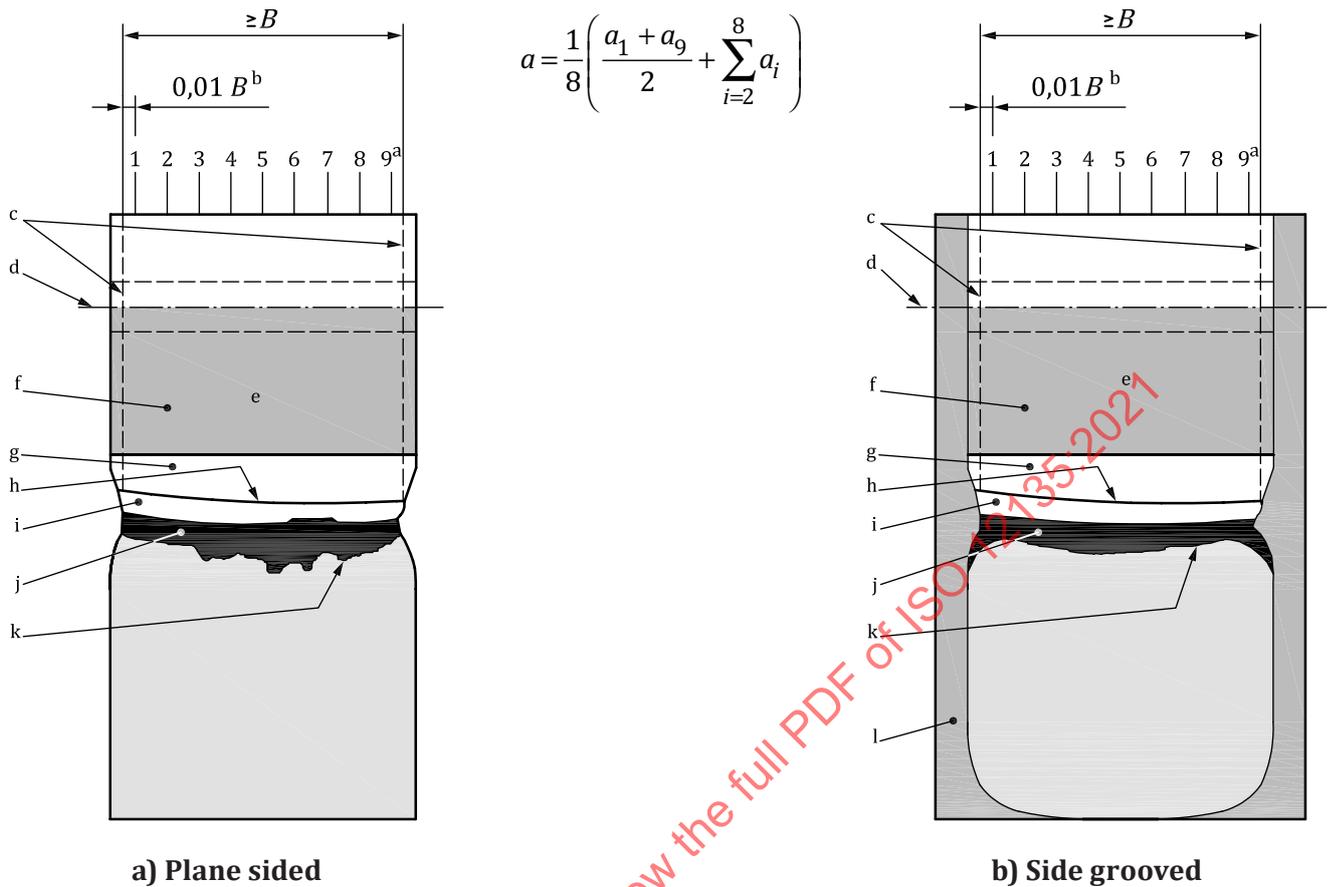
a	Measure the initial and final crack lengths from centreline of pinhole at positions 1 to 9.	g	Fatigue precrack.
b	Not to scale.	h	Initial crack front.
c	Reference lines.	i	Stretch zone.
d	Centreline of pinhole.	j	Crack extension.
e	Crack plane.	k	Final crack front.
f	Machined notch.	l	Side groove.

Figure 16 — 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.

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. If the fatigue precrack does not meet the straightness requirement of b), modifications to the fatigue precracking procedure may be made in accordance with Annex C in ISO 15653:2018. When such modifications are made, the fracture toughness result shall be identified with M as superscript such as K^M, J^M or δ^M.

5.8.3 Stable crack extension, Δa

The 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 can 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 17), 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
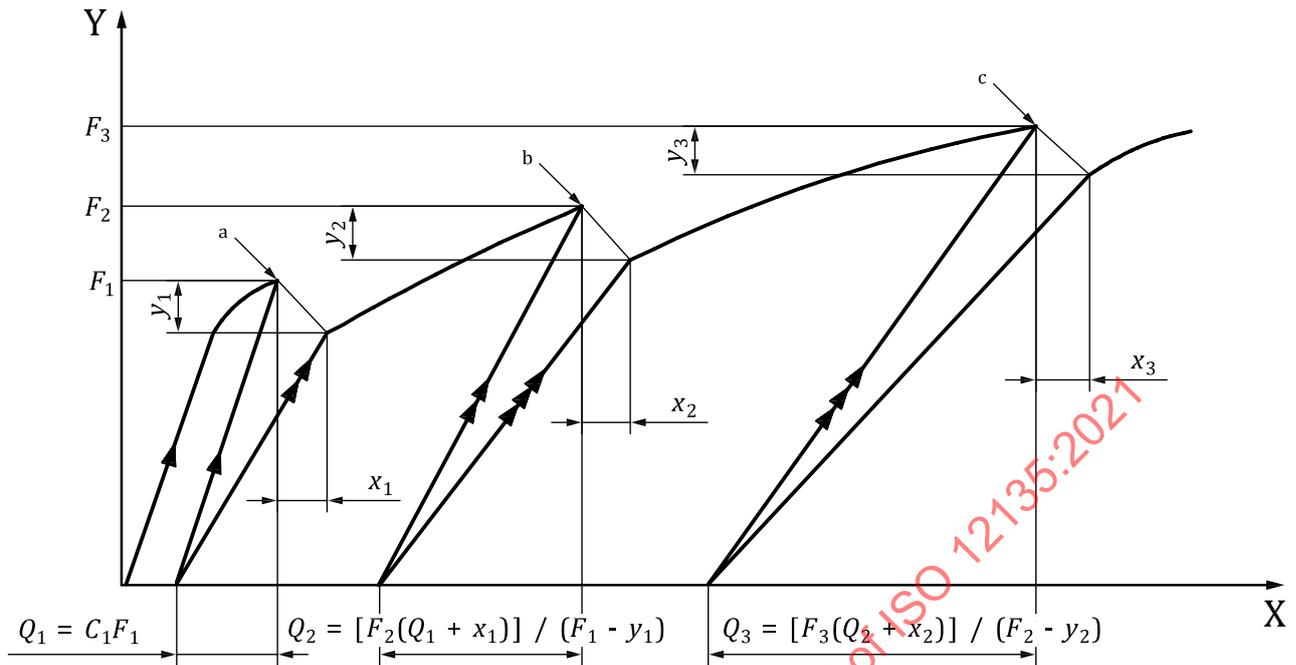
X crack-mouth opening displacement (V) or load-line displacement (q)

Y force (F)

NOTE 1 C_1 is the initial compliance.

NOTE 2 Q_1 represents V or q.

NOTE 3 Pop-ins are exaggerated for clarity.

[a] Pop-in 1.

[b] Pop-in 2.

[c] Pop-in 3.

Figure 17 — 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 1 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_i, $\delta_{0,2BL}$, J_i, $J_{0,2BL}$, and $K_{J0,2BL}$, or

— size sensitive, corresponding to the symbols $\delta_{c(B)}$, $\delta_{0,2BL(B)}$, $\delta_{u(B)}$, $\delta_{uc(B)}$, $\delta_{m(B)}$, $J_{c(B)}$, $K_{Jc(B)}$, $J_{0,2BL(B)}$, $J_{u(B)}$, $J_{uc(B)}$, 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_{lc} determination, or

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

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

6.2.1 General

The test record shall be interpreted in accordance with 6.2.2, and a provisional result K_Q shall be 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_{lc} in accordance with this document, it is recommended that $a_0/W \approx 0,5$.

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 18). An optimization procedure like that described in Reference [7] can be used to obtain the best fit slope.

As illustrated in Figure 18, 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.

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

Key
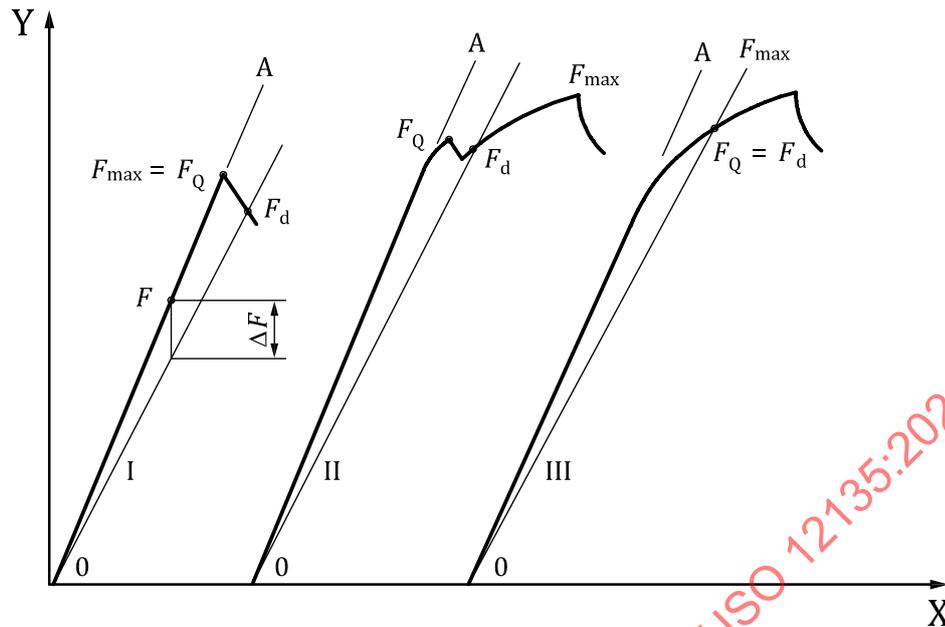
X   crack-mouth opening displacement (V) or load-line displacement (q)

Y   force (F)

NOTE $\Delta F/F$ offset slopes are exaggerated for clarity.

Figure 18 — Definition of F_Q (for determination of K_Q)

F_Q is the highest force that precedes F_d shown in Figure 18 for types I and II test records, or the force that coincides with F_d shown in Figure 18 for the type III test record.

The maximum force, F_{max}, (see Figure 18) 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 2   In Figure 18, the type II test record corresponds to a pop-in event that 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_0 from 5.8.2 and F_Q from 6.2.2.

K_Q is calculated for three-point bend specimens as:

$$K_Q = \frac{S}{W} \cdot \frac{F_Q}{(BB_N W)^{0,5}} \cdot g_1\left(\frac{a_0}{W}\right) \tag{11}$$

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

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

NOTE 2   The relationship for $g_1(a_0/W)$ 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 is in MPam^{0,5}. If B and W are in mm and F is in kN, then the calculated quantity shall be multiplied by $10^{3/2}$ to give K_Q in MPam^{0,5}.

K_Q is calculated for compact specimens as:

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

NOTE 3   For plane-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 is in MPam^{0,5}. If B and W are in mm and F is in kN, then the calculated quantity shall be multiplied by $10^{3/2}$ to give K_Q in MPam^{0,5}.

6.2.4   Qualification of K_Q as K_{lc}

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

$$a_0, B, W - a_0 \geq 2,5\left(\frac{K_Q}{R_{p0,2}}\right)^2$$ (13)

and

$$0,45 \leq \frac{a_0}{W} \leq 0,55$$ (14)

Pay attention to the units when evaluating Formula (13). Thus K_Q shall be in MPam^{0,5} and $R_{p0,2}$ in MPa for a_0, B, and $(W - a_0)$ to be in m, and

$$K_f \leq 0,6\, K_Q \cdot \frac{\left(R_{p0,2}\right)_P}{\left(R_{p0,2}\right)_t}$$ (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_{lc}, 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 17(see Annex F and Reference [8]);

$$P \geq \frac{\Delta F}{F}$$ (16)

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

$$P < \frac{\Delta F}{F}$$ (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):

$$P = 1 - \frac{Q_1}{F_1} \cdot \frac{F_n - y_n}{Q_n + x_n}$$ (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 nth pop-in;

Q_1 is the elastic displacement at pop-in 1 (see Figure 17);

F_n is the force at the nth pop-in;

Q_n is the elastic displacement at the nth pop-in;

y_n is the force drop at the nth pop-in;

x_n is the displacement increase at the nth pop-in;

n is the sequential number (see Figure 17) 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 17). 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 corresponds to crack instability (5.8.4) after stable crack extension (5.8.3), so that

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

F shall be recorded as value F_c, and V which corresponds to F_c shall be recorded as value V_c.

When F corresponds to crack instability (5.8.4) after stable crack extension (5.8.3), so that

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

F shall be recorded as value F_u, and V which corresponds to F_u shall be recorded as value 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), value of F_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)], and V which corresponds to F_m shall be recorded as value V_m.

6.3.3 Determination of V_p

The plastic component of crack-mouth opening displacement V_p corresponding to the crack-mouth opening displacement V_c, V_u, V_{uc}, or V_m (determined in 6.3.1 and 6.3.2, see Figure 19) is determined and recorded either manually from the test record, or automatically using a computer technique.
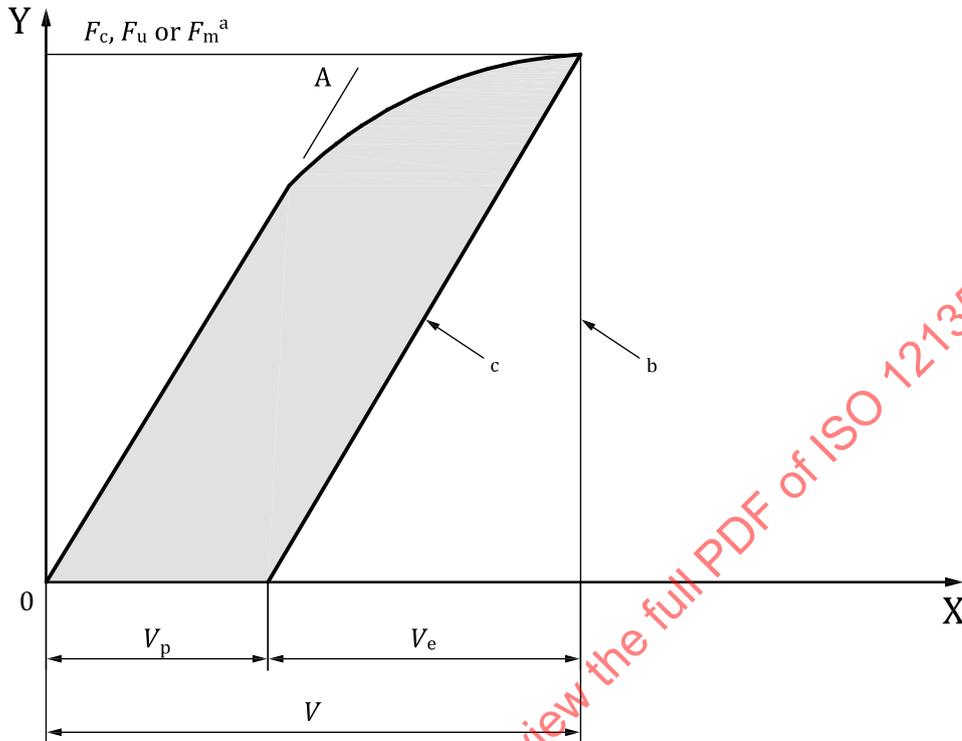
Key

X   crack-mouth opening displacement (V) or load-line displacement (q)

Y   force (F)

[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 19 — Definition of V_p (for determination of CTOD)

An analytical procedure based on compliance relationships may also be used by which the theoretical elastic crack-mouth opening displacement, V_e, is deducted from total crack-mouth opening displacement, V, as described in 6.1.

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 6.3.3:

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

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

δ_0 is calculated for the three-point bend specimen as (see Reference [9]):

$$\delta_0 = \left[\left(\frac{S}{W}\right)\frac{F}{\left(B \cdot B_N \cdot W\right)^{0,5}} \times g_1\left(\frac{a_0}{W}\right)\right]^2 \left[\frac{\left(1-v^2\right)}{mR_{p0,2}E}\right] + \tau \cdot \frac{0,43\left(W-a_0\right)}{0,43W+0,57a_0} \cdot V_p \tag{21}$$

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

NOTE 3   The relationship for $g_1(a_0/W)$ is given in Annex D.

δ_0 is calculated for the compact specimen as:

$$\delta_0 = \left[\frac{F}{\left(B \cdot B_N \cdot W\right)^{0,5}} \times g_2\left(\frac{a_0}{W}\right)\right]^2 \left[\frac{\left(1-v^2\right)}{mR_{p0,2}E}\right] + \tau \cdot \frac{0,52\left(W-a_0\right)}{0,52W+0,48a_0} \cdot V_p \tag{22}$$

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

where V_p is the plastic component of V. When attached knife edges are employed, the clip gauge output V_g is converted into V, using the following relationships.

The values of m and τ are calculated by the following formulae.

$$m = 4,9 - 3,5\frac{R_{p0,2}}{R_m} \tag{23}$$

$$\tau = \left\{-1,4\left(\frac{R_{p0,2}}{R_m}\right)^2 + 2,8\left(\frac{R_{p0,2}}{R_m}\right) - 0,35\right\}\left[0,8+0,2\exp\left\{-0,019(B-25)\right\}\right] \tag{24}$$

For bend specimens,

$$V = \frac{0,43\left(W-a_0\right)+a_0}{0,43\left(W-a_0\right)+a_0+z}V_g \tag{25}$$

For stepped notch compact specimens,

$$V = V_g \ (=q) \tag{26}$$

For straight notch compact specimens,

$$V = \frac{0,52\left(W-a_0\right)+a_0}{0,52\left(W-a_0\right)+a_0+0,25W+z}V_g \tag{27}$$

NOTE 5   When V_g is measured at a position beyond the notch edge of the specimen [see Figure 8 b], z is positive, when V_g is measured at a position inside the notch edge, z is negative.

NOTE 6   Derivation of V from V_g in straight notch compact specimens is permitted provided that it can be demonstrated that V so derived is equivalent to directly measured V (=q).

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 V_c or q_c, F_u and V_u or q_u, or F_{uc} and V_{uc} or q_{uc}

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

When the value of F corresponds to small amounts of measured stable crack extension (see 5.8.2), i.e.

$$\Delta a < 0,2 \text{ mm} + \left(\frac{J}{3,75R_m}\right) \tag{28}$$

F shall be recorded as F_c, and V or q which corresponds to F_c shall be recorded as value V_c or q_c.

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

$$\Delta a \geq 0,2 \text{ mm} + \left(\frac{J}{3,75R_m}\right) \tag{29}$$

F shall be recorded as F_u, and V or q which corresponds to F_u shall be recorded as value V_u or q_u.

When it is not possible to determine Δa (see 5.8.3), F and q shall be recorded as F_{uc} and V_{uc} or 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 value F_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)], and q which corresponds to F_m shall be recorded as value q_m.

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) or crack-mouth displacement (V_c, V_u or V_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 20). The plastic component is obtained by subtraction of the theoretical elastic area (U_e) from the total area as described in G.3.
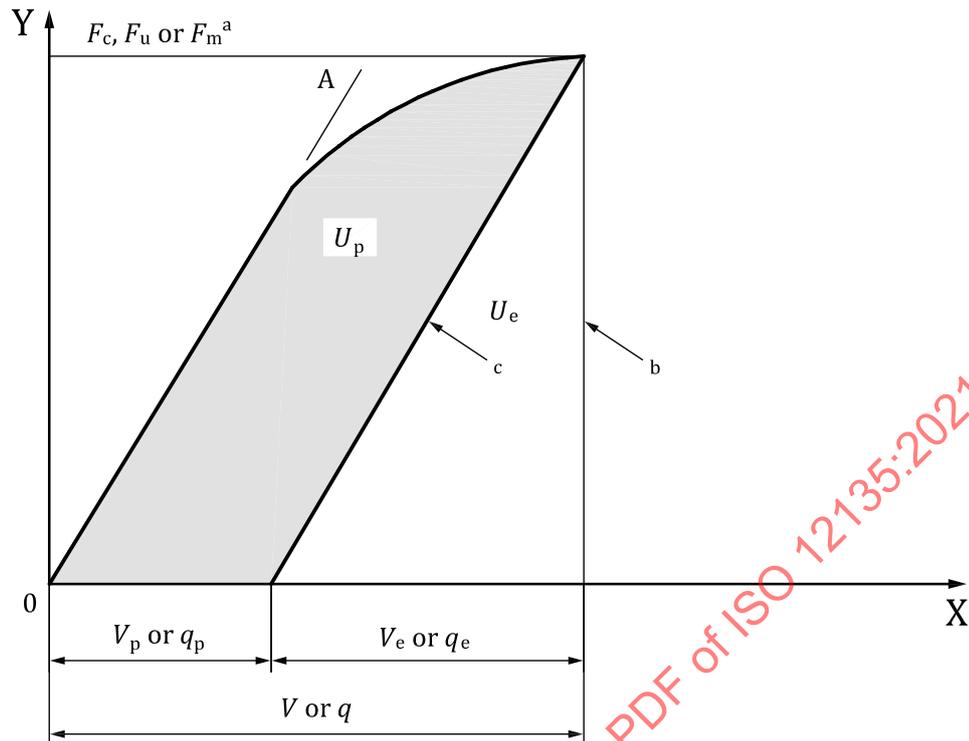
Key

X   crack-mouth opening displacement (V) or load-line displacement (q)

Y   force (F)

[a]   See Figure 2.

[b] V_c, V_u or V_m, or q_c, q_u or q_m, corresponding to F_c, F_u or F_m.

[c]   Parallel to 0A.

Figure 20 — 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_0

J_0 is calculated from the following relationships for bend and compact specimens, using B, B_N and W from 5.5.1, a_0 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_0 are not corrected for crack extension Δa.

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

J_0 is calculated for the three-point bend specimen when U_p is determined from the load-line displacement, q, as:

$$J_0 = \left[\frac{F \cdot S}{\left(B \cdot B_N\right)^{0,5} W^{1,5}} g_1\left(\frac{a_0}{W}\right) \right]^2 \cdot \frac{1-v^2}{E} + \frac{1,9 U_p}{B_N \left(W - a_0\right)} \tag{30}$$

J_0 is calculated for the three-point bend specimen when U_p is determined from the crack-mouth opening displacement, V, as:

$$J_0 = \left[\frac{F \cdot S}{\left(B \cdot B_N\right)^{0,5} W^{1,5}} g_1\left(\frac{a_0}{W}\right) \right]^2 \cdot \frac{1-v^2}{E} + \frac{\eta_p U_p}{B_N \left(W - a_0\right)} \tag{31}$$

where S is the bending span established in 5.7.1.1 (see Figure 10), and where:

$$\eta_p = 3,667 - 2,199\left(\frac{a_0}{W}\right) + 0,437\left(\frac{a_0}{W}\right)^2 \tag{32}$$

NOTE 3   The relationship for $g_1(a_0/W)$ is given in Annex D.

J_0 is calculated for the stepped-notch compact specimen as:

$$J_0 = \left[\frac{F}{\left(B \cdot B_N \cdot W\right)^{0,5}} g_2\left(\frac{a_0}{W}\right) \right]^2 \cdot \frac{1-v^2}{E} + \frac{\eta_p U_p}{B_N \left(W - a_0\right)} \tag{33}$$

where

$$\eta_p = 2 + 0,522\left(1 - \frac{a_0}{W}\right) \tag{34}$$

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

NOTE 5   For plane-sided specimens, $B_N = B$ in Formula (33).

When U_p is derived in straight-notch compact specimens, V_g may be converted to q (=V) using Formula (27). J_0 is calculated for straight-notch compact specimens in the same way as for the stepped-notch compact specimen using Formula (33).

6.4.5   Qualification of J_0 fracture toughness value

Values of J_0 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_0 calculated using values of F_c and V_c or q_c;

— $J_{u(B)}$, for J_0 calculated using values of F_u and V_u or q_u;

— $J_{uc(B)}$, for J_0 calculated using values of F_{uc} and V_{uc} or q_{uc};

— $J_{m(B)}$, for J_0 calculated using values of F_m and V_m or q_m.

For example, for J_0 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-Δa and J-Δa and initiation toughness $\delta_{0,2BL}$ and $J_{0,2BL}$ and δ_i 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 or J with crack extension Δa. The variation of δ with crack extension Δa is geometry- and size-insensitive, and δ is corrected for stable crack extension. Methods are given for interpreting the δ-Δa and J-Δa crack resistance curves in terms of the single-point engineering initiation toughness parameters $\delta_{0,2BL}$ or $J_{0,2BL}$.

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

7.2 Test procedure

7.2.1 General

The 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 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-Δa or J-Δa crack resistance curve (hereafter referred to generically as the R-curve).

Six or more favourably positioned points are required to generate an R-curve (see 7.4) and to determine fracture toughness $\delta_{0,2BL}$ 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.

A set of nominally identical specimens shall have the residual stress modification specified in 5.8.2 on either all or none of the specimens.

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, the 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 the crack extension using the results from the first test.

The agreement between the estimated and the 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

The 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_0; otherwise, the result is not acceptable.

7.3 Calculation of J and δ

7.3.1 Calculation of J

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

$$J = \left[\frac{F \cdot S}{\left(B \cdot B_N\right)^{0,5} W^{1,5}} g_1\left(\frac{a_0}{W}\right) \right]^2 \cdot \frac{1-v^2}{E} + \frac{\eta_p U_p}{B_N\left(W-a_0\right)} \cdot \left[1 - \frac{\gamma_p \cdot a}{\left(W-a_0\right)} \right] \tag{35}$$

where S is the bending span established in 5.7.1.1 (see Figure 10); η_p is equal to 1,9 when determined from q, and is given by Formula (32) when determined from V; and γ_p is equal to 0,5 when determined from q, and is given by Formula (36) when determined from V.

NOTE 1   The relationship for $g_1(a_0/W)$ is given in Annex D.

$$\gamma_p = 0,131 + 2,131\left(\frac{a_0}{W}\right) - 1,465\left(\frac{a_0}{W}\right)^2 \tag{36}$$

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

$$J = \left[\frac{F}{\left(B \cdot B_N \cdot W\right)^{0,5}} g_2\left(\frac{a_0}{W}\right) \right]^2 \cdot \frac{1-v^2}{E} + \frac{\eta_p U_p}{B_N\left(W-a_0\right)} \cdot \left[1 - \frac{\left(0,75\eta_p - 1\right)\Delta a}{W - a_0} \right] \tag{37}$$

where η_p is given by Formula (34).

NOTE 2   The relationship for $g_2(a_0/W)$ is given in Annex D.

NOTE 3   For plane-sided specimens, $B_N = B$ in Formula (37).

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 is equivalent to the directly measured q to within 1 %. J is calculated using Formula (37).

7.3.2 Calculation of δ

δ is calculated for three-point bend specimen as follows (see Reference [10]):

$$\delta = \left[\frac{F \cdot S}{\left(B \cdot B_N\right)^{0,5} W^{1,5}} g_1\left(\frac{a_0}{W}\right) \right]^2 \frac{1-v^2}{m R_{p0,2} E} + \frac{\left(1-r_p\right)\Delta a + r_p B_N}{\left(1-r_p\right)\Delta a + r_p B_N + a_0 + z} \cdot V_p \tag{38}$$

where m is defined in Formula (39) and r_p is defined in Formula (40).

$$m = 4,9 - 3,5\left(\frac{R_{p0,2}}{R_m}\right) \tag{39}$$

$$r_{\text{p}} = R_1 \left(\frac{R_{\text{p0,2}}}{R_{\text{m}}} \right) + R_2 \tag{40}$$

where

$$R_1 = -0,62 \left(\frac{a_0}{W} \right) + 0,76 \tag{41}$$

$$R_2 = 0,61 \left(\frac{a_0}{W} \right) - 0,22 \tag{42}$$

δ is calculated the stepped-notch compact specimen as follows:

$$\delta = \left[\frac{F}{\left(B \cdot B_{\text{N}} \cdot W \right)^{0,5}} g_2 \left(\frac{a_0}{W} \right) \right]^2 \cdot \frac{1 - v^2}{2 R_{\text{p0,2}} E} + \frac{0,54 \Delta a + 0,46 \left(W - a_0 \right)}{0,54 \left(a_0 + \Delta a \right) + 0,46 W + z} \cdot V_{\text{p}} \tag{43}$$

NOTE 1   The relationship for $g_2(a_0/W)$ is given in Annex D.

NOTE 2   For plane-sided specimens, $B_{\text{N}} = B$ in Formula (43).

NOTE 3   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 is equivalent to the directly measured q to within 1 %. δ is calculated using Formula (43).

7.4 R-curve plot

The points of δ 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 or J versus crack extension Δa is constructed from the data obtained in 7.2 and 7.3 (see Figure 21).
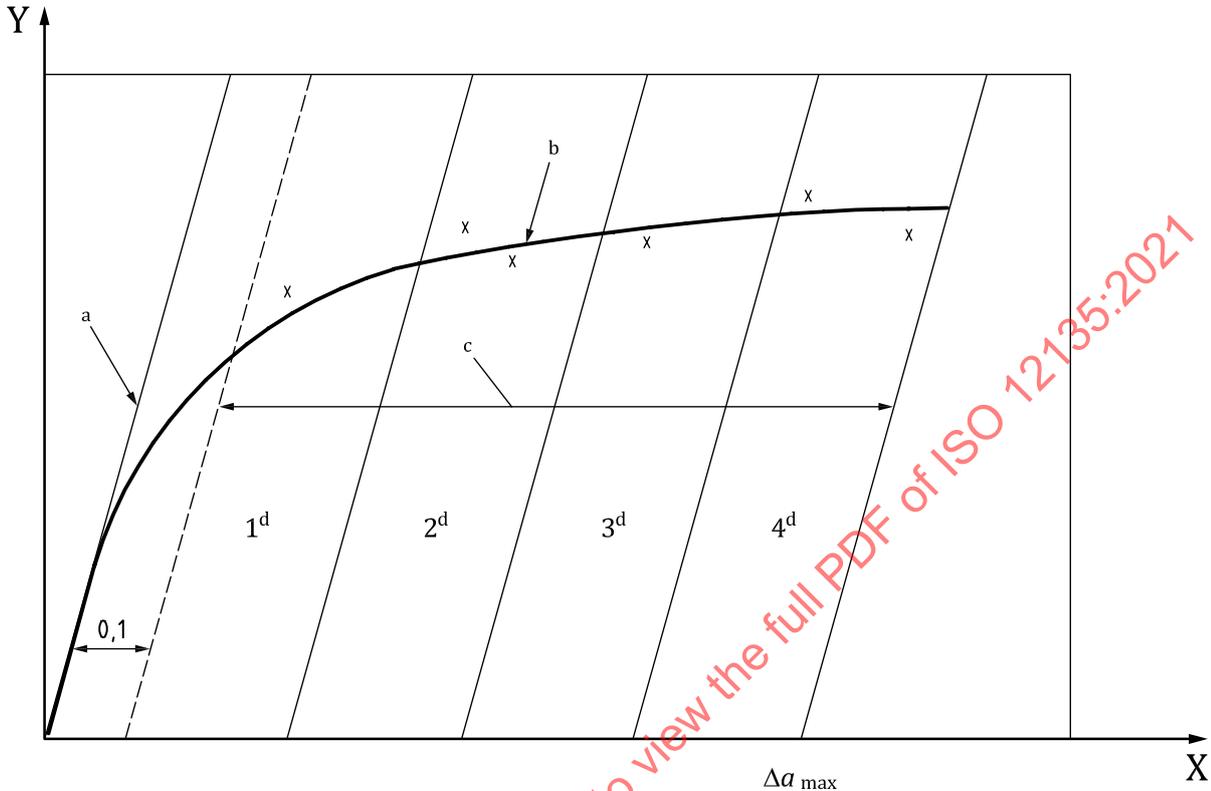
Key

X crack extension (Δa) in millimetres

Y fracture resistance (δ) or (J)

× 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.

a Construction line.

b Fitted curve.

c Exclusion lines.

d Crack sector.

Figure 21 — Data spacing for R-curve determination-

7.4.1.2 For each specimen tested, $\Delta a_{\max}$ is calculated from:

$$\Delta a_{\max} = 0{,}25\left(W - a_0\right), \text{ for both } \delta \text{ and } J \tag{44}$$

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

$$\delta = 1{,}87 \cdot \frac{R_{\mathrm{m}}}{R_{\mathrm{p0,2}}} \cdot \Delta a \tag{45}$$

or

$$J = 3{,}75 \cdot R_{\mathrm{m}} \cdot \Delta a \tag{46}$$

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

NOTE   Formula (45) is derived from Formula (46) by assuming that the δ construction line can be approximated by $\delta = \dfrac{J}{2R_{\mathrm{p0,2}}}$.

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 21).

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 21).

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 21. The curve shall be best-fitted through the data points lying between the 0,1 mm and Δa_{max} exclusion lines (see Figure 21) using the power-law Formula (47):

$$\delta \ (\text{or } J) = \alpha + \beta (\Delta a)^{\gamma} \tag{47}$$

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.

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 22.

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:

$$J_{max} = B \cdot \frac{R_{p0,2} + R_m}{20} \tag{48}$$

$$J_{max} = a_0 \cdot \frac{R_{p0,2} + R_m}{20} \tag{49}$$

$$J_{max} = (W - a_0) \cdot \frac{R_{p0,2} + R_m}{20} \tag{50}$$

7.5.1.2 An exclusion line is constructed to the J-Δa data at the minimum J_{max} value calculated above (see Figure 22).

7.5.1.3 J at the intersection of the best-fit curve with either the J_{max} or Δa_{max} [from Formula (44)] exclusion line defines J_g (see Figure 22). J_g shall be the upper limit to J-controlled crack extension behaviour for the test specimen size used.

7.5.2 Qualification of $\delta - \Delta a$ resistance curves

7.5.2.1 δ_{max} is calculated for each specimen as the smallest of:

$$\delta_{max} = \frac{B}{15} \tag{51}$$

$$\delta_{max} = \frac{a_0}{15} \tag{52}$$

$$\delta_{max} = \frac{W - a_0}{15} \tag{53}$$

7.5.2.2 An exclusion line is constructed on the $\delta-\Delta a$ data at the minimum δ_{max} value calculated from 7.5.2.1 (see Figure 22).

Key
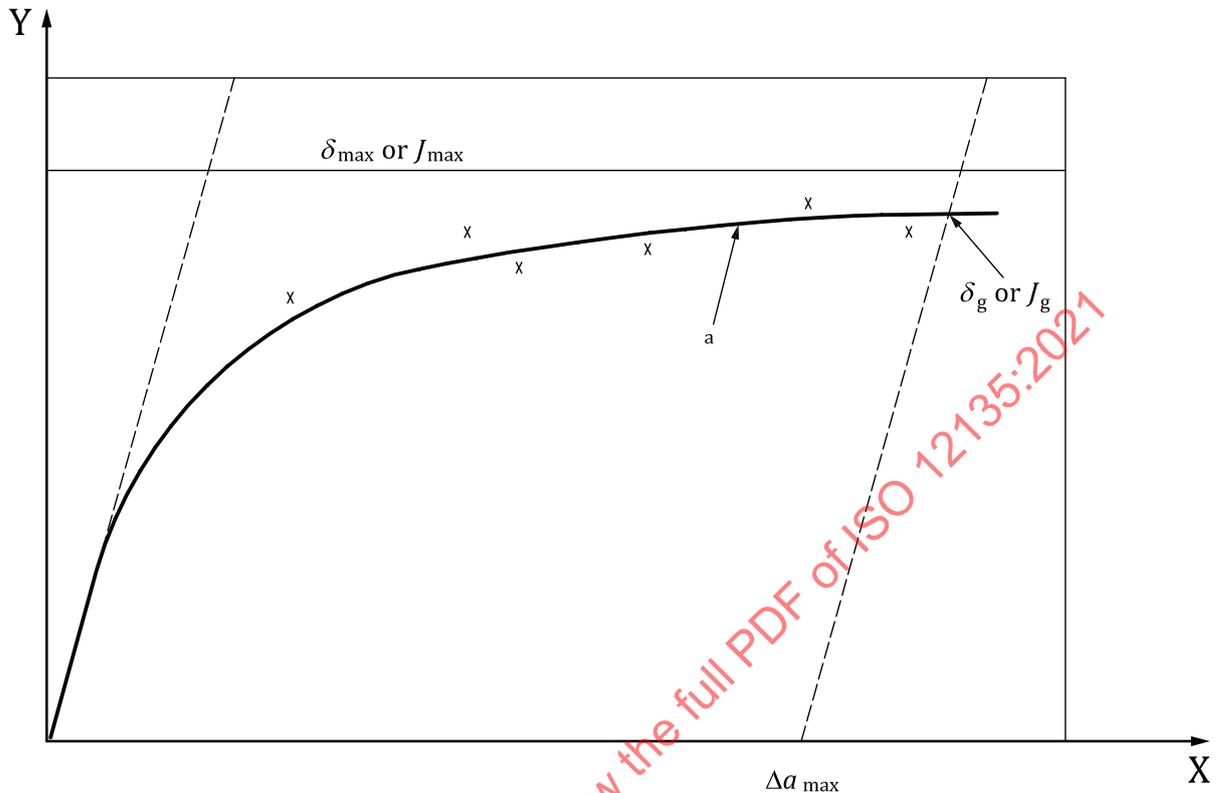
X crack extension (Δa) in millimetres

Y fracture resistance (δ) or (J)

× test data

NOTE   If the R-curve intersects the δ_{max} or J_{max} limit within the Δa_{max} limit, then δ_g or J_g equals δ_{max} or J_{max}.

a   Fitted curve.

Figure 22 — Qualification limits and definitions of J_g or δ_g

7.5.2.3 δ at the intersection of the best-fit curve with either the δ_{max} or Δa_{max} [from Formula (44)] exclusion lines defines δ_g (see Figure 22). δ_g shall be the upper limit to δ-controlled crack extension behaviour for the test specimen size used.

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

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 23). The best-fit curve [Formula (47)] 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 23. 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:

$$3,75R_{\mathrm{m}} > \left[2\left(\frac{\mathrm{d}J}{\mathrm{d}a} \right) \right]_{0,2\mathrm{BL}} \tag{54}$$

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 the specimen thickness.

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

$$K_{J0,2\mathrm{BL}} = \sqrt{\frac{E \, J_{0,2\mathrm{BL}}}{1-v^2}} \tag{55}$$

7.6.2 Determination of $\delta_{0,2\mathrm{BL}}$

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 23). The best-fit curve [Formula (46)] shall pass through a minimum of six δ−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 23. The intersection of the best-fit curve with the 0,2 mm offset line defines $\delta_{0,2\mathrm{BL}}$.

7.6.2.3 If $\delta_{0,2\mathrm{BL}}$ exceeds δ_{max} (see 7.5.2.1), then it does not qualify.

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

$$1,87 \cdot \frac{R_{\mathrm{m}}}{R_{\mathrm{p0,2}}} > \left[2\left(\frac{\mathrm{d}\delta}{\mathrm{d}a} \right) \right]_{0,2\mathrm{BL}} \tag{56}$$

then the $\delta_{0,2\mathrm{BL}}$ determined in 7.6.2.2 does not qualify.

7.6.2.5 If $\delta_{0,2BL}$ conforms to 7.6, as well as 8.7, then $\delta_{0,2BL}$ determined in 7.6.2.2 is considered size-insensitive. If not, the value shall be reported as size-sensitive $\delta_{0,2BL(B)}$, where B is the specimen thickness.
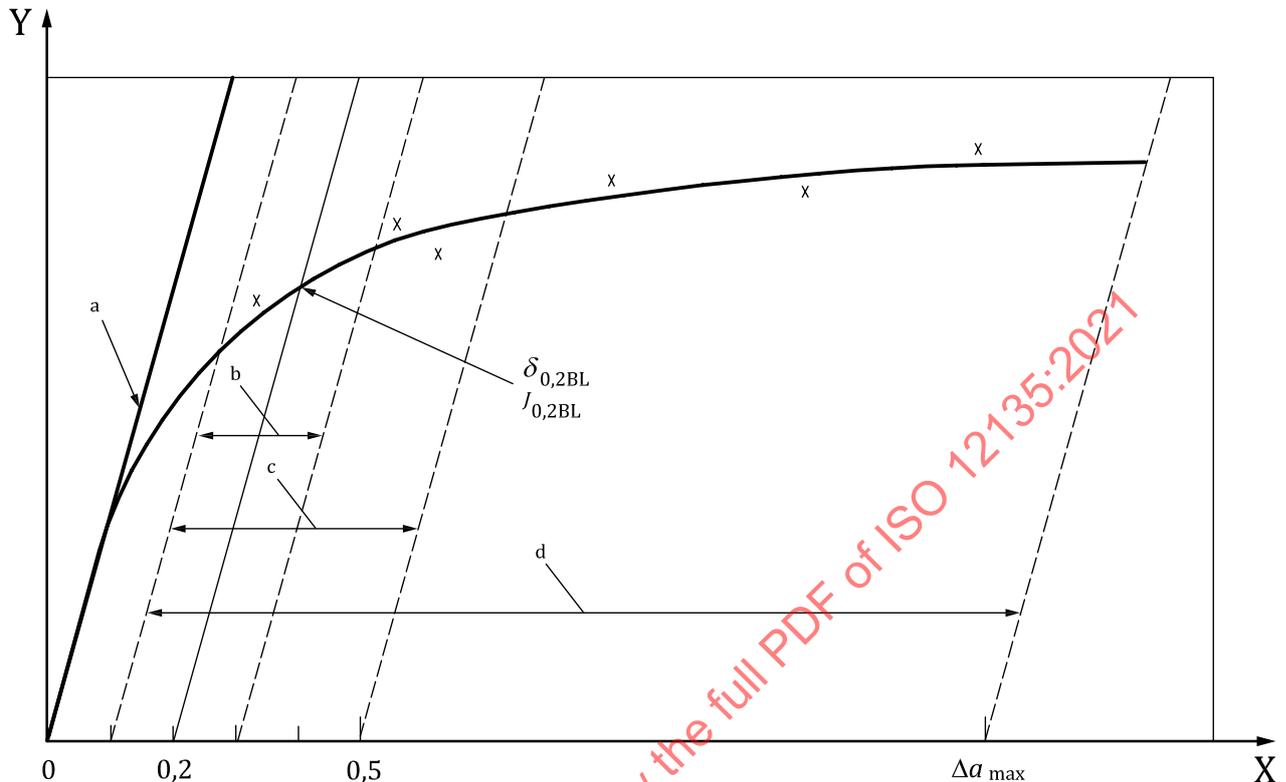
Key

X   crack extension (Δa) in millimetres

Y   fracture resistance (δ) or (J)

×   test data

At least six data points are required.

a   Construction line.

b   At least one point.

c   At least two points.

d   Region of data dispersion in accordance with Figure 21.

Figure 23 — Data spacing for $J_{0,2BL}$ or $\delta_{0,2BL}$

7.7 Determination of initiation toughness J_i and δ_i by scanning electron microscopy (SEM)

Values of initiation toughness J_i and δ_i 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_i 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 the 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 15 and 16. The following values shall be reported:

— the initial machined notch length (a_m);

— the initial crack length to the fatigued notch tip (a_0);

— the fatigue precrack length ($a_0 - a_m$);

— the final crack length (a_f);

— the average crack extension ($\Delta a = a_f - a_0$).

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_0 is within the range 0,45 W to 0,7 W, or within the range 0,45 W to 0,55 W for K_{lc} 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 ($a_0 + \Delta a$) 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 the purposes of manual record analysis);

k) for a single-specimen *direct* crack length measurement method used to estimate crack extension, the final estimated crack extension is within 15 % of the nine-point average measured crack extension, or 0,15 mm, whichever is greater, up to a crack extension of 0,2(W-a_0), and to within 0,03(W-a_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 extension or 0,15 mm, whichever is greater, to a crack extension of 0,2(W-a_0) and to within 0,03(W-a_0) thereafter;

n) the data number and spacing requirements of 7.4.2 and 7.6.1 are satisfied for δ-Δa curve and $\delta_{0,2\text{BL}}$ determinations;

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

8.4 Qualification of K_{lc}

The following requirements shall be met for K_Q (calculated in accordance with 6.2.3) to qualify as K_{lc} 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) $2,5\left(\dfrac{K_Q}{R_{\text{p0,2}}}\right)^2 \le a_0$;

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

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

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

8.5 Qualification of $\delta_{\text{c}(B)}$, $\delta_{\text{u}(B)}$, $\delta_{\text{uc}(B)}$ or $\delta_{\text{m}(B)}$

The single point value of size-sensitive CTOD is qualified based on the criteria given in 6.3.5, using the classifications of the force and displacement in Figure 2, and the amount of measured stable crack extension Δa given in 6.4.1. The thickness shall be noted in millimetre units in parentheses as a subscript to the symbol for the fracture toughness. For example, for CTOD calculated from values of F_{c} and V_{c} for a test specimen of thickness B = 25 mm, the $\delta_{\text{c}(B)}$ fracture toughness shall be symbolized $\delta_{\text{c}(25)}$.

8.6 Qualification of $J_{c(B)}$, $J_{u(B)}$, $J_{uc(B)}$ or $J_{m(B)}$

The single point value of size-sensitive J is qualified based on the criteria given in 6.4.5, using the classifications of the force and displacement in Figure 2, and the amount of measured stable crack extension Δa given in 6.4.1. The thickness shall be noted in millimetre units in parentheses as a subscript to the symbol for the fracture toughness. For example, for J calculated from values of F_c and V_c for a test specimen of thickness B = 25 mm, the $J_{c(B)}$ fracture toughness shall be symbolized $J_{c(25)}$.

8.7 Qualification of the δ-R Curve

The δ-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-R curve in accordance with this method:

a) the data are qualified in accordance with 8.3;

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

8.8 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.

8.9 Qualification of $\delta_{0,2BL(B)}$ as $\delta_{0,2BL}$

If the following requirements are not met for $\delta_{0,2BL}$ calculated according to 7.6.1, it shall be qualified as size-dependent and denominated $\delta_{0,2BL(B)}$ in accordance with this method:

a) all requirements of 8.3 are satisfied;

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

c) $15\,\delta_{0,2BL} \leq a_0$;

d) $15\,\delta_{0,2BL} \leq B$;

e) $15\,\delta_{0,2BL} \leq W - a_0$.

8.10 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 smaller than 1,875 R_m;

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

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

e) $20\dfrac{J_{0,2\mathrm{BL}}}{R_{\mathrm{p}0,2}+R_{\mathrm{m}}} \leq W - a_0$.

Annex A
(informative)

Determination of δ_i and J_i

A.1 General

The determination of δ_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 [11] and [12]). A large scatter in the values of δ_i 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, δ_i and J_i cannot be determined.

A.2 Critical stretch zone width (SZW) measurement

A.2.1 The local critical stretch zone width SZW,L is measured at the nine positions shown in Figures 15 and 16 using calibrated photographs taken in a SEM. An example of SEM photograph is shown in Figure A.1.
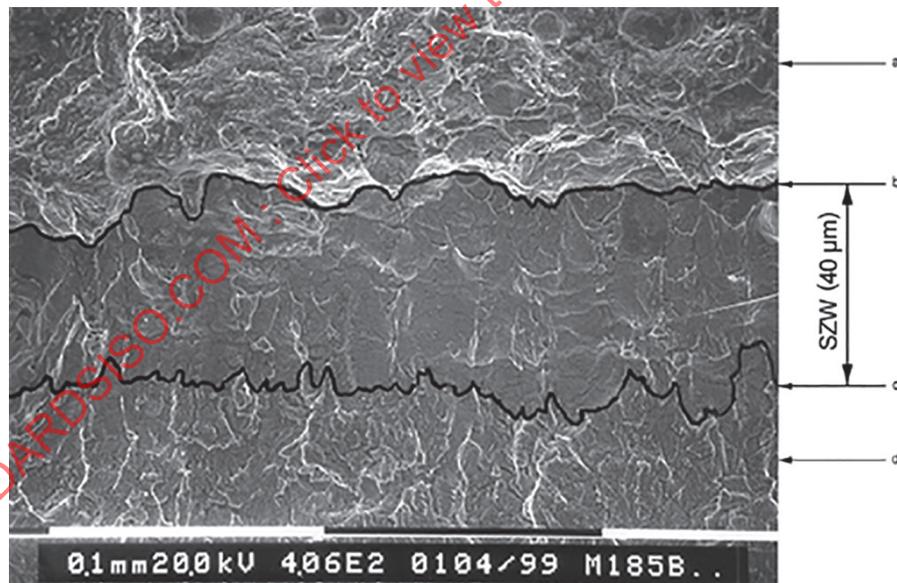
a Fracture.
b End of stretch zone.
c Start of stretch zone.
d Fatigue.

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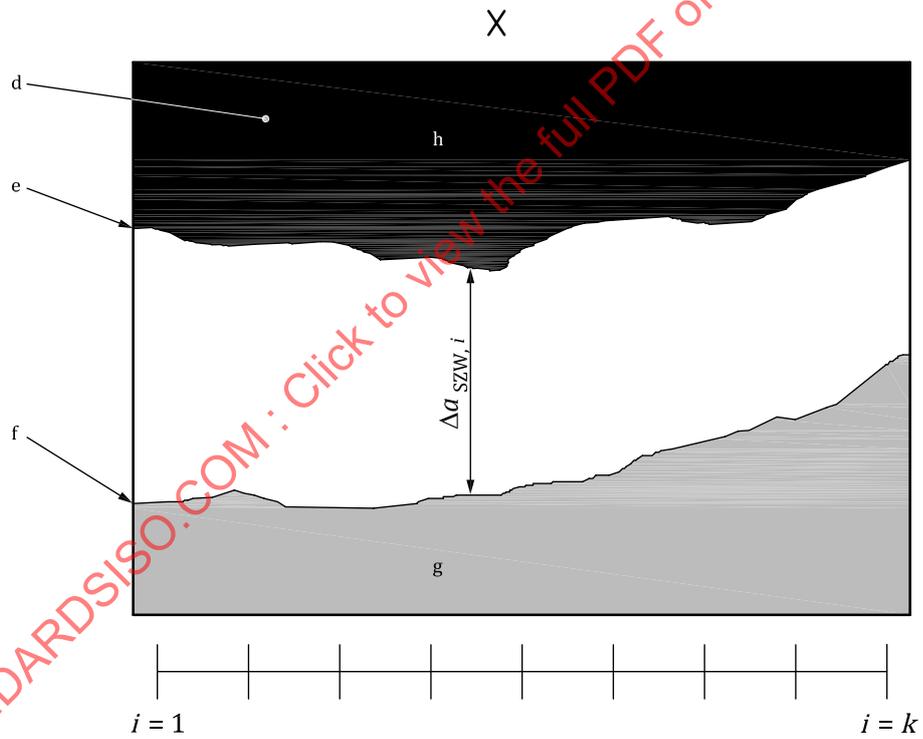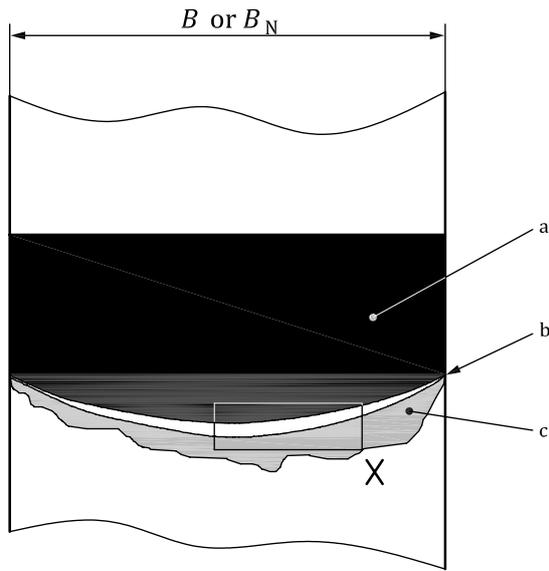
$$\Delta a_{SZW,L} = \frac{1}{k}\sum_{i=1}^{k}\Delta a_{SZW,i}$$

a Fatigue precrack.	e Beginning of stretch zone.
b Stretch zone.	f End of stretch zone.
c Stable crack extension.	g SEM photograph.
d Image plane parallel to fatigue surface.	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,

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

A.2.2   The critical stretch zone width is established as the average of nine local measurements; thus,

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

A.2.3   The 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,

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

A.3   Determination of δ_i

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

Dimensions in millimetres

Key
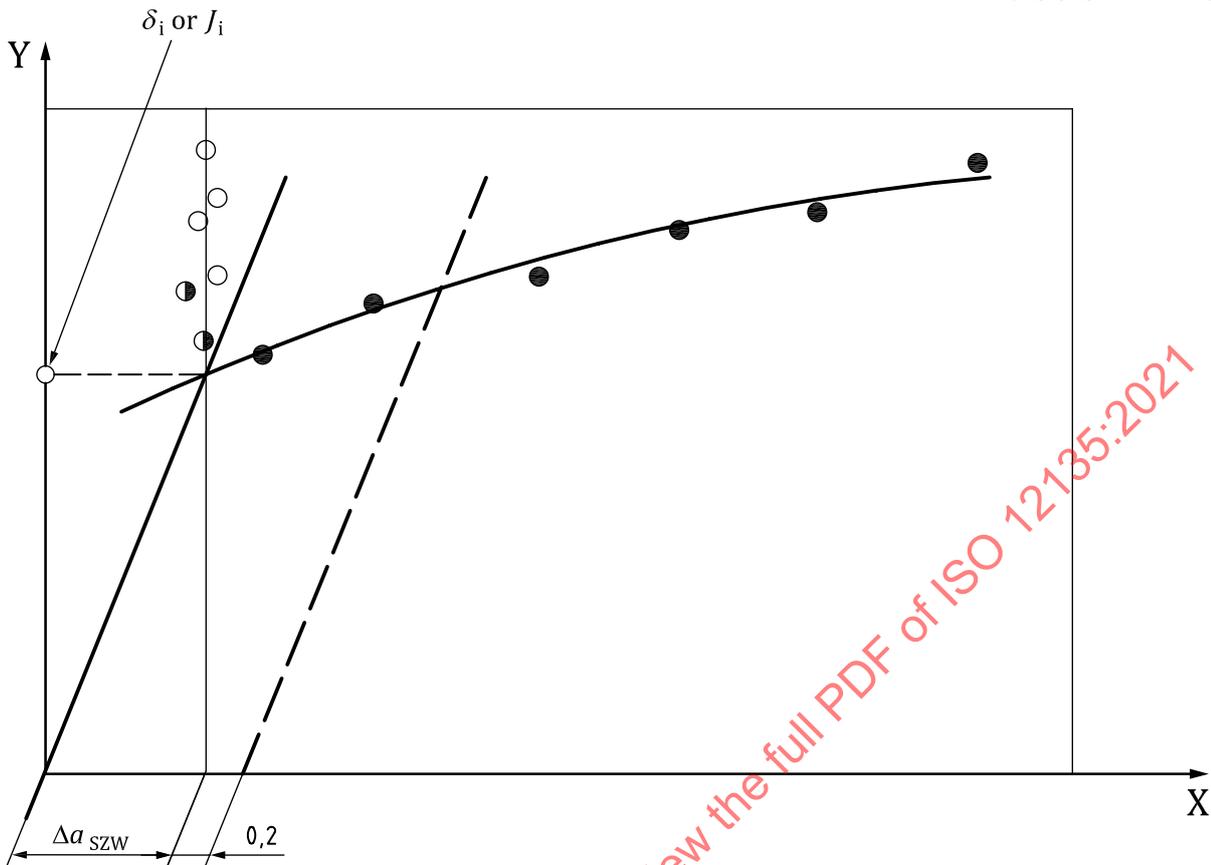
X   Crack extension (Δa)

Y   Fracture resistance (δ)or (J)

◉ δ - Δa or J - Δa data

○   valid stretch zone width data

◑   invalid stretch zone width data

Figure A.3 — Determination of δ_i and J_i

A.3.2   A line shall be drawn parallel to the δ-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-Δa data that exceed Δa_{SZW}. The intercept of the best-fit curve with the drawn parallel line defines δ_i.

A.3.3   A line shall be drawn from the origin through δ_i (see Figure A.3). At least one δ-Δa datum point shall reside within 0,2 mm of this line. If δ_i exceeds δ_{max} determined in accordance with 7.5.1.1, δ_i is not qualified in accordance with this method.

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

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

δ_i is qualified in accordance with this method.

A.4   Determination of J_i

A.4.1   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.4.2   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.4.3   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.4.4   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.4.2 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, and 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.
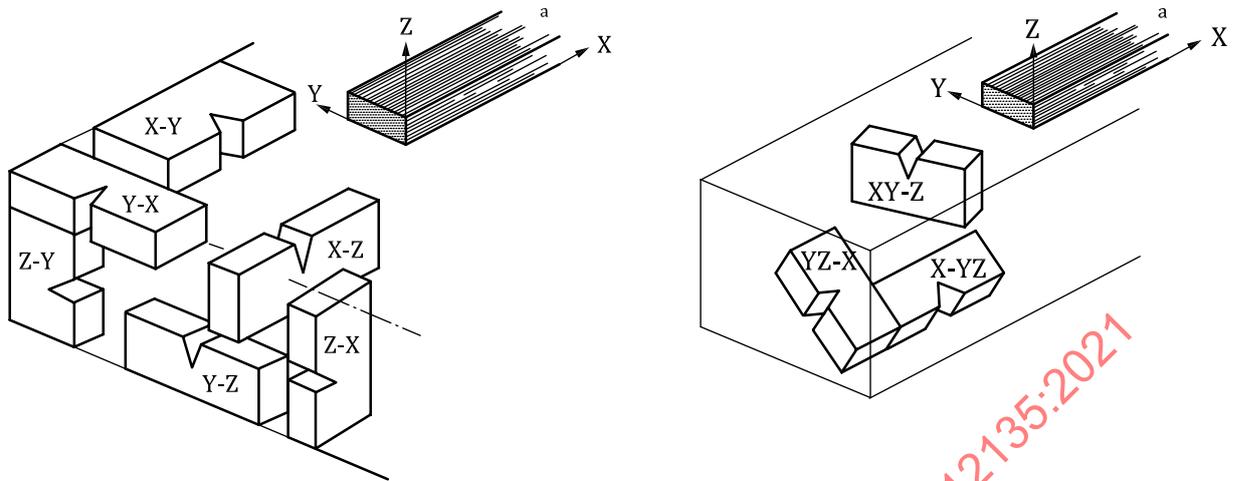
a) Basic identification

b) Non-basic identification
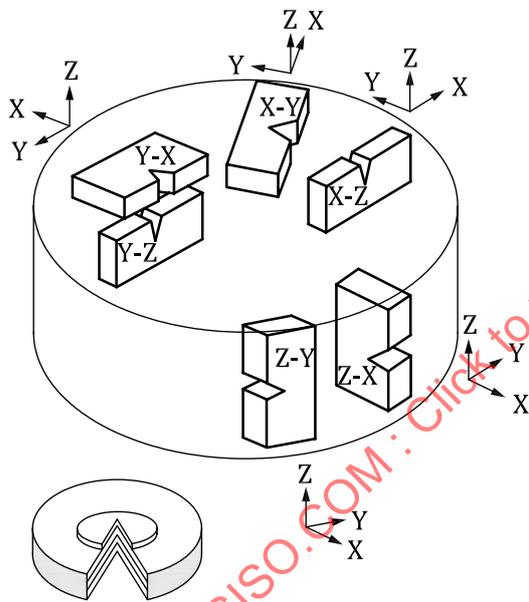
c) Radial grain flow, axial working direction
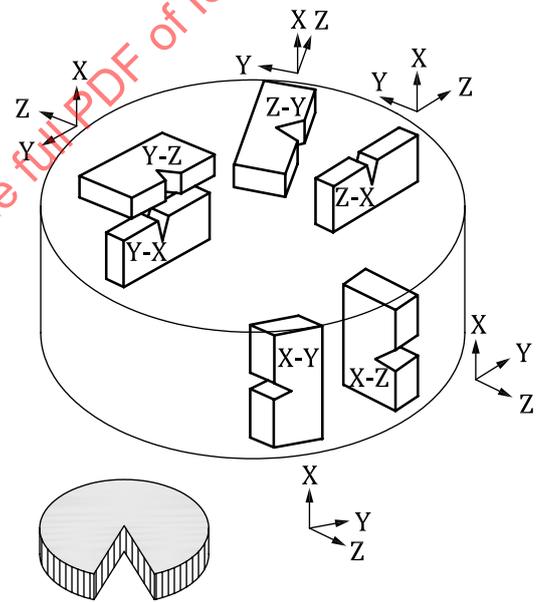
d) Axial grain flow, radial working direction

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 $\qquad$ = _____ (°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)		_____
R_m (ultimate tensile strength) = _____ (MPa)		_____

Precracking

Fatigue temperature = _____ (°C)

Final K_f = _____ (MPa m$^{0.5}$)

Final F_f = _____ (kN)

Final K_f/E = _____ (m$^{0.5}$)

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	Δa mm
1			
2			
3			
4			
5			
6			
7			
8			
9			

a_0 Average initial crack length[a]   _____ (mm)

$a_0 - a_m$ Average fatigue precrack length[a]   _____ (mm)

Δa Average crack extension[a]   _____ (mm)

$a_0 + \Delta a$ Average final crack length[a]   _____ (mm)

[a] See 5.8.

Estimated crack lengths

$a_{0,est}$ 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 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_{lc}

F_{max} =_____ (kN)

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

F_Q =_____ (kN)

K_Q =_____ (MPa m^{0,5})

a_0 =_____ (mm)

B =_____ (mm)

$W - a_0$ =_____ (mm)

$2,5\left(\dfrac{K_Q}{R_{p0,2}}\right)^2$ =_____ (m)

Requirements (see 8.4):

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

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

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

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

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

f) $K_f < 0{,}6\, K_Q \cdot \dfrac{\left(R_{p0,2}\right)_P}{\left(R_{p0,2}\right)_t}(W - a_0)$

If all requirements are met: K_{lc} = _____ (MPa m^{0,5}).

C.5 Qualification of $\delta_{c(B)}$, $\delta_{u(B)}$, $\delta_{uc(B)}$ or $\delta_{m(B)}$

a_0 = _____ (mm)

B = _____ (mm)

δ_0 = _____ (mm)

Stable crack extension, Δa = _____ (mm)

Classification of F, and V or q as given in Figure 2   _____

Classification of single point CTOD   _____

C.6 Qualification of $J_{c(B)}$, $J_{u(B)}$, $J_{uc(B)}$ or $J_{m(B)}$

a_0 = _____ (mm)

B = _____ (mm)

J_0 = _____ (MJ/m^2)

Stable crack extension, Δa = _____ (mm)

Classification of F, and V or q as given in Figure 2   _____

Classification of single point J _____

C.7 Qualification of δ-R curve

a_0 =_____ (mm)

B =_____ (mm)

$W - a_0$ =_____ (mm)

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

α = _____

β = _____

γ = _____

δ_{max} = smallest of: $\dfrac{B}{15}$, $\dfrac{a_0}{15}$ or $\dfrac{W - a_0}{15}$ _____ (mm)

$\Delta a_{max} = 0{,}25(W - a_0)$ _____ (mm)

δ_g (intersection of power law curve and limits set by δ_{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-R curve is set by δ_g.

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

C.8 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 $\left(W-a_0\right)\dfrac{R_{p0,2}+R_m}{20}$ =_____ (MJ/m^2)

Δa_{max} = $0,25(W-a_0)$ =_____ (mm)

J_g (intersection of power law curve and limits set by J_{max}, Δa_{max} bounds)   =_____ (MJ/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.9 Qualification of $\delta_{Q0,2BL(B)}$ as $\delta_{0,2BL}$

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

R_m =_____ (MPa)

$\delta_{Q0,2BL}$ =_____ (mm)

$15\delta_{Q0,2BL}$ =_____ (mm)

$d\delta/da$ in Δa_Q =_____

$W - a_0$ =_____ (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 $d\delta/da$ 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) $15\,\delta_{0,2BL} \le a_0$;

d) $15\,\delta_{0,2\mathrm{BL}} \leq B$;

e) $15\,\delta_{0,2\mathrm{BL}} \leq W - a_0$.

If all requirements are met: $\delta_{0,2\mathrm{BL}}$ = _____ (mm)

C.10 Qualification of $J_{\mathrm{Q0,2BL}}$ as $J_{0,2\mathrm{BL}}$

a_0	=_____ (mm)
B	=_____ (mm)
$W - a_0$	=_____ (mm)
$R_{\mathrm{p0,2}}$	=_____ (MPa)
R_{m}	=_____ (MPa)
$J_{\mathrm{Q0,2BL}}$	=_____ (MJ/m^2)
$\dfrac{R_{\mathrm{p0,2}} + R_{\mathrm{m}}}{2}$	=_____ (MPa)
dJ/da in Δa_{Q}	=_____ (MPa)
$20\,\dfrac{J_{0,2\mathrm{BL}}}{R_{\mathrm{p0,2}} + R_{\mathrm{m}}}$	=_____ (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) $20\,\dfrac{J_{0,2\mathrm{BL}}}{R_{\mathrm{p0,2}} + R_{\mathrm{m}}} \leq a_0$;

d) $20\,\dfrac{J_{0,2\mathrm{BL}}}{R_{\mathrm{p0,2}} + R_{\mathrm{m}}} \leq B$;

e) $20\,\dfrac{J_{0,2\mathrm{BL}}}{R_{\mathrm{p0,2}} + R_{\mathrm{m}}} \leq W - a_0$.

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

Annex D
(informative)

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 $g_1(a_0/W)$ is given in Reference [13].

$$g_1\left(\frac{a_0}{W}\right)=\frac{3\left(\frac{a_0}{W}\right)^{0,5}\left[1,99-\frac{a_0}{W}\left(1-\frac{a_0}{W}\right)\left\{2,15-3,93\frac{a_0}{W}+2,7\left(\frac{a_0}{W}\right)^2\right\}\right]}{2\left(1+2\frac{a_0}{W}\right)\left(1-\frac{a_0}{W}\right)^{1,5}}$$

(D.1)

NOTE   To facilitate the calculation of K, values of $g_1(a_0/W)$ are given in Table D.1 for specific values of a_0/W.

D.1.2 Compact specimens

For compact specimens, the stress intensity factor coefficient $g_2(a_0/W)$ is given in Reference [13].

$$g_2\left(\frac{a_0}{W}\right)=\frac{\left(2+\frac{a_0}{W}\right)\left[0,886+4,64\frac{a_0}{W}-13,32\left(\frac{a_0}{W}\right)^2+14,72\left(\frac{a_0}{W}\right)^3-5,6\left(\frac{a_0}{W}\right)^4\right]}{\left(1-\frac{a_0}{W}\right)^{1,5}}$$

(D.2)

NOTE   To facilitate the calculation of K, values of $g_2(a_0/W)$ are given in Table D.2 for specific values of a_0/W.

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

a_0/W	$g_1(a_0/W)$	a_0/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 $g_2(a_0/W)$ for compact specimens

a_0/W	$g_2(a_0/W)$	a_0/W	$g_2(a_0/W)$
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 [14].

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

where

$$B_e = B - \frac{\left(B-B_N\right)^2}{B}; \tag{D.4}$$

$$g_3\left(\frac{a}{W}\right)=6\frac{a}{W}\left\{0{,}76-2{,}28\frac{a}{W}+3{,}87\left(\frac{a}{W}\right)^2-2{,}04\left(\frac{a}{W}\right)^3+\frac{0{,}66}{\left(1-\frac{a}{W}\right)^2}\right\}. \tag{D.5}$$

D.2.2 Compact specimens instrumented for measurement of F versus crack-mouth opening displacement V_{M2}

For compact specimens instrumented for measurement of F versus crack-mouth opening displacement V_{M2}, the elastic compliance V_{M2}/F is given in Reference [15].

$$\frac{V_{M2}}{F}=\frac{1-v^2}{EB_e}\cdot g_4\left(\frac{a}{W}\right) \tag{D.6}$$

where B_e is given in Formula (D.4) and

$$g_4\left(\frac{a}{W}\right)=\frac{15{,}8}{1-\left(\frac{a}{W}\right)^2}\left\{0{,}121+1{,}21\frac{a}{W}-0{,}159\left(\frac{a}{W}\right)^2-1{,}47\left(\frac{a}{W}\right)^3+1{,}30\left(\frac{a}{W}\right)^4\right\}. \tag{D.7}$$

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 [16].

$$\frac{q_{e1}}{F}=\frac{1-v^2}{EB_e}\left(\frac{S}{W-a}\right)^2\cdot g_5\left(\frac{a}{W}\right) \tag{D.8}$$

where B_e is given in Formula (D.4) and

$$\frac{q_{e1}}{F}=\frac{1-v^2}{EB_e}\left(\frac{S}{W-a}\right)^2\cdot g_5\left(\frac{a}{W}\right) \tag{D.8}$$

$$g_5\left(\frac{a}{W}\right)=1{,}193-1{,}980\frac{a}{W}+4{,}478\left(\frac{a}{W}\right)^2-4{,}443\left(\frac{a}{W}\right)^3+1{,}739\left(\frac{a}{W}\right)^4. \tag{D.9}$$

D.2.4 Compact specimens instrumented for measurement of F versus load-line displacement q_{e2}

For compact specimens instrumented for measurement of F versus load-line displacement q_{e2} the elastic compliance q_{e2}/F is the same to Formula (D.7).

$$\frac{q_{e2}}{F}=\frac{1-v^2}{EB_e}\cdot g_4\left(\frac{a}{W}\right) \tag{D.10}$$

where B_e is given by Formula (D.4).

Annex E
(informative)

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

One method for determining K_{lc} values (see 6.2), and for determining J values (see 6.4), requires measurement of load-line displacement q; however, it is difficult to obtain direct measurements of load-line displacement for the three-point bend specimen (see Reference [10]). 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 [17]) bar whereby vertical displacement of the bar is measured relative to the crack-tip, or crack-mouth, as shown schematically in Figure E.1.
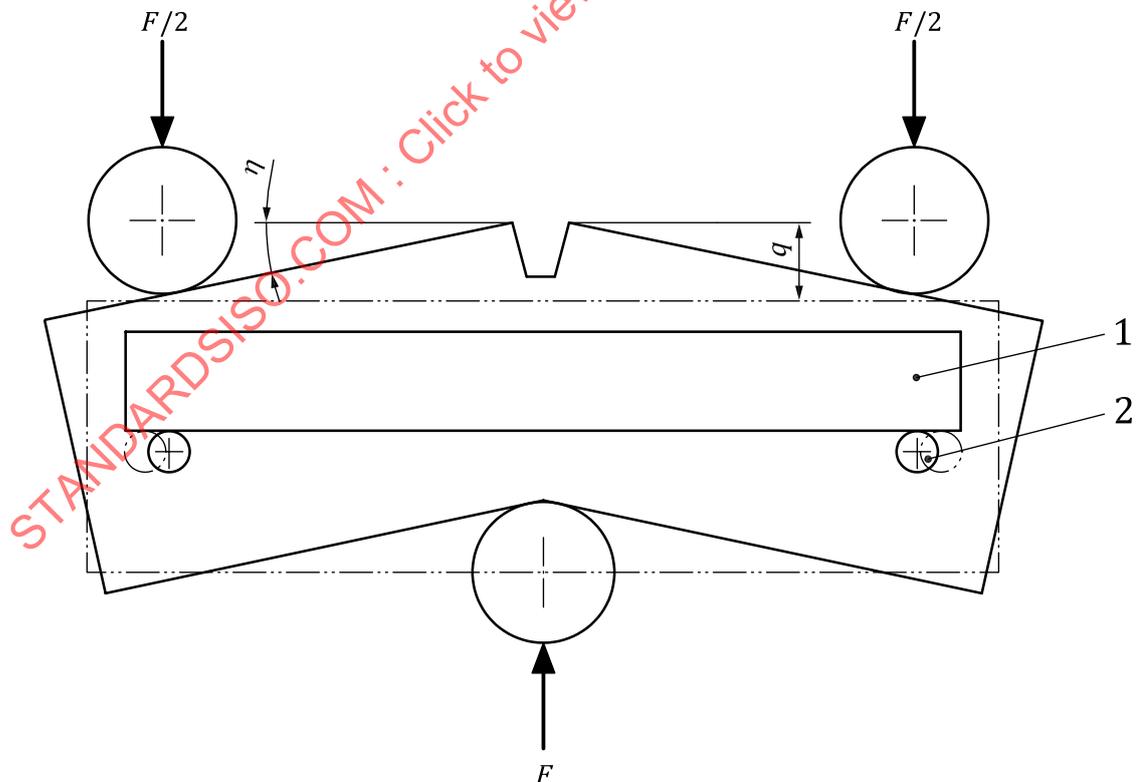

Key

1 comparator bar

2 pin

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

NOTE 1   Measurements made relative to the crack-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 [18]) 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 $0,14W$.
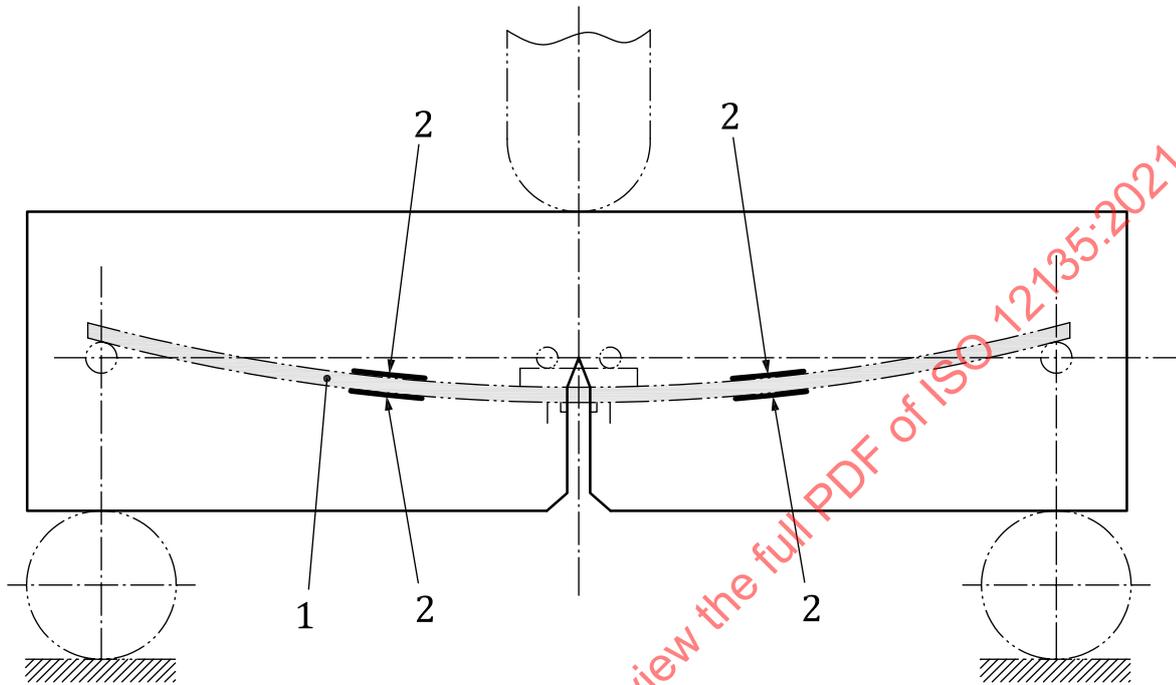

Key

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
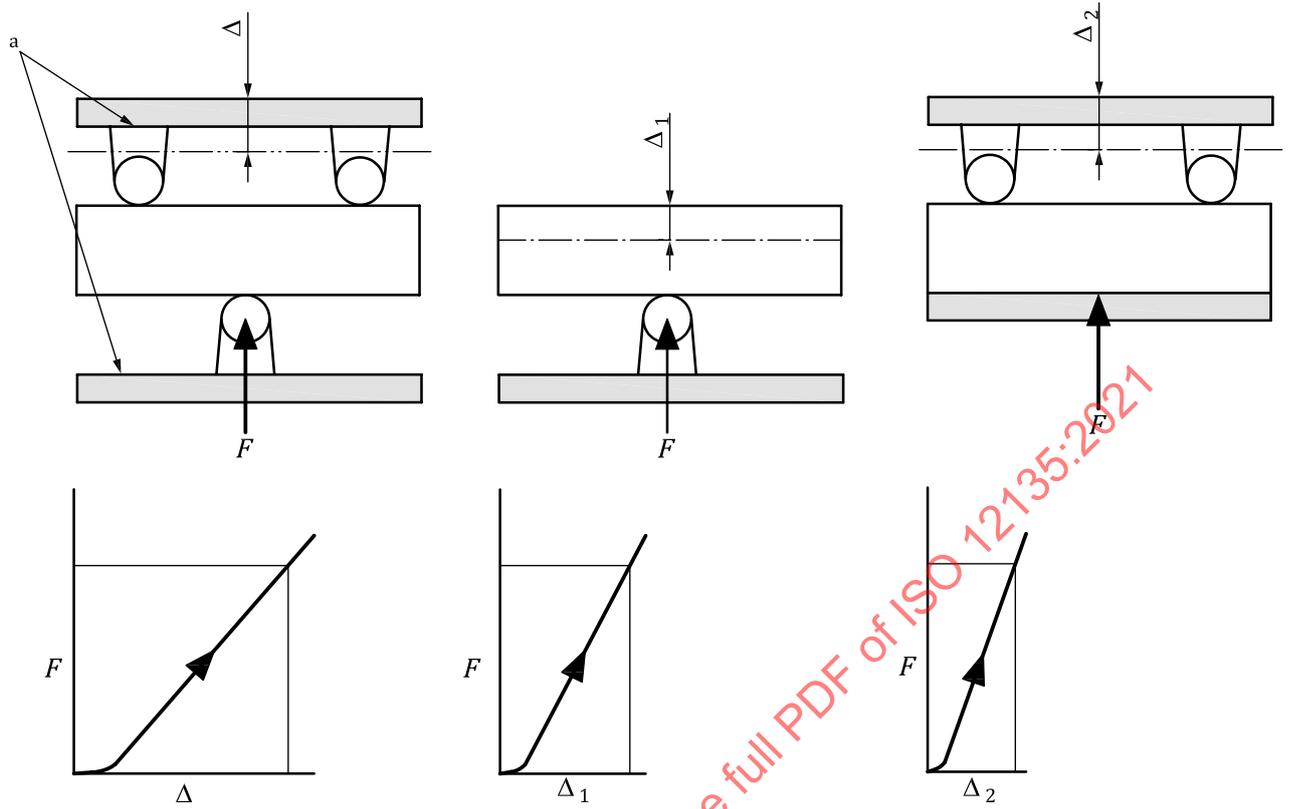
a) Crosshead displacement, Δ **b) Elastic plastic indentation of specimen and compression of central roller and anvil,** Δ_1 **c) Elastic plastic indentation of specimen and compression of outer roller and anvils,** Δ_2

a   Reference faces.

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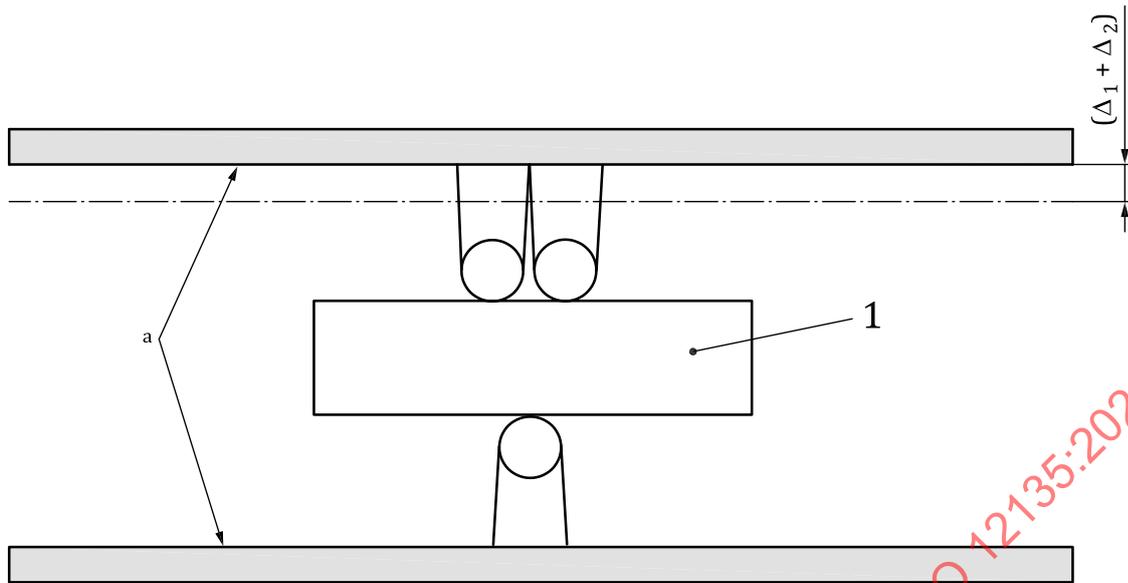
Key

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.

The indirect methods above [a) and b)] shall be modified for q measurements beyond maximum force (see Reference [19]).
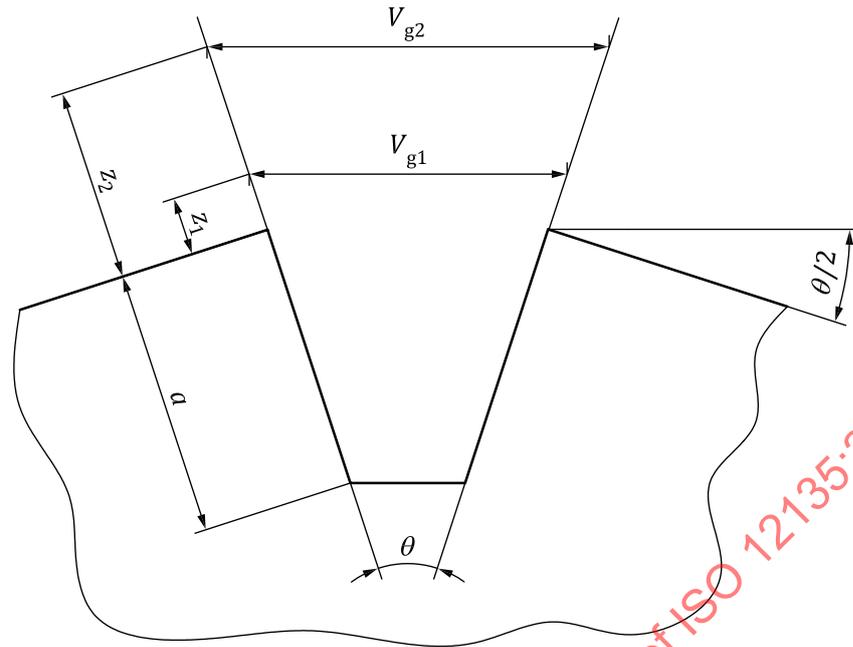
Figure E.5 — Location of two notch-opening displacements measurements (V_{g1} and V_{g2}) for the determination of load-line displacement

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 crack-mouth, and a second located above the crack-mouth (see Figure E.5), the load-line displacement (see Reference [20]) is determined from:

$$q = \frac{S\left(V_{g2} - V_{g1}\right)}{4\left(z_2 - z_1\right)} \qquad \text{(E.1)}$$

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 $\theta < 8°$. For $\theta \geq 8°$, the load-line displacement can be estimated with similar accuracy from:

$$q = \frac{S}{2} \tan\left[\arcsin\left\{\frac{V_{g2} - V_{g1}}{2\left(z_2 - z_1\right)}\right\}\right] \qquad \text{(E.2)}$$

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:

$$AD = BC \times \frac{OD}{OC} = \frac{Q_1(F_n - y_n)}{Q_n + x_n}$$

(F.1)

and

$$\Delta F_n = F_1 - AD = F_1 - \frac{Q_1(F_n - y_n)}{Q_n + x_n}$$

(F.2)

Hence,

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

(F.3)

For simplicity, if

$$\frac{\Delta F_n}{F_1} = P$$

(F.4)

then

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

(F.5)