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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).

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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_{Ic}	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_{Ic}

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.

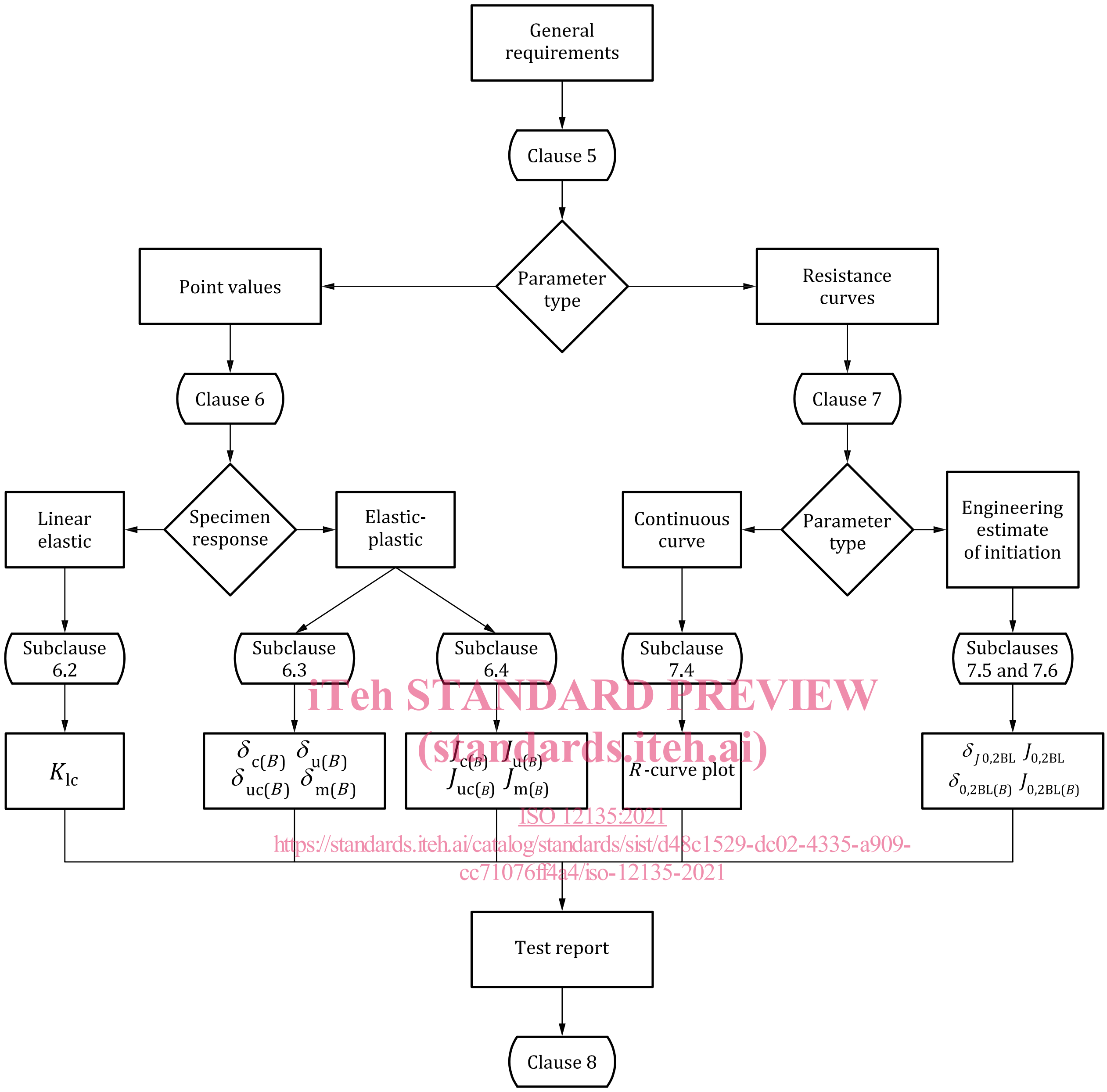
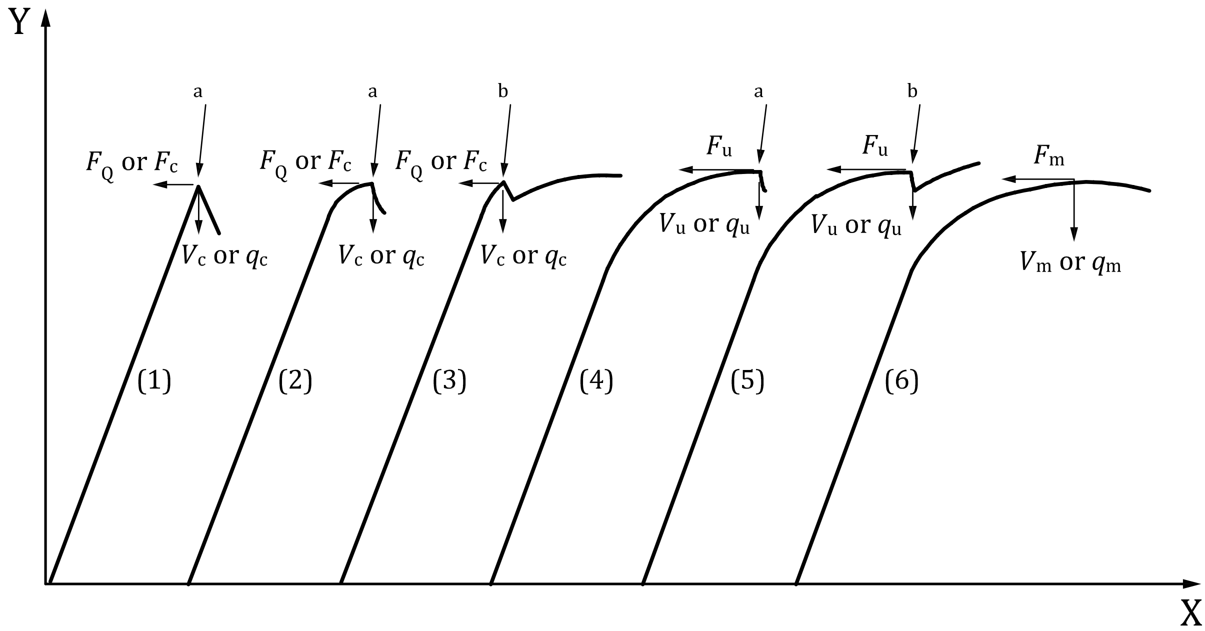


Figure 1 — General flowchart showing how to use the standard method of test



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

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

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

When stable crack extension is extensive, 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 $\delta_{0,2BL}$ or $J_{0,2BL}$ 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.

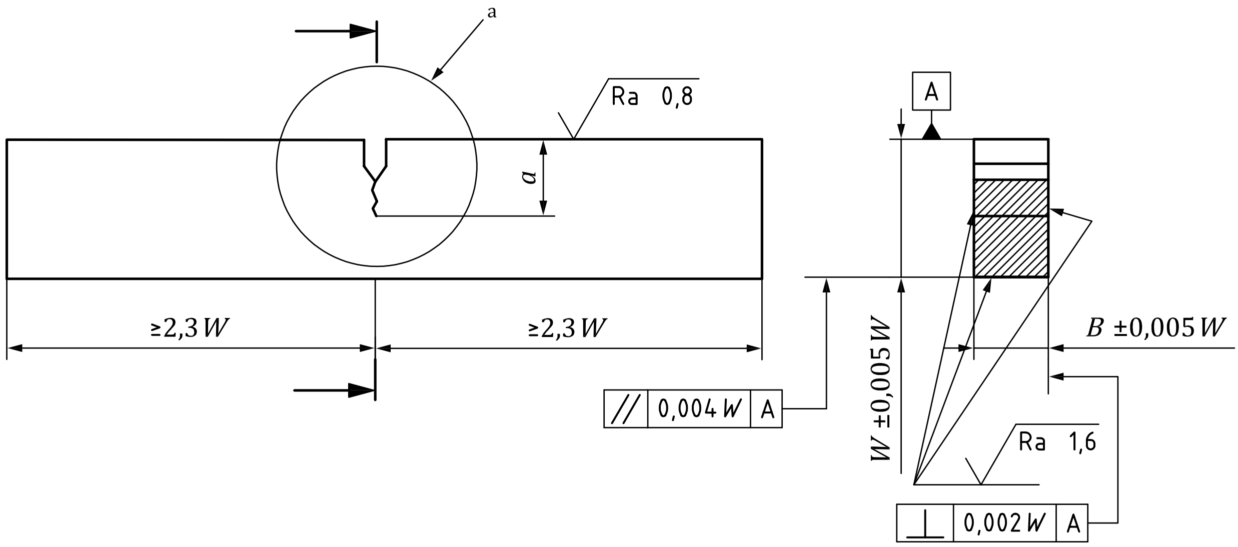
Table 1 — Fracture toughness symbols

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

5.4 Test specimens

5.4.1 Specimen configuration and size

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



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_{Ic} 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