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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

ICS: 77.040.10

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Contents

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

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

1 Scope

This document specifies methods for determining fracture toughness in terms of *K*, *δ*, *J* and *R*-curves for homogeneous metallic materials subjected to quasistatic loading. Specimens are notched, precracked by fatigue and tested under slowly increasing displacement. The fracture toughness is determined for individual specimens at or after the onset of ductile crack extension or at the onset of ductile crack instability or unstable crack extension. In some cases in the testing of ferritic materials, unstable crack extension can occur by cleavage or ductile crack initiation and growth, interrupted by cleavage extension. The fracture toughness at crack arrest is not covered by this document. In cases where cracks grow in a stable manner under ductile tearing conditions, a resistance curve describing fracture toughness as a function of crack extension is measured. In most cases, statistical variability of the results is modest and reporting the average of three or more test results is acceptable. In cases of cleavage fracture of ferritic materials in the ductile-to-brittle transition region, variability can be large and additional tests may be required to quantify statistical variability. Special testing requirements and analysis procedures are necessary when testing weldments and these are described in ISO 15653[1] which is complementary to this document.

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

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

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

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

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

3 Terms and definitions

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

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

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

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

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

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

3.3
***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, 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

3.7
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 may result from unstable crack extension in the plane of the precrack and are to be distinguished from discontinuity indications arising from: i) delaminations or splits normal to the precrack plane; ii) roller or pin slippage in bend or compact specimen load trains, respectively; iii) improper seating of displacement gauges in knife edges; iv) ice cracking in low-temperature testing; v) electrical interference in the instrument circuitry of force and displacement measuring and recording devices.

3.8
crack extension resistance curves, *R*-curves
variation in δ or J with stable crack extension

4 Symbols and designations

See Table 1.

Table 1 — Symbols and their designations

Symbol	Unit	Designation
a	mm	Nominal crack length (for the purposes of fatigue precracking, an assigned value less than a_o)
a_f	mm	Final crack length (a_o + Δa)
a_i	mm	Instantaneous crack length
a_m	mm	Length of machined notch
a_o	mm	Initial crack length
A_p	J	Plastic component of the area under the force vs. notch opening displacement diagram (Figure 17)
Δa	mm	Stable crack extension including blunting
Δa_{max}	mm	Crack extension limit for δ or J controlled crack extension

B	mm	Specimen thickness
B_N	mm	Specimen net thickness between side grooves
C	m/N	Specimen elastic compliance
E	GPa	Modulus of elasticity at the pertinent temperature
F	kN	Applied force
F_c	kN	Applied force at the onset of unstable crack extension or pop-in when Δa is less than 0,2 mm offset from the construction line (Figure 2)
F_d	kN	Force value corresponding to the intersection of the test record with the secant line (Figure 16)
F_f	kN	Maximum fatigue precracking force
F_m	kN	Maximum force for a test which exhibits a maximum force plateau preceding fracture with no significant prior pop-ins (Figure 2)
F_Q	kN	Provisional force value used for the calculation of K_Q
F_u	kN	Applied force at the onset of unstable crack extension or pop-in when Δa is equal to or greater than the 0,2 mm offset from the construction line (Figure 2)
J	MJ/m²	Experimental equivalent to the J-integral
$J_{c(B)}$	MJ/m²	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/m²	J at upper limit of J-controlled crack extension
J_i	MJ/m²	Size-insensitive fracture resistance J at initiation of stable crack extension
$J_{m(B)}$	MJ/m²	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/m²	Limit of J-R material behaviour defined by this method of test
$J_{u(B)}$	MJ/m²	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/m²	Size sensitive fracture resistance J at the onset of unstable crack extension or pop-in when stable crack extension cannot be measured (B = specimen thickness in mm)
J_o	MJ/m²	J uncorrected for stable crack extension
$J_{0,2BL}$	MJ/m²	Size insensitive fracture resistance J at 0,2 mm stable crack extension offset from the construction line
$J_{0,2BL(B)}$	MJ/m²	Size sensitive fracture resistance J at 0,2 mm stable crack extension offset from the construction line (B = specimen thickness in mm)
K	$\text{MPa}\sqrt{\text{m}}$	Stress intensity factor
K_f	$\text{MPa}\sqrt{\text{m}}$	Maximum value of K during the final stages of fatigue precracking
K_{Ic}	$\text{MPa}\sqrt{\text{m}}$	Plane strain linear elastic fracture toughness
$K_{J0,2BL}$	$\text{MPa}\sqrt{\text{m}}$	Plane strain linear elastic fracture toughness equivalent to $J_{0,2BL}$
K_Q	$\text{MPa}\sqrt{\text{m}}$	A provisional value of K_{Ic}

q	mm	Load-line displacement. q equals V in stepped-notch compact specimens
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 at the load-line
U_e	J	Elastic component of U
U_p	J	Plastic component of U (Figure 18)
V	mm	In bend specimens, V is the crack-mouth opening displacement, which is the opening displacement at the notch edge. In compact specimens the opening displacement, V is determined at the load-line. V equals q in stepped-notch compact specimens.
V_e	mm	Elastic component of V
V_g	mm	Displacement measured by clip gauges mounted on knife edges.
V_p	mm	Plastic component of V
W	mm	Width of the test specimen
z	mm	For bend and straight-notch compact specimens, the initial distance of the notch opening gauge measurement position from the notched edge of the specimen, either further from the crack tip [$+z$ in Figure 8 b)] or closer to the crack tip ($-z$); or, for a stepped-notch compact specimen, the initial distance of the notch opening gauge measurement position either beyond ($+z$) or before ($-z$) the initial load-line
δ	mm	Crack-tip opening displacement (CTOD)
$\delta_{c(B)}$	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_o	mm	δ 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 here, other parameters are referred to in the text.

NOTE 2 The values of all parameters used in calculations are assumed to be those measured or calculated for the temperature of the test, unless otherwise specified.

5 General requirements

5.1 General

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

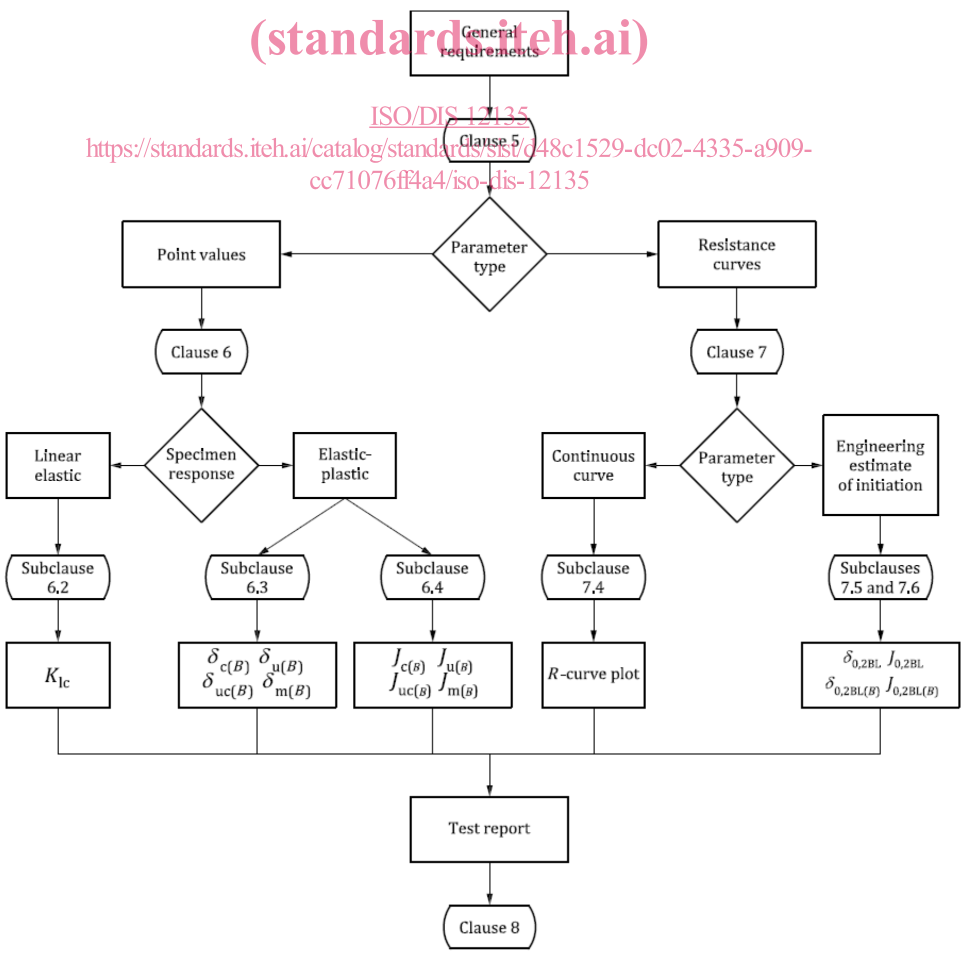
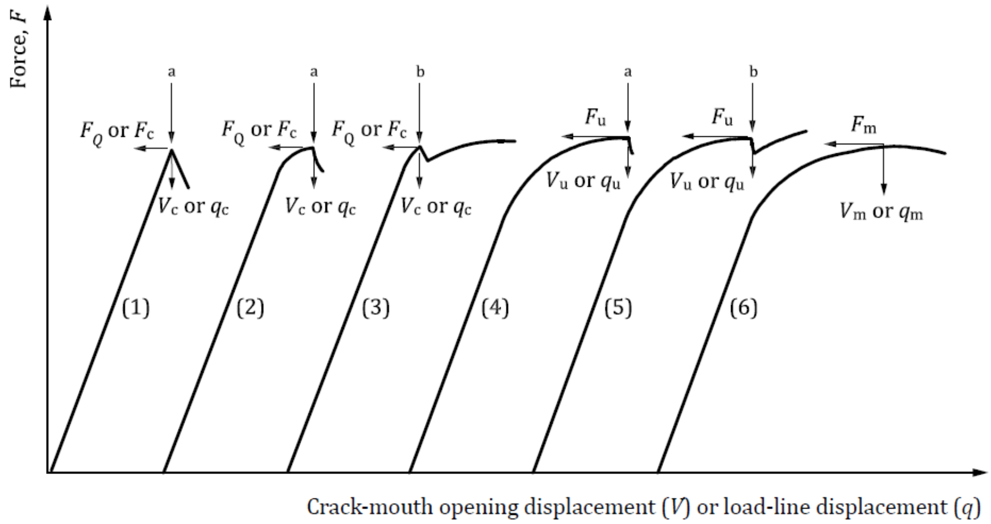


Figure 1 — General flowchart showing how to use the standard method of test



Key

a Fracture.

b Pop-in.

NOTE 1 F_c and F_u shall be finally classified by Formulae (19) and (20).

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

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

5.2 Fracture parameters

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

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

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

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

When stable crack extension is extensive, test procedure and fracture toughness measurement shall be performed as specified in Clause 7. Stable crack extension is characterized either in terms of crack tip opening displacement $\delta_{0,2BL}$ 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 may be helpful in preserving crack front markings prior to breaking open the specimens.

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

Table 2 — Fracture toughness symbols

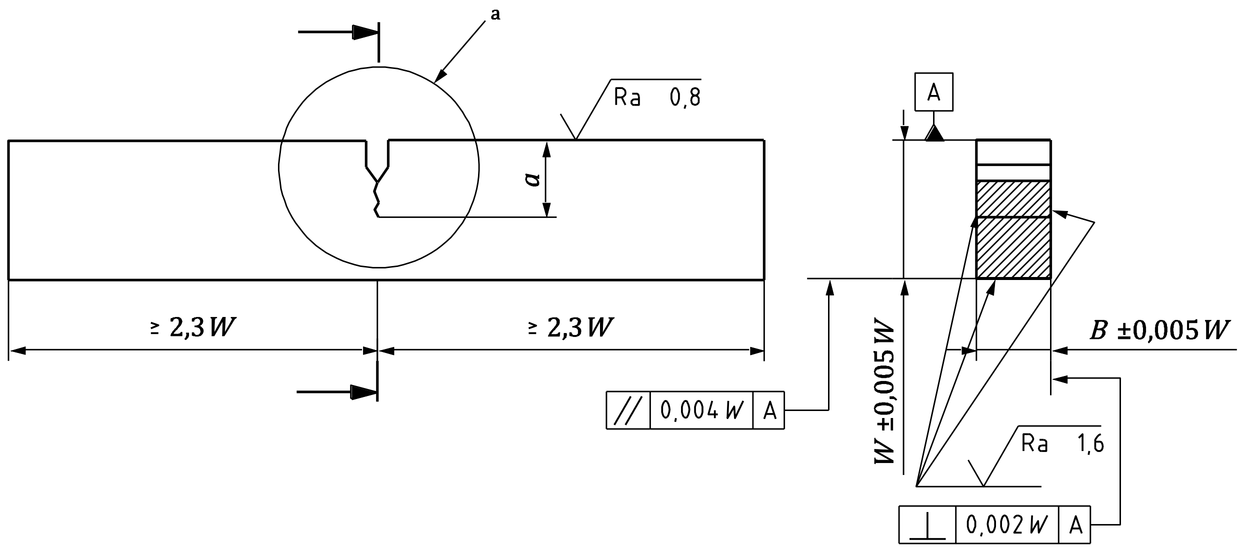
Parameter	**Size insensitive quantities**	**Size sensitive quantities** (specific to thickness *B* tested)	**Qualifying limits to *R*-curves**
K	K_{Ic} $K_{J0,2BL}$		
δ	δ_i $\delta_{0,2BL}$	$\delta_{c(B)}$ $\delta_{0,2BL(B)}$ $\delta_{u(B)}$, $\delta_{uc(B)}$, $\delta_{m(B)}$	δ_g, $\delta_g(\Delta a_{max})$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

Surface roughness values in micrometres



Key

a See Figures 6 to 8 and 5.4.2.3.

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

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

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

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

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

Figure 3 — Proportional dimensions and tolerances for bend specimen

Surface roughness values in micrometres