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

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

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Contents

Page

Foreword

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

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

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

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

Introduction

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

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

— the component thickness is much less than that required for size-insensitive properties as determined using ISO 12135,

— the thickness of the available material does not enable fabrication of specimens meeting the criteria for size insensitivity, and

— the loading conditions in the structural component are characterized by tension rather than bending.

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

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

1 Scope

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

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

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

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

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

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

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

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

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

2 Normative references

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

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

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

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

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

3 Terms and definitions

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

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

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

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

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

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

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

4 Symbols

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

Symbol	Unit	Designation
a	mm	crack length
a_f	mm	final crack length ($a_0 + \Delta a_f$)
a_m	mm	length of machined crack starter notch
a_0	mm	initial crack length
Δa	mm	stable crack extension
Δa_{min}	mm	crack extension beyond which ψ_c is nearly constant
Δa_{max}	mm	crack extension limit for δ_5 or ψ_c controlled crack extension
Δa_f	mm	final stable crack extension
B	mm	specimen thickness
E	MPa	Young's modulus of elasticity
F	kN	applied force
F_f	kN	maximum fatigue precracking force
$R_{p0,2}$	MPa	0,2 % offset yield strength perpendicular to crack plane at the test temperature
R_m	MPa	tensile strength perpendicular to crack plane at the test temperature
α	degrees	crack path deviation
W	mm	width of compact specimen, half width of middle-cracked tension specimen
$W - a$	mm	uncracked ligament length
$W - a_0$	mm	initial uncracked ligament length
$W - a_f$	mm	final uncracked ligament length
ψ	degrees	crack tip opening angle (CTOA)
ψ_c	degrees	critical crack tip opening angle (critical CTOA)
ν		Poisson's ratio
δ_5	mm	crack opening displacement over a 5 mm gauge length at tip of fatigue precrack
NOTE This is not a complete list of parameters. Only the main parameters are given here; other parameters are referred to and defined in the text.		

5 General requirements

5.1 Introduction

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

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

Table 1 — Fracture resistance symbols

Parameter	Size-insensitive quantities	Size-sensitive quantities (specific to thickness B tested)	Qualifying limits
δ_5, point value of fracture toughness	See Annex D	Not applicable	
δ_5 R-curve	Not applicable	a_0, $(W - a_0) \geqslant 4B$	$\Delta a < \Delta a_{max} = 0,25(W - a_0)$ for compact specimens; $\Delta a < \Delta a_{max} = W - a_0 - 4B$ for middle-cracked tensile specimens
ψ_c	Not applicable	a_0, $(W - a_0) \geqslant 4B$	$\Delta a > \Delta a_{min} = 50/(5 + B)$ $\Delta a < \Delta a_{max} = W - a_0 - 4B$ (see Figure 11)

NOTE The qualifying limit for ψ_c, $\Delta a > \Delta a_{min} = 50/(5 + B)$ was established using surface measurements of crack extension for aluminium alloys and steels in sheet thicknesses ranging from 1 mm to 25 mm.

5.2 Test specimens

5.2.1 Specimen configuration and size

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

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

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

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

5.2.2 Specimen preparation

5.2.2.1 Material condition

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

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

5.2.2.2 Crack plane orientation

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

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

5.2.2.3 Machining

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

5.2.2.4 Fatigue precracking

5.2.2.4.1 General

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

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

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

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

5.2.2.4.2 Equipment and fixtures

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

5.2.2.4.3 Compact specimens

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

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

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

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

5.2.2.4.4 Middle-cracked tension specimens

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

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

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

5.3 Pre-test requirements

5.3.1 Pre-test measurements

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

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

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

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

5.3.2 Crack front shape and length requirements

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

— for compact specimens (see Figure 2), the ratio a_0/W shall be in the range 0,45 to 0,65;

— for middle-cracked tension specimens, the ratio a_0/W shall be in the range 0,25 to 0,50.

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

5.4 Test apparatus

5.4.1 Calibration

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

5.4.2 Force application

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

The test machine shall operate at a constant displacement rate.

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

— for compact specimens

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

— or for middle-cracked tension specimens

$$F_L = 2B(W-a_0)R_m \quad (5)$$

5.4.3 Displacement measurement

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

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

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

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

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

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

5.4.4 Test fixtures

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

5.5 Test requirements

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

5.5.1 Compact specimen testing

5.5.1.1 Specimen and fixture alignment

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

5.5.1.2 Crack opening displacement δ_5

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

5.5.1.3 Crack tip opening angle ψ

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

5.5.2 Middle-cracked tension specimen testing

5.5.2.1 Specimen and fixture alignment

The fixture shall be designed to distribute the load uniformly over the cross-section of the specimen. The fixture may be rigidly connected to the machine if uniform loading of the specimen in the machine can be assured at all loads. Otherwise, pinloading via detachable grips is recommended.

5.5.2.2 Crack opening displacement δ_5

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

5.5.2.3 Crack tip opening angle ψ

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

5.5.3 Specimen test temperature

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

5.5.4 Recording

The force and corresponding displacement outputs shall be recorded.

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

5.5.5 Testing rates

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

5.5.6 Test analyses

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

5.6 Post-test crack measurements

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

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

5.6.1 Initial crack length a_0

5.6.1.1 Compact specimens

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

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