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Metallic materials — Determination of plane-strain fracture toughness

Matériaux métalliques — Détermination du facteur d'intensité de contrainte critique

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Foreword

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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 12737 was prepared by Technical Committee ISO/TC 164, *Mechanical testing of metals*, Subcommittee SC 4, *Toughness testing — Fracture (F), Pendulum (P), Tear (T)*.

This third edition cancels and replaces the second edition (ISO 12737:2005), of which it constitutes a minor revision.

Metallic materials — Determination of plane-strain fracture toughness

1 Scope

This International Standard specifies the ISO method for determining the plane-strain fracture toughness of homogeneous metallic materials using a specimen that is notched and precracked by fatigue, and subjected to slowly increasing crack displacement force.

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 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*

ASTM E399-09, *Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness* K_{Ic} *of Metallic Materials*

3 Terms and definitions

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

3.1
plane-strain stress intensity factor
K_{I}
magnitude of the elastic stress field at the tip of a crack subjected to opening mode displacement (mode I)

NOTE It is a function of applied force and test specimen size, geometry, and crack length, and has the dimensions of force times length$^{-3/2}$.

3.2
plane-strain fracture toughness
K_{Ic}
measure, by the operational procedure of this method, of a material's resistance to crack extension when the state of stress near the crack tip is predominantly plane strain and plastic deformation is limited

NOTE It is the critical value of K_{I} at which significant crack extension occurs on increasing load with high constraint to plastic deformation.

3.3
crack-plane orientation
method for relating the plane and direction of crack extension to the characteristic directions of the product

NOTE A hyphenated code is used wherein 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 anticipated direction of crack extension (see Figure 1). For wrought metals, the letter X always denotes the direction of principal deformation (maximum grain flow in the product), the letter Y the direction of least deformation, and the letter Z the direction normal to the X-Y plane. In the notation used in ASTM E399-09, X corresponds to L, Y corresponds to T and Z corresponds to S.

If specimen directions do not coincide with the product's characteristic directions, then two letters are used to denote the normal to the crack plane or the expected direction of crack extension, or both [see Figure 1 b)]. If there is no grain flow direction (as in a casting), reference axes may be arbitrarily assigned but must be clearly identified.

3.4
notch opening displacement
V
displacement measured at or near the notch mouth

4 Symbols and designations

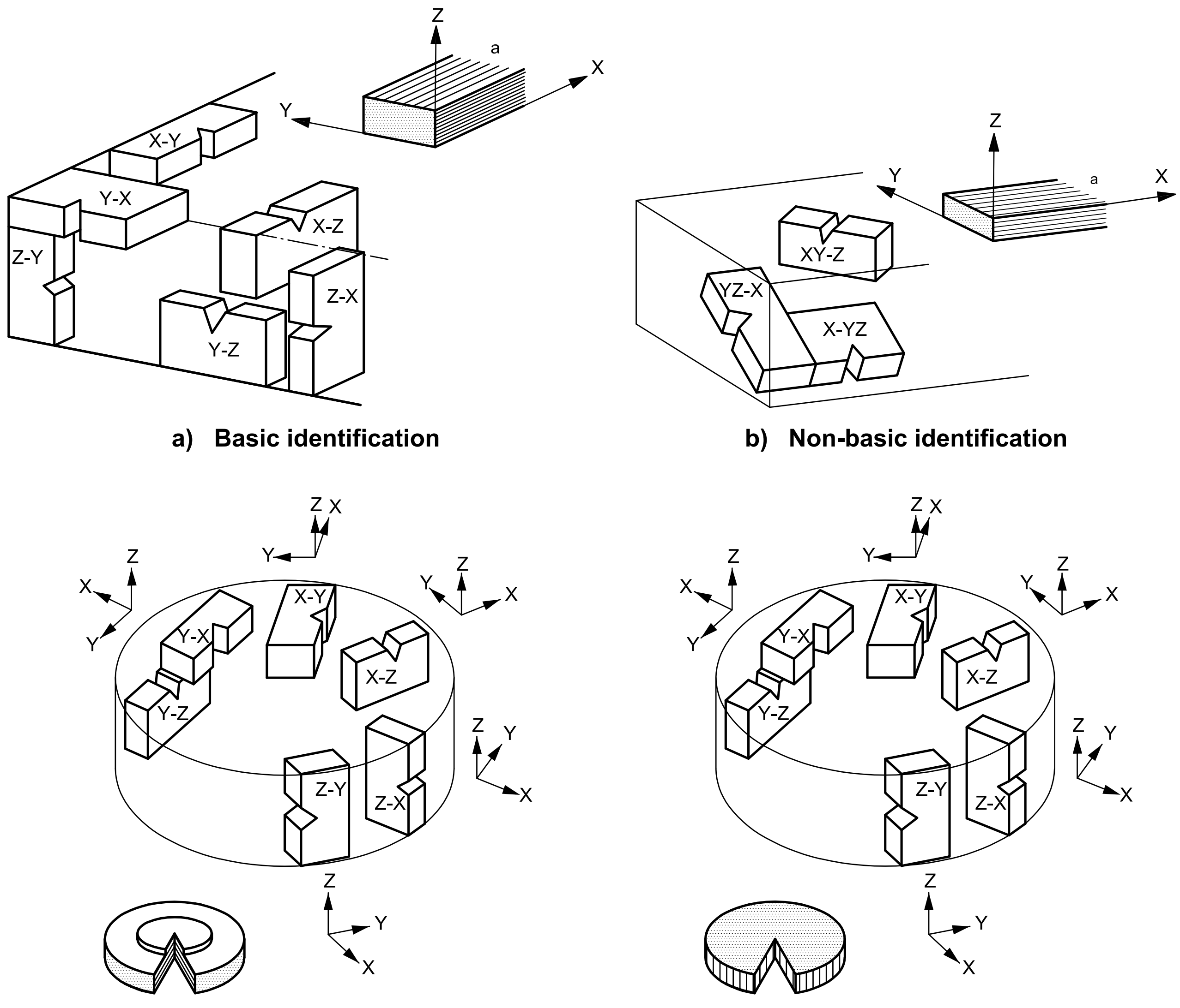
For the purposes of this document, the following symbols apply (see also Figures 1, 2 and 4).

Symbol	Unit	Designation
a	mm	Crack length
B	mm	Specimen thickness
E	MPa	Young's modulus
F	kN	Applied force
F_Q	kN	Particular value of F (see Figure 4)
F_5	kN	Particular value of F (see Figure 4)
K_f	MPa·m$^{1/2}$[a]	Maximum stress intensity factor during the final stage of fatigue cracking
K_Q	MPa·m$^{1/2}$	Provisional value of K_{Ic}
K_I	MPa·m$^{1/2}$	Stress intensity factor (mode I)
K_{Ic}	MPa·m$^{1/2}$	Critical value of K_I (plane-strain fracture toughness)
R	—	Ratio of minimum to maximum fatigue cracking force during any single cycle of fatigue operation
$R_{p0,2}$	MPa	0,2 % offset yield strength
S	mm	Span between outer loading points in case of bending
V	mm	Notch opening displacement
W	mm	Width of specimen
ΔK_I	MPa·m$^{1/2}$	Difference between maximum and minimum values of K_I during any single cycle of fatigue operation

[a] 0,031 6 MPa·m$^{1/2}$ = 1 N·mm$^{-3/2}$ = 0,031 6 MN·m$^{-3/2}$.

5 Principle

This method covers the determination of the plane-strain fracture toughness (K_{Ic}) of metallic materials by increasing-force tests of fatigue-precracked test specimens. Details of the test specimens and experimental procedures are given in Annexes B and C. Force versus notch opening displacement is recorded autographically, or converted to digital form for accumulation in a computer information storage facility and subsequent processing. The force corresponding to 2 % apparent crack extension is established by a specified deviation from the linear portion of the test record. If certain validity requirements are satisfied, the value of K_{Ic} is calculated from this force.



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 1 — Crack-plane identification

The property K_{Ic} characterizes the resistance of a material to fracture in the presence of a sharp crack under severe tensile constraint, such that

a) the state of stress near the crack front approaches plane strain, and

b) the crack-tip plastic zone is small compared to the crack size, specimen thickness, and ligament ahead of the crack.

K_{Ic} is believed to represent a lower limiting value of fracture toughness in the environment and at the temperature of test.

Cyclic or sustained loads can cause crack extension at K_I values less than K_{Ic}. Crack extension under cyclic or sustained loads can be influenced by temperature and environment. Therefore, when K_{Ic} is applied to the design of service components, differences between laboratory test and field conditions should be considered.

With plane-strain fracture toughness testing, there can be no advance assurance that a valid K_{Ic} will be determined in a particular test.

6 Apparatus

6.1 Testing machine and force measurement

The testing machine shall be calibrated in accordance with ISO 7500-1 and shall be of at least grade 1. The testing machine shall have provisions for the autographic recording of the force applied to the specimen; alternatively, a computer data acquisition system may be used to record force and displacement for subsequent analysis. The combination of force-sensing device and recording system shall permit the force F_Q (as defined in Clause 10) to be determined from the test record to ± 1 %.

6.2 Fatigue cracking machine

When possible, the fatigue machine and force-indicating device shall be calibrated statically in accordance with ISO 7500-1 and shall have a grade of at least 2. If the machine cannot be calibrated statically, the applied force shall be known to ± 2,5 %. Careful alignment of the specimen and fixturing is necessary to encourage straight fatigue cracks. The fixturing shall be such that the stress distribution is uniform across the specimen thickness and symmetrical about the plane of the prospective crack.

6.3 Displacement gauge

The displacement-gauge electrical output shall represent the relative displacement (V) of two precisely located gauge positions spanning the notch mouth. The design of the displacement gauge and knife edges shall allow free rotation of the points of contact between the gauge and the specimen.

The displacement gauge shall be calibrated in accordance with ISO 9513, as interpreted in relation to this method, and shall be of at least class 1; however, calibration shall be performed at least weekly during the time the gauge is in use. Periodic verification of greater frequency may be required, depending on use and agreement between contractual parties.

Verification of the gauge shall be performed at the temperature of test to ± 5 °C. The response of the gauge shall correspond to the calibration apparatus to ± 0,003 mm for displacements up to 0,3 mm, and ± 1 % for higher values.

The determination of an absolute displacement value is not necessary since only changes in displacement are used in this method. Two proven designs of displacement gauge are given in ASTM E399-09 and Reference [1] and similar gauges are commercially available.

6.4 Testing fixtures

The bend test shall be performed using a fixture designed to minimize friction effects by allowing the support rollers to rotate and translate slightly as the specimen is loaded, thus achieving rolling contact. A design suitable for testing bend specimens is shown in Figure D.1.

A loading clevis suitable for testing compact specimens is shown in Figure D.2.

7 Test specimen size, configuration and preparation

7.1 Specimen size

In order for a result to be considered valid according to this method, the specimen thickness (B), crack length (a) and ligament length ($W - a$) must all be not less than $2,5(K_{Ic}/R_{p0,2})^2$, where $R_{p0,2}$ is the 0,2 % offset yield strength of the material in the environment and at the temperature of test. Meeting this requirement cannot be ensured in advance, thus specimen dimensions should be conservatively established for the first test in a series. If the form of the available material is such that it is not possible to obtain a test specimen with thickness, crack length and ligament length equal to or greater than $2,5(K_{Ic}/R_{p0,2})^2$, then it is not possible to make a valid K_{Ic} measurement according to this method.

7.2 Recommended specimen proportions

7.2.1 Recommended specimens

The recommended specimens are shown in Figures B.1 and C.1. Width (W) is nominally twice the thickness (B). Crack length (a) is between 0,45 and 0,55 times the width.

7.2.2 Alternative proportions

In certain cases, it may be necessary or desirable to use specimens having W/B ratios other than 2, and alternative proportions are allowed (see Annex B or C). Specimens having alternative proportions shall nevertheless have the same crack length-to-width (a/W) ratio as the recommended specimens.

7.2.3 Alternative specimen configurations

By prior agreement, alternative specimen configurations and their associated methods of analysis may be used, provided that they be accepted as national standards for K_{Ic} testing by an ISO member body, including those standards which have the multiple purpose of measuring K_{Ic} along with J or CTOD (crack tip opening displacement) properties, or both: e.g. ASTM E399-09 and References [1] and [2].

7.2.4 Fatigue-crack starter notch

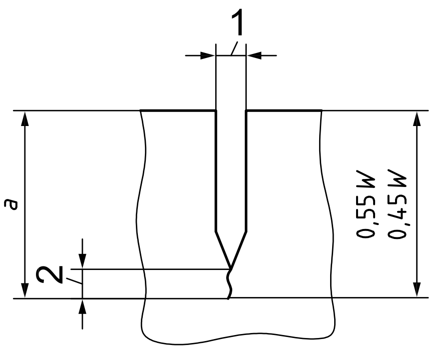
Two fatigue-crack starter notch configurations are shown in Figures 2 a) and 2 b). The suggested root radius for the straight-through slot terminating in a V-notch is 0,10 mm or less. For the chevron form of notch, the suggested root radius is 0,25 mm or less. The method of notch preparation is discretionary. The starter notch (plus fatigue crack) must lie within the envelope shown in Figure 2 c) (see Annex A).

Two types of knife edges for attaching the displacement gauge are illustrated in Figure 3.

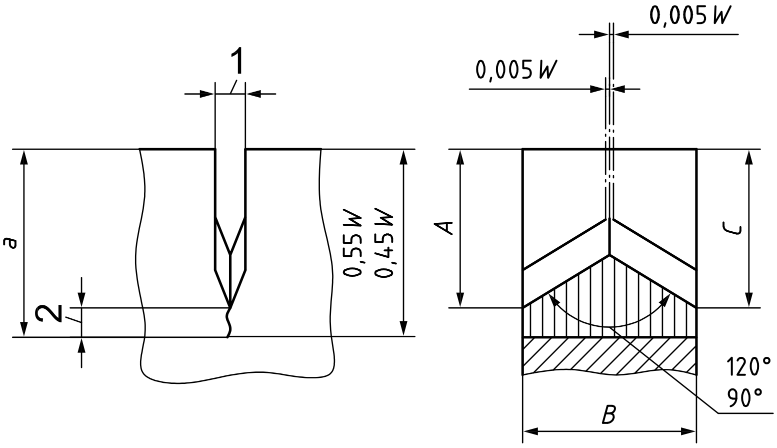
7.3 Specimen preparation and fatigue precracking

7.3.1 Material condition

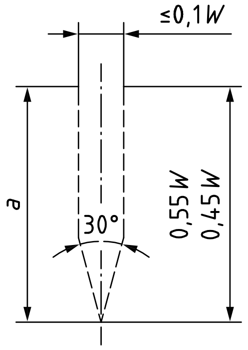
All specimens shall be tested in the final heat-treated, mechanically-worked and environmentally-conditioned state. Normally, specimens shall also be machined in this final state. However, for material that cannot be machined in the final condition, the final treatment may be carried out after machining, provided that the required dimensions and tolerances on specimen size, shape and overall surface finish are met (see Figures B.1 and C.1), and that full account is taken of the effects of specimen size on metallurgical conditions induced by certain heat treatments, e.g. water quenching of steels.



a) Straight-through notch



b) Chevron notch[c]



c) Envelope

Key

1 notch width[a]

2 fatigue crack[b]

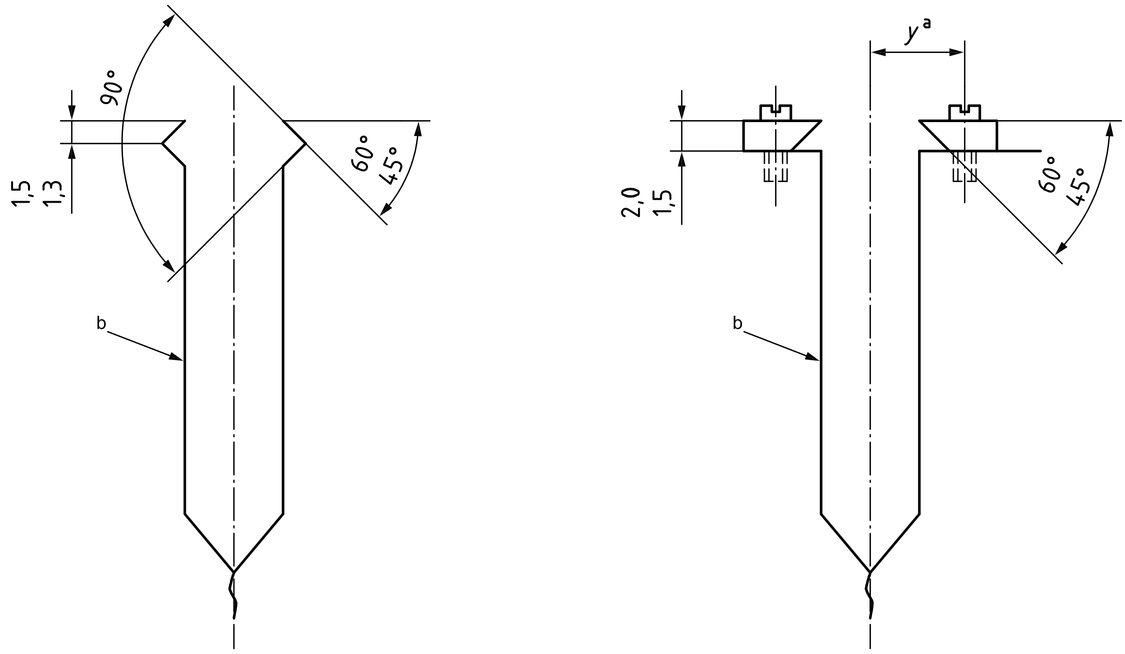
[a] The crack starter notch shall be perpendicular to specimen surfaces to ± 2°. Notch width shall not exceed 0,1W but shall not be less than 1,6 mm.

[b] For straight-through notch: suggested notch root radius 0,10 mm maximum. Cutter tip angle 90° maximum. Fatigue crack extension on each surface of specimen shall be at least 0,025W or 1,3 mm, whichever is greater.

[c] For chevron notch: suggested notch root radius 0,25 mm maximum. Cutter tip angle 90° maximum, $A = C$ within ± 0,01W. Fatigue crack shall emerge on both surfaces of specimen.

Figure 2 — Crack starter notches and maximum permissible notch/crack envelope

Dimensions in millimetres



a) Integral type

b) Attached type

Knife edges shall be square with specimen surfaces and parallel to ± 0,5°.

a 2y plus the diameter of screw thread shall not exceed W/2. If knife edges are glued or similarly attached to the edge of the specimen, dimension 2y shall correspond to the distance between extreme points of attachment.

b See Figure 2.

Figure 3 — Knife edge detail

7.3.2 Crack-plane orientation

The fracture toughness of a material is usually dependent on the orientation and direction of propagation of the crack in relation to the principal directions of metal working, grain flow or otherwise-produced texture. Orientation of the crack plane shall be decided before machining (see 7.3.3), identified in accordance with the prescribed coordinate systems (see 3.3) and recorded (see Clause 11).

7.3.3 Machining

Specimen sizes, shapes, dimensional tolerances and surface finishes shall be as given in Figures B.1 and C.1.

7.3.4 Fatigue precracking

Fatigue precracking normally shall be done at room temperature with the specimen in the final heat-treated, mechanically-worked or environmentally-conditioned state in which it is to be tested. Different fatigue precracking temperatures and intermediate thermal/mechanical/environmental treatments between fatigue precracking and testing shall be used only when such treatments are necessary to simulate the conditions for a specific structural application, and required dimensions and tolerances on specimen size and shape can be maintained. Such fatigue precracking shall be performed according to the requirements of Annex A.

8 Procedure

8.1 Specimen measurement

Measure specimen thickness (B) to the nearest 0,025 mm or to 0,1 %, whichever is larger, at not less than three equally spaced positions along the anticipated crack extension path. Take the average of these measurements as the thickness.

Measure specimen width (W) to the nearest 0,025 mm or to 0,1 %, whichever is larger, at not less than three positions near the notch location. Take the average of these measurements as the width. For the compact specimen, measure the width from the plane of the centreline of the loading pin holes.

After fracture, measure specimen crack length (a) to the nearest 0,05 mm or to 0,5 %, whichever is larger, at mid-thickness and at the two quarter-thickness points. Take the average of these measurements as the crack length. The difference between any two of the three crack-length measurements shall not exceed 10 % of the average.

Measure the crack length also at each surface. For the straight-through starter notch, no part of the crack front shall be closer to the starter notch than 1,3 mm or 0,025W, whichever is larger; furthermore, neither surface crack-length measurement shall differ from the average crack length by more than 15 % and their difference shall not exceed 10 % of the average crack length. For the chevron-notch starter, the fatigue crack shall emerge from the chevron on both surfaces; furthermore, neither surface crack-length measurement shall differ from the average crack length by more than 15 % and their difference shall not exceed 10 % of the average crack length.

The fracture plane shall be parallel to the plane of the starter notch to ± 10° and there shall be no evidence of multiple cracking (i.e. more than one crack).

8.2 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 not further than 5 mm from the crack tip. Tests shall be made *in situ* in a 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 11, item d).

8.3 Fixture measurements for bend specimen

Align the bend test fixture such that the line of action of the applied force passes midway between the support rollers to ± 1 % of the span (S) and is perpendicular to the roller axes to ± 2°. Measure the span (S) to ± 0,5 %.

9 Test procedure

If an autographic recorder is used, adjust it such that the slope of the linear portion of the force-displacement record is between 0,85 and 1,5. Alternatively, if a computer data acquisition system is used, programme it to capture enough data to allow the calculations in Clause 10. In either case, the concluding requirement of 6.1 (i.e. F_Q ± 1 %) shall be satisfied.

Load the specimen such that the rate of increase of stress intensity is between 0,5 MPa·m$^{1/2}$/s and 3,0 MPa·m$^{1/2}$/s during initial elastic deformation. Continue the test until the specimen can sustain no further increase in applied force. Record the maximum force (F_{max}).

10 Calculation and interpretation of results

10.1 General

If an autographic recorder is used, the conditional value F_Q shall be determined as follows. Draw the secant line 0F_5 (see Figure 4) from the point 0 with slope $(F/V)_5 = 0{,}95\,(F/V)_0$, where $(F/V)_0$ is the slope of the tangent 0A to the linear portion of the record. The force F_Q is then defined as follows: if the force at every point on the record which precedes F_5 is lower than F_5 (type I), then F_5 is F_Q. If, however, there is a maximum force (F_{max}) preceding F_5 and which exceeds it (type II or type III), then this maximum force is equal to F_Q.

If a computer data acquisition system is used, the data reduction program shall determine the same forces (F_Q and F_{max}) as above. The algorithms for doing this are left to the discretion of the user.

Calculate the ratio F_{max}/F_Q, where F_{max} is the maximum force. If this ratio does not exceed 1,10, proceed to calculate K_Q as described in Annex B or C, as appropriate. If the ratio exceeds 1,10, the test is not a valid K_{Ic} test.

Calculate the value $2{,}5(K_Q/R_{p0,2})^2$. If this quantity is less than the specimen thickness, the crack length and the ligament length, then K_Q is equal to K_{Ic}. Otherwise, the test is not a valid K_{Ic} test.

10.2 Residual stresses

K_Q and K_{Ic} measurements can be significantly affected by residual stresses, especially for specimens removed from as-heat treated or otherwise non-stress relieved stock, welds, complex wrought parts, or parts with intentionally induced (beneficial) residual stresses. Indications of residual stress may be

a) distortion during specimen machining,

b) test results that are specimen-configuration dependent, and

c) irregular fatigue precrack growth (either excessive crack front curvature or out-of-plane growth).

Care shall be exercised in the application of results from specimens suspected of harboring residual stresses. See ASTM E399-09.

11 Test report

The test report shall include at least the following information:

a) reference to this International Standard;

b) characterization of the material and the product form tested;

c) 0,2 % offset yield strength;

d) temperature and environment for test and for fatigue precracking;

e) type of test specimen;

f) crack-plane orientation (see Figure 1);

g) measured properties and results for each test specimen, including

   1) force-displacement record, and

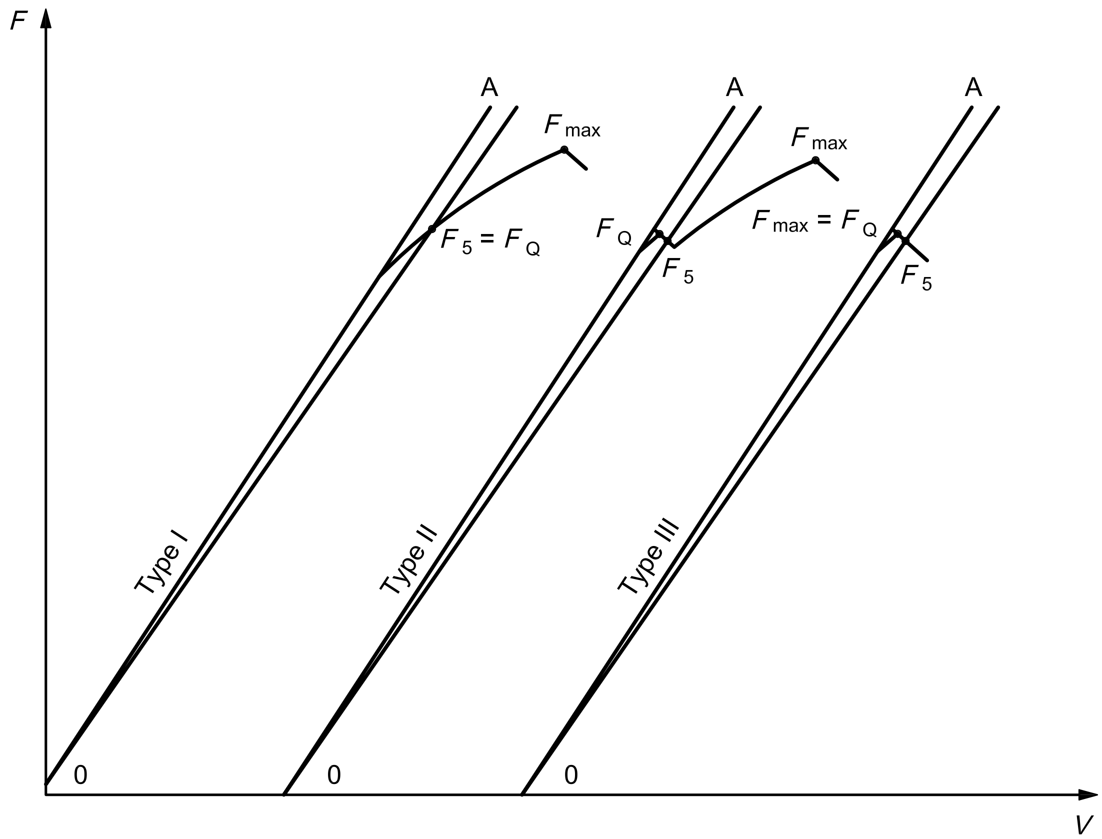
   2) width (W) and thickness (B),

3) maximum fatigue stress intensity K_f and stress intensity range ΔK_I over the final 2,5 % of the overall length of notch plus crack extension (a),

4) average crack length (a),

5) force ratio F_{max}/F_Q,

6) plane-strain fracture toughness (K_{Ic}).



Key

V displacement

F force

Figure 4 — Typical force-displacement records

Annex A
(normative)

Fatigue precracking of K_{Ic} fracture toughness specimens

The object of fatigue precracking is to produce a sharp crack which is not affected by details of the precracking procedure. The following requirements will accomplish this objective.

A.1 Fixtures

The fixtures recommended for fracture testing are also suitable for fatigue precracking. If other fixtures are used, the K-calibration shall be known to $\pm$ 5 %.

A.2 Specimen requirements

Fatigue precracking shall be conducted in accordance with 7.3. To facilitate precracking at a low level of stress intensity, specimen-notch root radii shall be as prescribed in 7.2.4.

A.3 Precracking procedure

Fatigue precracking may be conducted under either force control or displacement control. The ratio of cyclic minimum stress to maximum stress (R) shall not exceed 0,1. The maximum stress intensity factor during fatigue precracking shall not exceed 80 % of the K_Q value determined in the subsequent test if K_Q is to qualify as a valid K_{Ic} result. For the terminal stage of fatigue precracking (2,5 % of length a), K_f shall not exceed 60 % of K_Q. If precracking and testing are conducted at different temperatures, K_f shall not exceed $0{,}6[(R_{p0,2})_p/(R_{p0,2})_t]K_Q$, where $(R_{p0,2})_p$ and $(R_{p0,2})_t$ are the 0,2 % offset yield strengths at the precracking and test temperatures, respectively.

Annex B
(normative)

Bend specimen

B.1 Test specimen

The standard bend specimen is a single-edge notched and fatigue-cracked beam loaded in three-point bending. The span (S) is nominally equal to four times the width (W). The general proportions of this specimen configuration are shown in Figure B.1. Alternative specimens may have $1 < W/B < 4$ and shall also have a nominal span equal to $4W$.

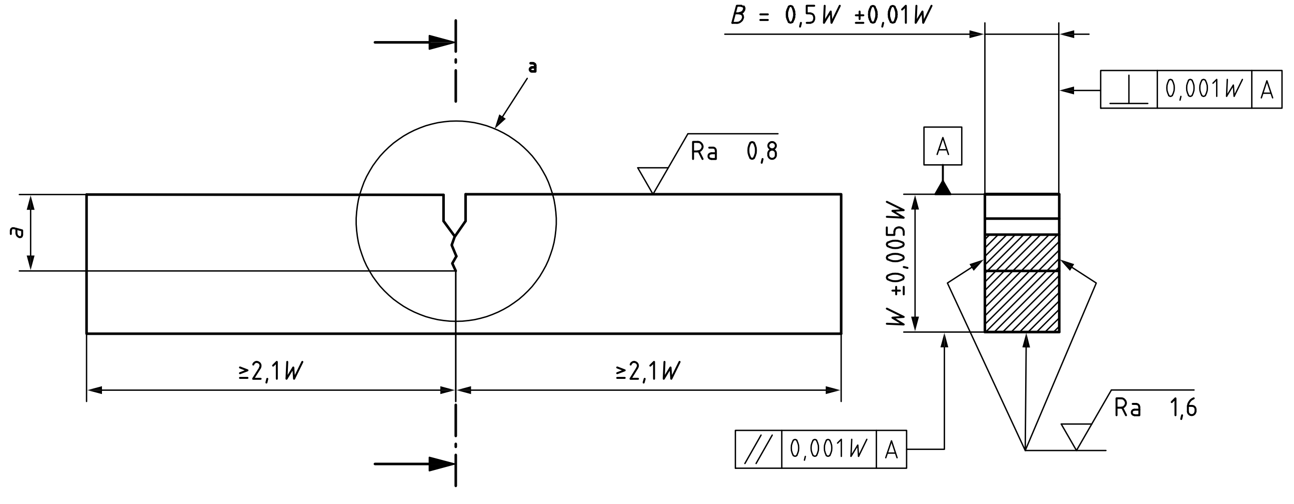
B.2 Test fixture

General principles of the bend test fixture are illustrated in Figure D.1. The fixture shall be designed to minimize friction effects by allowing the rollers to rotate and translate slightly as the specimen is loaded, thus providing rolling contact.

B.3 Test procedure

Align the test fixture and measure the span (S) as stipulated in 8.3. Position the specimen with the crack tip midway between the outer roller centres to within 1 % of the span, and align it perpendicular to the rollers to ± 2°.

Values of surface roughness (Ra) in micrometres



[a] See Figure 2.

NOTE 1 Integral or attachable knife edges for clip gauge attachment may be used (see Figure 3).

NOTE 2 For starter-notch and fatigue-crack configurations, see Figure 2.

Figure B.1 — Bend specimen

B.4 Calculation

For the bend specimen, K_Q is calculated in MPa·m$^{1/2}$ as follows:

$$K_Q = F_Q \frac{S}{BW^{3/2}} f(a/W)$$

where

F_Q is in kilonewtons;

S, B and W are in centimetres;

$$f(a/W) = 3(a/W)^{1/2} \times \frac{1{,}99 - (a/W)(1-a/W)\left[2{,}15 - 3{,}93(a/W) + 2{,}7(a/W)^2\right]}{2(1+2a/W)(1-a/W)^{3/2}}$$

EXAMPLE For $a/W = 0{,}500$, $f(a/W) = 2{,}66$.

Annex C
(normative)

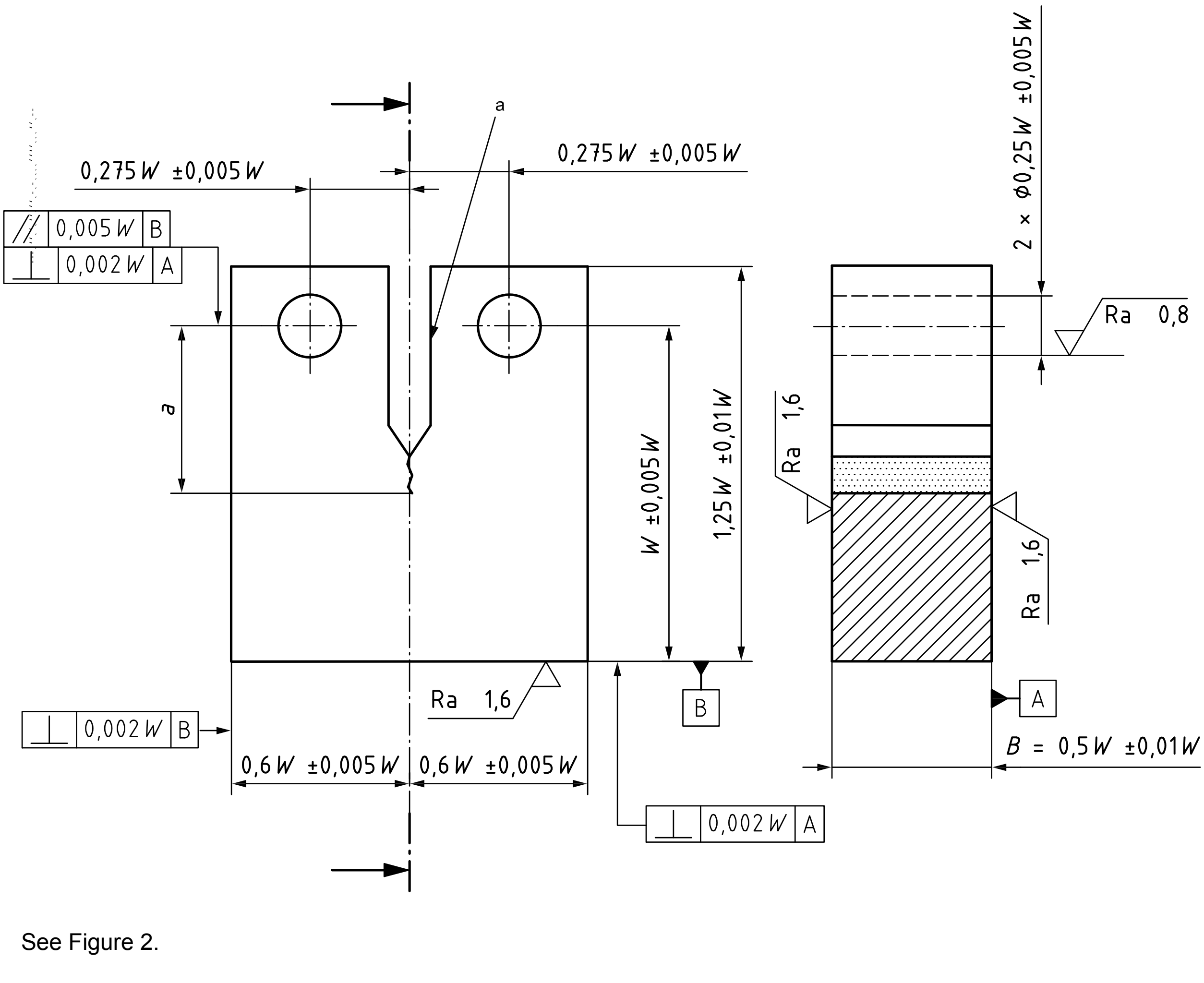
Compact specimen

C.1 Test specimen

The standard compact specimen is a single-edge notched and fatigue-cracked plate loaded in tension. General proportions of this specimen configuration are shown in Figure C.1. Alternative specimens may have $2 < W/B < 4$, but with no change in other proportions.

If specimen configurations (or proportions) other than those specified are used as specified in 7.2.3, their appropriate formulae and methods of record analysis shall also be used.

Values of surface roughness (Ra) in micrometres



[a] See Figure 2.

NOTE 1 Integral or attachable knife edges for clip gauge attachment may be used (see Figure 3).

NOTE 2 For starter-notch and fatigue-crack configurations, see Figure 2.

Figure C.1 — Compact specimen

C.2 Test fixture

A loading clevis suitable for testing compact specimens is shown in Figure D.2. Both ends of the specimen are held in such a clevis and loaded through pins in order to allow rotation of the specimen during testing. The clevis holes are designed with small flats on the loading surfaces to provide rolling contact, thereby minimizing friction effects.

C.3 Test procedure

To minimize eccentricity in the loading train, align the loading rods to ± 0,75 mm and centre the specimen in the clevis slot to ± 0,75 mm.

C.4 Calculation

For the compact specimen, K_Q is calculated in MPa·m$^{1/2}$ as follows:

$$K_Q = \frac{F_Q}{BW^{1/2}} f(a/W)$$

where

F_Q is in kilonewtons;

B and W are in centimetres;

$$f(a/W) = (2 + a/W) \times \frac{0{,}886 + 4{,}64(a/W) - 13{,}32(a/W)^2 + 14{,}72(a/W)^3 - 5{,}6(a/W)^4}{(1 - a/W)^{3/2}}$$

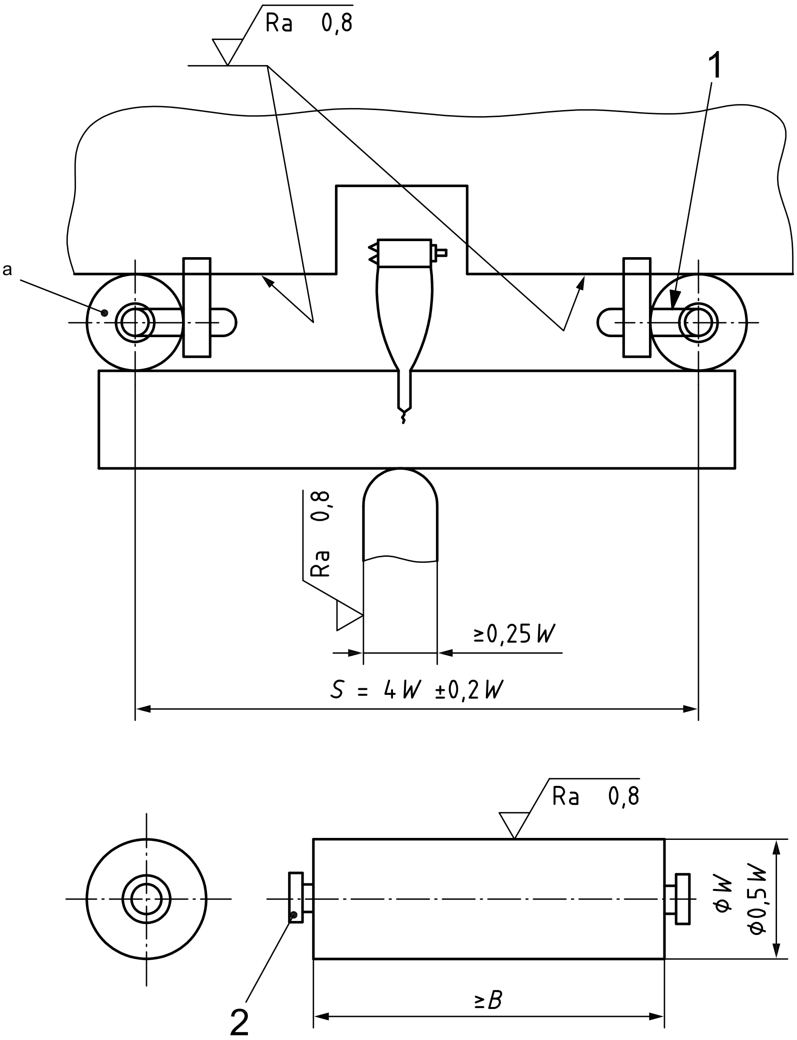
EXAMPLE For $a/W = 0{,}500$, $f(a/W) = 9{,}66$.

Annex D
(informative)

Test fixtures

A recommended fixture design for the bend specimen is shown in Figure D.1. An equivalent design is given in British Standard BS 7448-1[1]. A recommended clevis design for the compact specimen is shown in Figure D.2.

Values of surface roughness (Ra) in micrometres



Roller pins and specimen contact surface of loading ram shall be parallel to each other to ± 2°.

Fixture and roller pin hardness shall be > 40 HRC.

Key

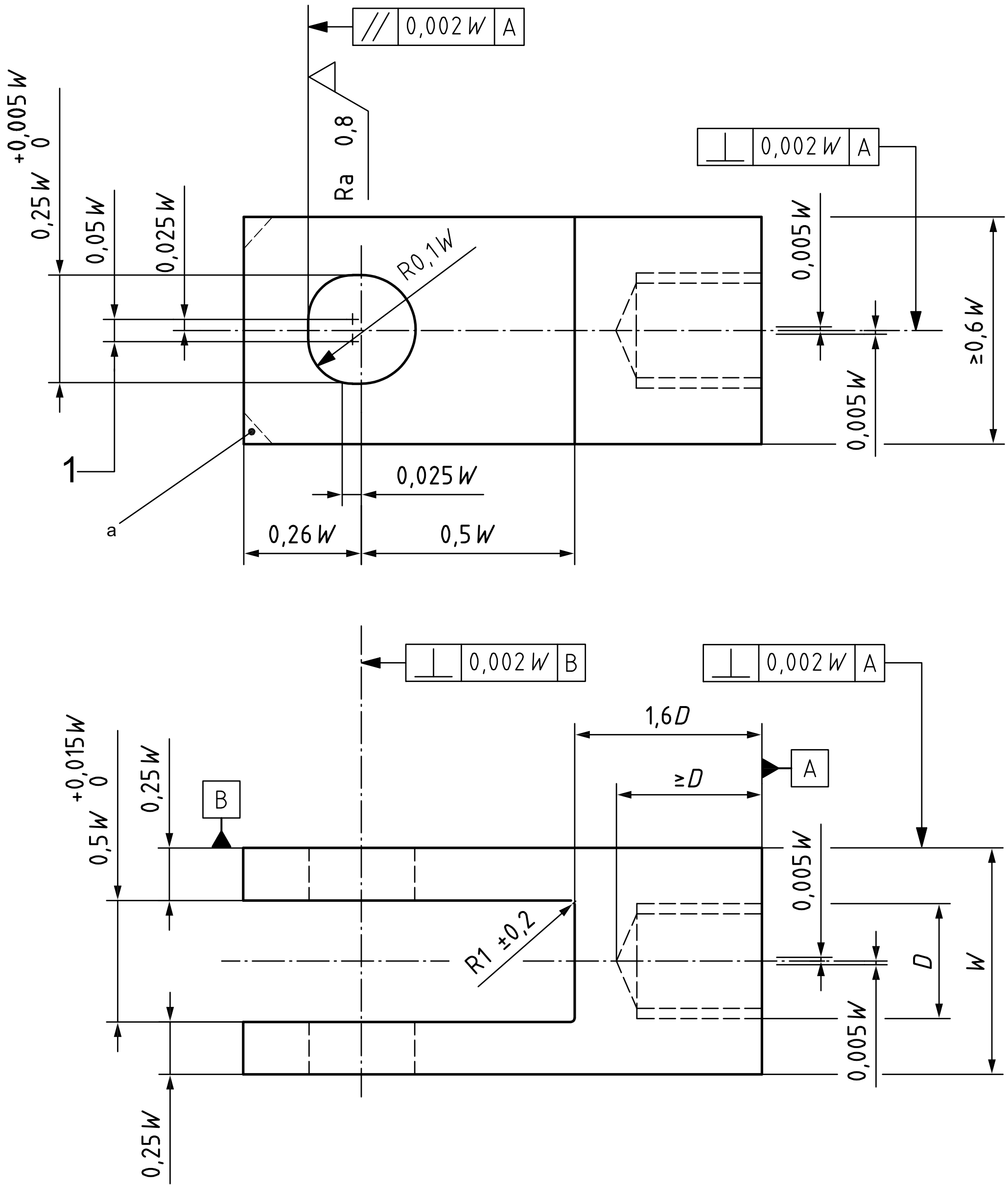
1 rubber band or spring

2 bosses for rubber bands or springs

[a] See roller detail below.

Figure D.1 — Test fixture for bend specimen

Dimensions in millimetres
Values of surface roughness (Ra) in micrometres



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

Clevis and pin hardness shall be $>$ 40 HRC.

Key

1 loading flat

[a] Corners of clevis may be removed if necessary to accommodate clip gage.

Figure D.2 — Clevis for compact specimen

Bibliography

[1] BS 7448-1:1991, *Fracture mechanics toughness tests — Part 1: Method for determination of* K_{Ic}, *critical CTOD and critical* J *values of metallic materials*

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

[3] ISO 15653, *Metallic materials — Method of test for the determination of quasistatic fracture toughness of welds*

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