INTERNATIONAL STANDARD

ISO 26843

First edition
2015-12-15

Metallic materials — Measurement of fracture toughness at impact loading rates using precracked Charpy-type test pieces

Matériaux métalliques — Mesure de la ténacité d'éprouvettes type Charpy préfissurées soumises à un chargement d'impact

Reference number
ISO 26843:2015(E)

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Foreword

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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)*.

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Introduction

This International Standard is closely related to ISO 14556 and was derived from a draft procedure prepared by the Working Party "European Standards on Instrumented Precracked Charpy Testing" of the European Structural Integrity Society (ESIS) Technical Subcommittee on Dynamic Testing at Intermediate Strain Rates (TC5).

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Metallic materials — Measurement of fracture toughness at impact loading rates using precracked Charpy-type test pieces

1 Scope

This International Standard specifies requirements for performing and evaluating instrumented precracked Charpy impact tests on metallic materials using a fracture mechanics approach. Minimum requirements are given for measurement and recording equipment such that similar sensitivity and comparable measurements are achieved.

Dynamic fracture mechanics properties determined using this International Standard are comparable with conventional large-scale fracture mechanics results when the corresponding validity criteria are met. Because of the small absolute size of the Charpy specimen, this is often not the case. Nevertheless, the values obtained can be used in research and development of materials, in quality control, and to establish the variation of properties with test temperature under impact loading rates.

Fracture toughness properties determined through the use of this International Standard may differ from values measured at quasistatic loading rates. Indeed, an increase in loading rate causes a decrease in fracture toughness when tests are performed in the brittle or ductile-to-brittle regimes; the opposite is observed (i.e. increase in fracture toughness) in the fully ductile regime. More information on the dependence of fracture toughness on loading (or strain) rate is given in Reference [1]. In addition, it is generally acknowledged that fracture toughness also depends on test temperature. For these reasons, the user is required to report the actual test temperature and loading rate for each test performed.

In case of cleavage fracture of ferritic steels in the ductile-to-brittle transition region, variability can be very large and cannot be adequately described by simple statistics. In this case, additional tests are required and the analysis is to be performed using a statistical procedure applicable to this type of test, see for example Reference [2].

NOTE Modifications to the analytical procedures prescribed in Reference [2] might be necessary to account for the effect of elevated (impact) loading rates.

2 Normative references

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

ISO 148-1, *Metallic materials — Charpy pendulum impact test — Part 1: Test method*

ISO 148-2, *Metallic materials — Charpy pendulum impact test — Part 2: Verification of testing machines*

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

ISO 14556, *Steel — Charpy V-notch pendulum impact test — Instrumented test method*

ISO 26203-2, *Metallic materials — Tensile testing at high strain rates — Part 2: Servo-hydraulic and other test systems*

3 Symbols

For the purposes of this International Standard, the following symbols given in Table 1 apply.

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Table 1 — Symbols and definitions used in this International Standard

Symbol	Definition	Unit
a	Nominal crack length (for the purposes of fatigue precracking, an assigned value less than a_0)	mm
a_f	Final crack length (a_0 + Δa)	mm
a_m	Length of machined notch	mm
a_0	Initial crack length	mm
Δa	Crack extension (a – a_0)	mm
Δa_{max}	Crack extension limit for J-controlled crack extension	mm
Δa_s	Crack extension corresponding to displacement s	mm
B	Specimen thickness	mm
B_e	Specimen effective thickness as defined in Formula (E.7)	mm
B_N	Specimen net thickness after side-grooving	mm
C_M	Compliance of the test machine	m/N
C_0	Specimen elastic compliance	m/N
C_S	Specimen theoretical compliance	m/N
E	Young's modulus of elasticity	GPa
$\mathrm{d}\varepsilon/\mathrm{d}t$	Strain rate	s^{-1}
f_g	Output frequency limit	Hz
F	Applied force	N
F_{cd}	Applied force at onset of unstable crack extension in Figure 1	N
F_f	Maximum fatigue precracking force during the final precracking stage	N
F_{gy}	Applied force at onset of general yielding as defined in ISO 14556	N
F_m	Maximum applied force as defined in ISO 14556	N
F_s	Applied force corresponding to a displacement s	N
J_d	Dynamic J-integral	MJ/m^2
J_{cd}	Dynamic equivalent of $J_{c(B)}$ in ISO 12135 (with B = 10 mm)	MJ/m^2
J_g	J at upper limit of J-controlled crack extension	MJ/m^2
$J_{d,max}$	Limit of J_d-R material behaviour defined by this test method	MJ/m^2
J_{ud}	Dynamic equivalent of $J_{u(B)}$ in ISO 12135 (with B = 10 mm)	MJ/m^2
$J_{0,2Bd}$	Dynamic equivalent of $J_{0,2BL(B)}$ in ISO 12135 (with B = 10 mm)	MJ/m^2
$\mathrm{d}J_d/\mathrm{d}t$	Rate of change of dynamic J-integral	$MJ/m^2\ s^{-1}$
K_d	Dynamic stress intensity factor	$MPa\ m^{0,5}$
K_{Jd}	Dynamic stress intensity factor calculated from J-integral	$MPa\ m^{0,5}$
$K_I^{dyn}(t)$	Stress intensity factor – time history from the impact response curve method	$MPa\ m^{0,5}$
K_{Id}	Dynamic plane strain fracture toughness	$MPa\ m^{0,5}$
K_{Jcd}	Dynamic stress intensity factor calculated from J-integral at the onset of cleavage	$MPa\ m^{0,5}$
$\mathrm{d}K_d/\mathrm{d}t$	Rate of change of dynamic stress intensity factor	$MPa\ m^{0,5}\ s^{-1}$
KV	Absorbed energy as defined in ISO 148-1	J
KV_0	Available potential energy corresponding to a reduced pendulum impact velocity v_0	J
M	Total mass of the moving striker of the pendulum	kg
n	Strain hardening exponent of the Ramberg-Osgood material law	—
N	Number of available test specimens	—

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Table 1 *(continued)*

Symbol	Definition	Unit
R_{fd}	Dynamic flow stress, defined as the average of dynamic yield strength and dynamic tensile strength	MPa
R_{md}	Dynamic tensile strength determined at the strain rate of the fracture toughness test	MPa
R_{pd}	Dynamic yield (proof) strength determined at the strain rate of the fracture toughness test	MPa
R_p	Yield (proof) strength measured at quasistatic strain rate	MPa
s	Specimen displacement (calculated according to ISO 14556)	mm
s_{pl}	Plastic component of specimen displacement	mm
S	Span between outer loading points	mm
T	Temperature	°C
t	Time	s
t_f	Time to fracture	s
t_i	Time at the onset of crack propagation	s
t_r	Signal rise time	s
t_o	Time at striker impact	s
τ	Period of force oscillation	s
v_0	Initial striker impact velocity	m s^{-1}
v_{0s}	Striker impact velocity corresponding to the maximum available energy of the pendulum	m s^{-1}
W	Specimen effective width	mm
W_m	Energy at maximum force as defined in ISO 14556	J
W_p	Plastic component of the area under the force-displacement test record up to displacement s	J
W_s	Total fracture energy under the force-displacement test record up to displacement s	J
W_t	Calculated energy from area under complete force-displacement test record up to $F = 0{,}02\ F_m$ as defined in ISO 14556	J
W_o	Available impact energy	J
ν	Poisson’s ratio	—

4 Principle

This International Standard prescribes impact bend tests which may be performed on fatigue precracked Charpy-type specimens to obtain dynamic fracture mechanics properties of metallic materials. This International Standard extends the procedure for V-notch impact bend tests in accordance with ISO 148-1, and may be used for the evaluation of the master curve reference temperature in accordance with Reference [2] provided that the corresponding validity requirements are met. Instrumented testing machines are required together with ancillary instrumentation and recording equipment in accordance with ISO 14556.

Fracture toughness properties depend on material response reflected in the force-time diagrams described in Table 2 and Figure 1. The logical structure for fracture property determination and validation is shown in the flow chart of Figure 2.

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Table 2 — Fracture toughness properties to be determined

Material response/fracture behaviour	Corresponding diagram type (see Figure 1)	R-curve	Characteristic parameters
Linear-elastic	I	—	J_{cd}, K_{Jcd}, K_{Id} (B, dK_d/dt, dJ_d/dt)
Elastic-plastic, unstable fracture with Δa < 0,2 mm	II	—	J_{cd}, K_{Jcd} (B,dJ_d/dt)
Elastic-plastic, unstable fracture with 0,2 mm ≤ Δa ≤ 0,15 ($W - a_0$)	II	—	J_{ud} (B,Δa,dJ_d/dt)
Elastic-plastic, unstable fracture with Δa > 0,15 ($W - a_0$)	III	J_d-Δa	$J_{0,2Bd}$ (dJ_d/dt)
Elastic-plastic; no unstable fracture	IV	J_d-Δa	$J_{0,2Bd}$ (dJ_d/dt)

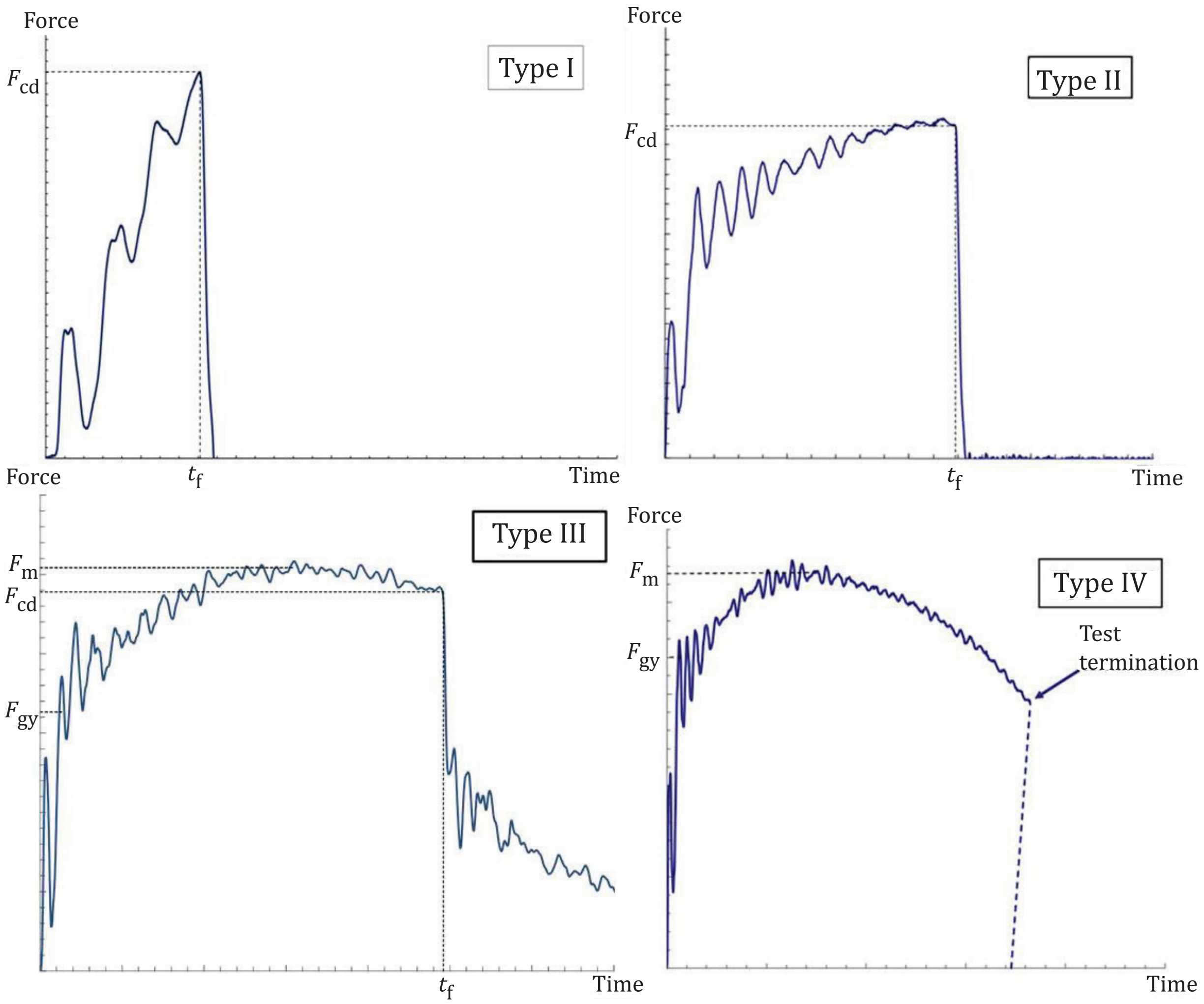

Figure 1 — Typical force-time diagrams (schematic)

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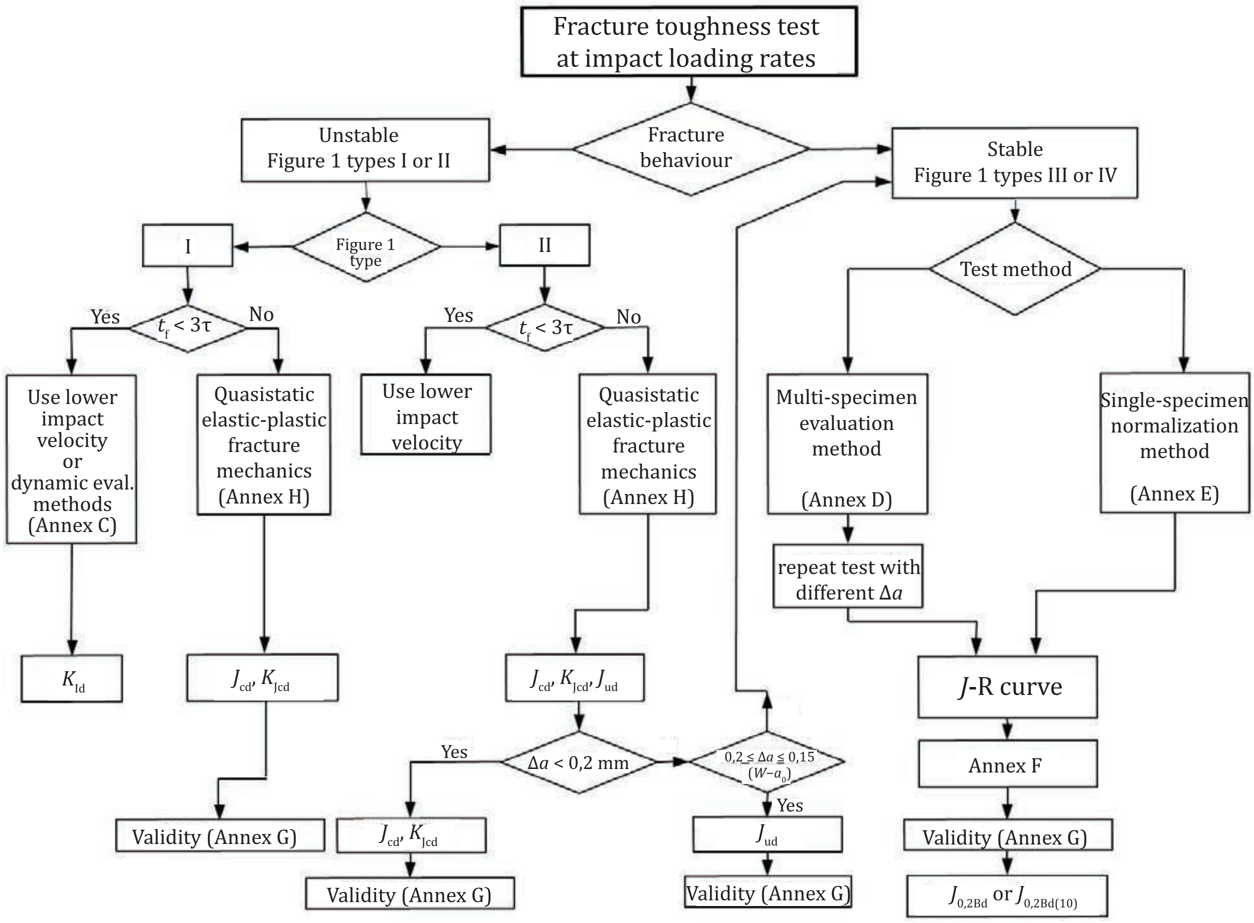

Figure 2 — Flow chart for the application of the test method

5 Test specimens

5.1 Specimens shall be prepared in accordance with the standard specimens of ISO 148-1, with or without the 2,0 mm V-notch, followed by fatigue precracking.

5.2 Specimens shall be fatigue precracked in bending to produce an initial crack length, a_0, in the range $0{,}30 \leq a_0/W \leq 0{,}70$.

If the results in terms of J are to be directly comparable with full-size standard fracture toughness values such as $J_{0,2BL}$ (as defined in ISO 12135), then a_0/W shall be in the range $0{,}45 < a_0/W < 0{,}70$. Shorter crack lengths may be more advantageous, as a stiffer test piece increases the probability of a successful test.

5.3 To initiate fatigue precracking, machine or spark erode a slot into the specimen. For specimens with an existing V-notch, fatigue precracking may initiate at the bottom of the notch. The length of the machined notch, a_m, shall be at least 1,0 mm shorter than the desired initial crack length, a_0.

5.4 During the final 1,3 mm or 50 % of precrack extension, whichever is less, the maximum fatigue precracking force shall be the lower of:

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$$F_f = \frac{0{,}8B\left(W - a_0\right)^2}{S} R_p \tag{1}$$

or

$$F_f = \xi \times E\left[\frac{\sqrt{WBB_N}}{f\left(\frac{a_0}{W}\right)}\right]\left(\frac{W}{S}\right) \tag{2}$$

where $\xi = 1{,}6 \times 10^{-4}\ m^{1/2}$ and the function $f\left(\frac{a_0}{W}\right)$ is given in Formula (H.2).

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

NOTE For plain-sided specimens, $B_N = B$.

5.5 When fatigue precracking is performed at temperature T_1 and testing is performed at temperature T_2, F_f in Formula (2) shall be factored by the ratio R_p [T_1] / R_{pd} [T_2], where R_p [T_1] is the quasistatic yield strength at temperature T_1 and R_{pd} [T_2] is the dynamic yield strength at temperature T_2. In addition, F_f determined from Formula (1) shall be evaluated using the smaller value of R_p [T_1] and R_{pd} [T_2].

5.6 Specimens may be side grooved, preferably after fatigue precracking, using a V-notch cutter in accordance with ISO 148-1 to a depth of 1,0 mm on each side. Side grooving is recommended for all J_d-Δa R-curve tests. For details of crack length measurement, see 9.4.2.

6 Testing machines

6.1 The tests may be carried out using testing machines of the general types specified in Annex A. Not all machines can perform all types of test (see Annex A for more details). In all cases, the striker and anvil dimensions shall conform to ISO 148-2.

6.2 Details of machine instrumentation and calibration procedures are specified in ISO 14556.

6.3 For every test in which the entire force signal has been recorded (i.e. the force returns to the baseline), the difference between KV and W_t shall be within ±15 % of KV or ±1 J, whichever is larger. If this requirement is not met but the difference does not exceed ±25 % of KV or ±2 J, whichever is larger, force values may be adjusted until $KV = W_t$.[3] If the difference exceeds ±25 % of KV or ±2 J, whichever is larger, the test shall be discarded and the calibration of the instrumented striker user shall be checked and if necessary repeated. If recording of the entire force signal is not possible (for example due to the specimen being ejected from the machine without being fully broken), conformance to the requirements stated earlier shall be demonstrated by testing, using the same experimental apparatus, at least five Charpy specimens (precracked, non-precracked, or a mix of precracked and non-precracked) of similar absorbed energy level, for which the entire force signal is recorded. In all cases, the difference between KV and W_t shall be within ±15 % of KV or ±1 J, whichever is larger.

7 Test procedures and measurements

7.1 General

Tests are performed in general accordance with the standard Charpy impact test of ISO 148-1, with allowance for other types of machines, as specified in Annex A.

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The force-displacement diagram is recorded according to ISO 14556, from which the key data values F_m, F_{cd}, W_m, and W_t are determined. In addition to the procedures of ISO 14556, specific procedures for determining striking velocity, available energy, and crack lengths are given below. These data form the basis for evaluation of toughness parameters according to Annexes D to F.

NOTE The force F_{cd} in this International Standard corresponds to the force F_{iu} (crack initiation force) in ISO 14556.

7.2 Impact velocity

This International Standard applies to any impact velocity, v_0, in excess of those corresponding to the testing rates prescribed by ISO 12135. Commonly used impact velocities are in the range from 1 ms^{-1} to 5,5 ms^{-1}.

NOTE 1 Impact velocities for pendulum or falling weight testing machines can vary by adjusting the striker release height.

NOTE 2 The reduced impact velocity, v_0, can be determined as follows: release the pendulum from the appropriately reduced height, without a specimen on the supports. Read the energy KV_0 (in J) indicated by the pointer on the analogue scale. From this, the reduced impact velocity is calculated for a 300 J pendulum as:

$$v_0 = v_{0s}\sqrt{\frac{300 - KV_0}{300}} \tag{3}$$

where v_{0s} is the impact velocity corresponding to the maximum potential energy of the pendulum (machine capacity), in this case 300 J. If the pendulum maximum available energy is different from 300 J, replace 300 in Formula (3) with the actual maximum available energy. A reduced velocity (1 m/s to 2 m/s) can be advantageous, particularly in case of brittle behaviour, as it reduces the effect of oscillations by lowering their relative amplitude and by increasing their number within the time to fracture t_f (see 8.2).

7.3 Time to fracture

When the time t_f to initiate unstable fracture is less than 3τ, with τ being the period of force oscillation, fracture occurs after less than three oscillations in the force-time or force-displacement record. In this case, the instant of crack initiation is not detectable in the force signal with adequate accuracy due to the force oscillations[4][5][6] (see Figure 1, type I) and the test cannot be evaluated in accordance with this International Standard. Reducing the test impact velocity is recommended for further testing in order to increase the number of oscillations preceding fracture.

NOTE Dynamic evaluation methods have been proposed for determining t_f independently of force measurements, when time to fracture $t_f < 3\tau$. Examples are the impact response curve method and the crack tip strain gauge method described in Annex C.

7.4 Multiple specimen tests

To determine dynamic J_d-R curves by multi-specimen techniques, the fracture process is interrupted at a certain stable crack extension Δa and the process is repeated until an adequate number of data points are available to define the J_d-R curve. This procedure is described in Annex D.

7.5 Single-specimen tests

Several single-specimen techniques have been proposed in the literature to estimate dynamic J_d-R curves. However, only the normalization method described in Annex E is supported by this International Standard.

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7.6 Post-test crack length measurements

After a test has been performed, the specimen shall be broken open, if necessary, and the fracture surfaces shall be examined to determine the initial crack length a_0 and the amount of stable crack extension Δa (if applicable). The measurement of initial crack length and stable or unstable crack extension (if applicable) shall be performed in accordance with ISO 12135 (nine-point average method).

NOTE 1 For some tests, it may be necessary to mark the extent of stable crack extension before opening the specimen. Stable crack extension may be marked by heat tinting or by post-test fatiguing. Care is to be taken to minimize post-test deformation. Cooling materials which exhibit a ductile-to-brittle transition may help to ensure brittle behaviour during specimen opening.

NOTE 2 In the case of poor contrast between fatigue crack, stable crack, and brittle crack after heat tinting, when using a microscope for crack length measurement, the use of dark field illumination and/or filters may be beneficial. Digitizing the fracture surface and subsequently evaluating the digital image by image analysis software may be advantageous.

The occurrence of irregular crack fronts shall in all cases be reported.

8 Evaluation of fracture mechanics parameters

8.1 The evaluation of fracture toughness parameters depends on the fracture behaviour of the test specimen as reflected in the force-displacement diagrams described in Table 2. Therefore, the measured force-displacement or force-time diagram shall be assigned to one of the diagram types shown in Figure 1.

8.2 In the case of unstable fracture as in Figure 1, types I or II, the applicable evaluation method depends on the oscillations superimposed on the force signal.

8.2.1 If fracture occurs after less than 3 oscillations, i.e. $t_f < 3\tau$, a reduced impact velocity should be employed for further testing in order to obtain a force signal with reduced oscillations. Alternatively, the dynamic evaluation methods described in the informative Annex C may be used.

8.2.2 If there are at least three oscillations before fracture occurs, i.e. $t_f \geq 3\tau$, fracture toughness (J_{cd} or J_{ud}) shall be evaluated using the formulas provided in Annex H. Fracture toughness values obtained shall be qualified in accordance with Annex G.

8.3 In the case of stable crack extension as in Figure 1, types III or IV, either the multi-specimen method or the normalization method (single-specimen technique) described in Annexes D and E, respectively, shall be used to determine the J_d-R curve. Results obtained shall be qualified in accordance with Annex G.

8.3.1 Multi-specimen methods and the corresponding evaluation of J_d-R curves are described in Annex D.

8.3.2 Single-specimen tests require numerical or analytical determinations of the J_d-Δa R-curve. Several approaches, besides the normalization method described in Annex E, have been proposed, such as the basic key curve method[7][8][9] and the analytical three-parameter approach.[10][11] However, only the normalization method is supported by this International Standard.

8.4 The determination of characteristic fracture toughness values ($J_{0,2Bd}$ or $J_{0,2Bd(10)}$) from dynamic crack resistance curves is described in Annex F. Values obtained have to be qualified in accordance with Annex G.

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8.5 Crack-tip loading rate

Fracture toughness values shall be stated with the corresponding loading rate added in parentheses. Loading rate may be estimated as follows

$$\text{Type I curves: } \frac{\mathrm{d}K_\mathrm{d}}{\mathrm{d}t} = \frac{K_\mathrm{d}}{t_\mathrm{f}} \tag{4}$$

$$\text{Type II curves: } \frac{\mathrm{d}J_\mathrm{d}}{\mathrm{d}t} = \frac{J_\mathrm{cd}}{t_\mathrm{f}} \text{ or } \frac{\mathrm{d}J_\mathrm{d}}{\mathrm{d}t} = \frac{J_\mathrm{ud}}{t_\mathrm{f}} \tag{5}$$

$$\text{Type III and IV curves: } \frac{\mathrm{d}J_\mathrm{d}}{\mathrm{d}t} = \frac{F_\mathrm{m} v_0}{B_\mathrm{N}\left(W - a_0\right)} \eta_\mathrm{pl} \left(\frac{a_0}{W}\right) \tag{6}$$

8.6 The dynamic yield stress at the relevant strain rate may be required for certain evaluation procedures and validity checks, and may be determined using ISO 26203-2. The relevant strain rate may be estimated in accordance with Annex B.

9 Test report

9.1 Organization

The test report shall make reference to this International Standard and shall be comprised of four parts (see 9.2 to 9.5). Details regarding test material, test specimen, and test conditions, including test environment, shall be reported as in 9.2. Fatigue cracking is addressed in 9.3, while crack front straightness and crack length data shall conform to 9.4. Derived fracture parameters shall also be qualified in accordance with 9.4.

9.2 Specimen, material, and test environment

See I.1.

9.2.1 Specimen description

— identification;

— crack-plane orientation;

— location within product form.

9.2.2 Specimen dimensions

— thicknesses B and B_N, (mm);

— width W, (mm);

— initial relative crack length, a_0/W.

9.2.3 Material description

— composition and standardized designation code;

— product form (plate, forging, casting, etc.) and condition;

— tensile properties at precracking temperature, referenced or measured;

— tensile properties at the test temperature, referenced or measured.

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9.2.4 Test environment

— temperature (°C);

— striker impact velocity (m/s);

— characteristics of test machine used.

9.3 Fatigue precracking conditions

— K_f (MPa m^{0,5});

— F_f (kN);

— precracking temperature (°C).

9.4 Test data qualification

9.4.1 Limitations

All data shall meet certain requirements in order to be qualified in accordance with this method. Only qualified data shall be used to define fracture resistance at impact loading rates according to this method. The data described in 9.4.2 to 9.4.4 can be assembled in the suggested format presented in Annex I.

9.4.2 Crack length measurements

Measurements shall be made at nine evenly spaced locations across the specimen thickness as prescribed in 7.6. The following average values, calculated from the measured data, shall be reported:

— the initial machined notch length (a_m);

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

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

— the final crack length (a_f);

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

9.4.3 Fracture surface appearance

— a record of unusual features on the fracture surface;

— a record of the occurrence of unstable crack extension such as cleavage.

9.4.4 Resistance curves

— include data for resistance curves from single-specimen tests in Table I.2.

9.4.5 Checklist for data qualification

The test results shall be considered qualified if they conform to the following criteria:

a) the specimen conforms to the dimensions and tolerances prescribed by ISO 148-1;

b) the test apparatus conforms to the requirements of ISO 148-1, ISO 14566, and Clause 6;

c) the average initial crack length a_0 is within the range 0,30 W to 0,70 W;

d) all parts of the fatigue precrack have extended at least 1,0 mm from the root of the machined notch;

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e) the maximum fatigue precracking force satisfies the requirements of 5.4;

f) none of the seven interior initial crack length measurements differs by more than 0,10 a_0 from the nine-point average initial crack length;

g) none of the seven interior final crack length measurements differs by more than 0,10 (a_0 + Δa) from the nine-point average initial crack length;

h) the data number and spacing requirements of Annex G are satisfied for J_d-Δa curve and $J_{0,2Bd}$ determinations.

9.5 Test results

The test report shall specify the following fracture parameters determined as:

a) the value of K_{Id} obtained, if applicable;

b) the value of dK_d/dt obtained, if applicable;

c) the value of J_{cd}, K_{Jcd}, J_{ud}, or $J_{0,2Bd}$ obtained, if applicable;

d) the value of dJ_d/dt obtained, if applicable;

e) the type of force-time diagram, with reference to Figure 1, types I to IV;

f) a copy of the test record.

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Annex A
(normative)

Test machines suitable for each test procedure

A.1 This Annex gives guidance on the general types of testing machines used to perform the tests detailed in this International Standard. It shall be noted that not all machines can perform all types of tests.

The reference testing machine is the instrumented Charpy pendulum according to ISO 14556, modified to have a variable pendulum release position and therefore a variable striking velocity.

Other pendulum machines may be used, with fixed anvil/moving striker or fixed striker/moving anvil and fixed or moving test specimen. The pendulum release position and therefore the striking velocity for such machines are normally variable and the striker or anvils are instrumented to provide force-time or force-displacement records.

A.2 Falling weight testing machines, which may be spring assisted, have no restrictions on impact velocity or mass of falling weight. The striker shall be instrumented to provide force-time or force-displacement records.

A.3 High-rate servo-hydraulic test machines may be used to apply force to the specimen, provided the system is in open-loop mode, optimized by simulation or evaluation of pre-tests, to obtain constant displacement rate. Care must be taken to ensure that the actuator has reached the desired rate before the striker impacts the specimen. Striker, anvils, and supports shall meet the requirements of ISO 148-2.

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Annex B
(informative)

Estimation of strain rate

The loading rate in fracture mechanics tests is characterized in terms of the rate of change of a fracture mechanics quantity with time; e.g. $\mathrm{d}J_\mathrm{d}/\mathrm{d}t$. Usually, the strain rate at the crack tip is not known. The required strength value R_pd at the temperature of the fracture mechanics test has to be determined in a tensile test at a strain rate that is representative of the fracture mechanics test, recognizing that R_pd can differ significantly from the quasistatic value R_p. An approximate equivalent strain rate for the fracture mechanics test may be calculated according to Formula (B.1):[12][13]

$$\frac{\mathrm{d}\varepsilon}{\mathrm{d}t} = \frac{2R_\mathrm{p}}{\bar{t}E} \tag{B.1}$$

where R_p and E are values at the temperature of the fracture mechanics test and corresponding to quasistatic loading rates, and $\bar{t}$ is the time to fracture in the case of small scale yielding, or the time interval of the initial linear part of the force-time record in the case of distinct elastic-plastic material behaviour.

Formula (B.1) provides a general estimate of strain rate values associated with fracture in the test specimen.

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Annex C
(normative)

Dynamic evaluation of fracture toughness

C.1 General

The evaluation of test records and calculation of results varies in detail depending on the particular test performed. However, all the tests have certain common characteristics involving time to fracture, force-time, or force-displacement responses. The impact response curve and the crack tip strain gauge procedures provide accurate and repeatable results.

C.2 Impact response curve method

C.2.1 The impact response curve method is a fully dynamic measuring technique.[14][15][16] It is applicable to any test condition, particularly higher impact velocities or low temperatures, and is applicable to steels only. The procedure is illustrated in Figure C.1. The method is applicable for $t_f \geq 25$ µs.

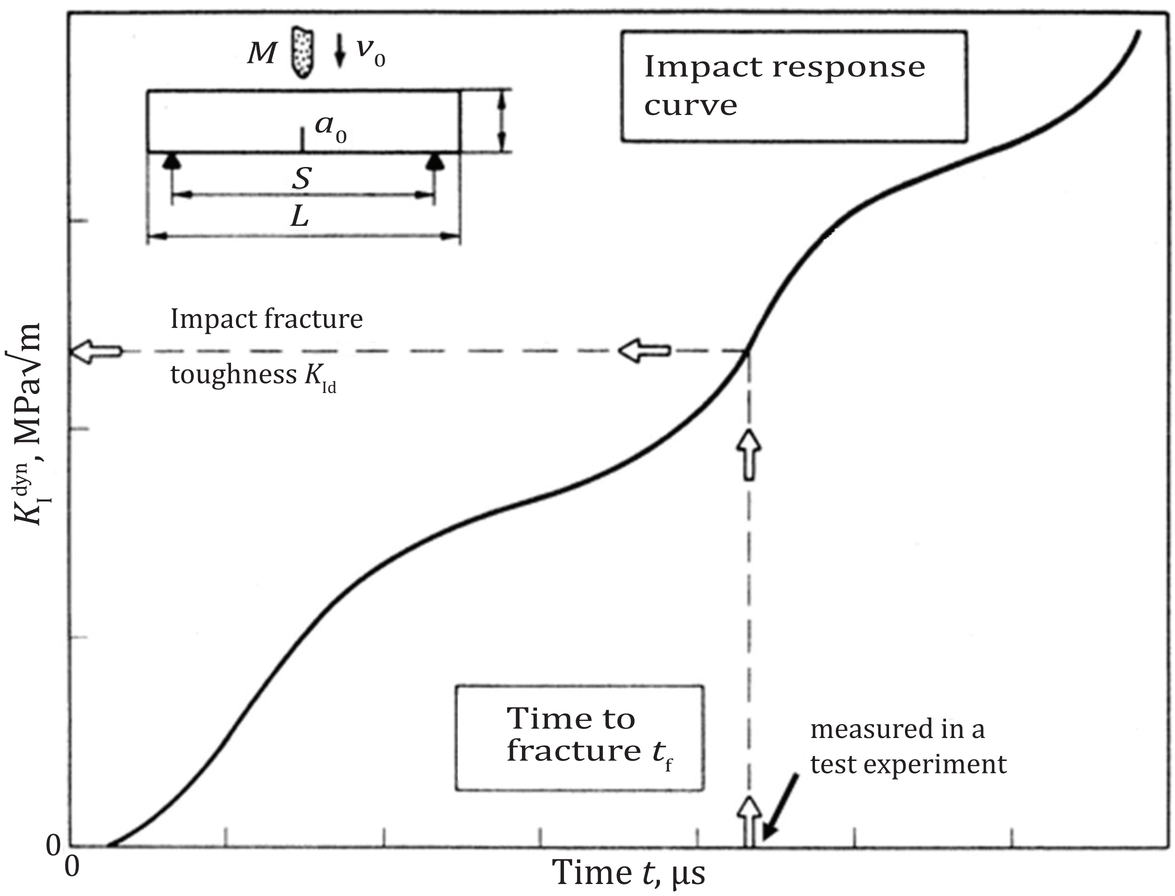

Figure C.1 — Schematic illustration of the impact response curve method

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The leading edge of the force signal marks the beginning of the impact event, t_0. The time at the onset of crack propagation, t_i, is determined as described in C.2.2. The time to fracture, t_f, is the interval between the two times t_i and t_0, see Figure C.2.

C.2.2 A strain gauge is bonded on the specimen, with its centre 1 mm to 2 mm from the fatigue crack tip and its grid direction perpendicular to the crack as shown in Figure C.2. This strain gauge does not require calibration.

C.2.3 The strain gauge shall have a grid size of not more than 1,5 mm × 1,5 mm and be bonded preferably using hot-cured solvent-thinned epoxy adhesive to obtain the thinnest possible glue line. The gauge is connected to a high frequency response amplifier using the three-wire quarter bridge configuration; the recommended frequency response is greater than or equal to 1 MHz. Typical gauge energization voltage is 1 V to 4 V.

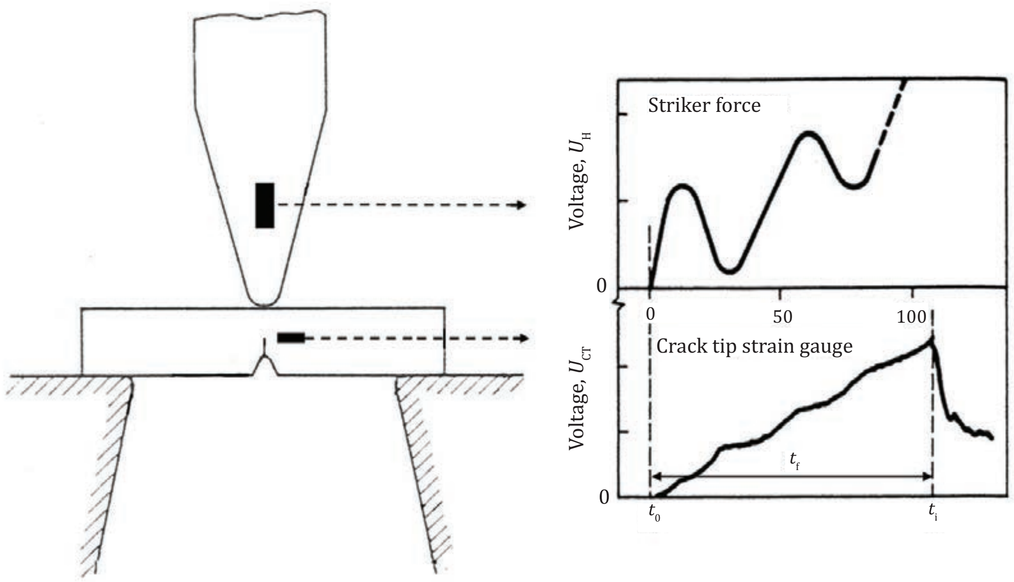

Figure C.2 — Typical striker force and crack tip strain gauge signals during impact. The onset of crack extension is defined as a sudden drop in the gauge signal

C.2.4 When there is a sufficiently long time to fracture, $t_f > 3\tau$,[4][5][6] crack initiation is defined as a sudden drop of at least 5 % of the force registered at the instrumented striker, for which a quasistatic evaluation may be performed in accordance with Annex H. If $t_f \leq 3\tau$, then crack initiation is defined as a sudden drop of at least 20 % in the crack tip strain gauge signal and dynamic toughness is evaluated using the impact response curve method.

C.2.5 The stress intensity factor - time history, $K_I^{dyn}(t)$, constitutes the impact response curve.[14] Using the measured t_f, the impact fracture toughness K_{Id} is determined as:

$$K_{Id} = K_I^{dyn}\left(t = t_f\right) \tag{C.1}$$

Impact response curves for three particular impact velocities v_0 = 2,0 ms^{-1}, 3,8 ms^{-1}, and 5,0 ms^{-1} and a/W = 0,5 are shown in Figure C.3. The curves scale with velocity.

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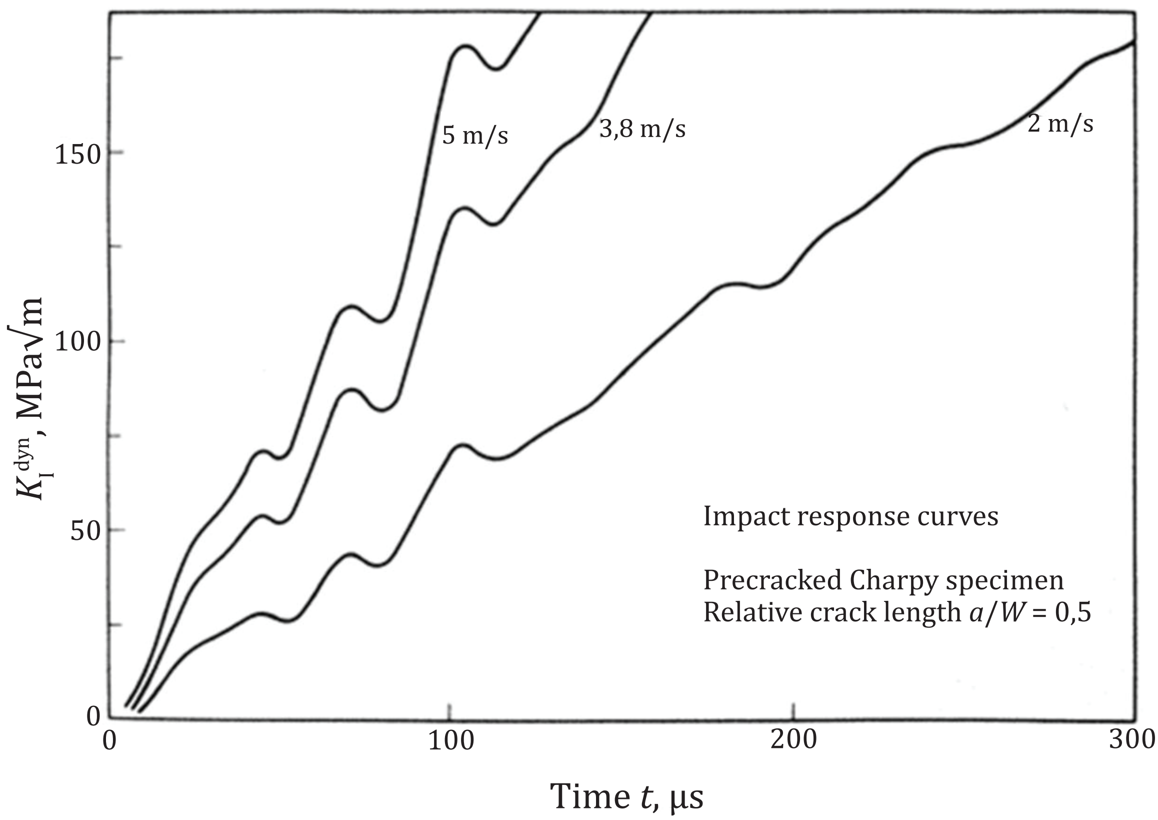

Figure C.3 — Impact response curves, $K_I^{dyn}(t)$, at velocities v_0 = 2,0 ms^{-1}, 3,8 ms^{-1}, and 5,0 ms^{-1} for a/W = 0,5

For practical applications use the expression:

$$K_I^{dyn} = R v_0 f\left(t'\right) \tag{C.2}$$

where the constant R = 301 GN/m$^{5/2}$ and the correction factor $f(t')$ is found in Table C.1, with

$$t' = t\left[1 - 0{,}62\left(\frac{a}{W} - 0{,}5\right) + 4{,}8\left(\frac{a}{W} - 0{,}5\right)^2\right] \tag{C.3}$$

where t is the measured physical time and t' is a modified time which compensates for variations of the initial crack length in the range 0,45 < a_0/W < 0,55. The correction factor is less than 5 % for t > 110 µs, and thus the $f(t')$-correction is limited to t' ≤ 110 µs (~2τ). $f(t')$ = t' for t' > 110 µs.

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Table C.1 — Functions for the determination of K_I^{dyn} for 0,45 ≤ a_0/W ≤ 0,55[14][15][16]

t' (µs)	$t'' = f(t')$ (µs)	t' (µs)	$t'' = f(t')$ (µs)	t' (µs)	$t'' = f(t')$ (µs)
0	0	40	45	80	69
2	0	42	46	82	70
4	2	44	47	84	75
6	4	46	46	86	81
8	6	48	45	88	88
10	9	50	45	90	94
12	13	52	46	92	100
14	17	54	49	94	106
16	20	56	53	96	111
18	24	58	57	98	116
20	28	60	61	100	118
22	30	62	65	102	119
24	33	64	69	104	118
26	35	66	72	106	117
28	36	68	73	108	115
30	38	70	73	110	115
32	39	72	72		
34	40	74	70		
36	42	76	69		
38	43	78	68		

NOTE This value of the constant R applies for stiff pendulum test devices according to ISO 148-2 with a machine compliance, C_m = 8,1 × 10^{-9} m/N. If the actual compliance of the test device differs from this value, the resulting influence can be taken into account by multiplying the given value of R by the first-order correction factor, 1,276/(1 + 0,276 × C_m × 8,1 × 10^{-9} m/N). Procedures for determining the machine compliance of impact test devices are described in References [4] and [14].

C.3 Crack tip strain gauge method

C.3.1 The crack tip strain gauge method uses the output of a small strain gauge mounted on one or both sides of the test specimen close to, and with its centre aligned with, the fatigue crack tip, with its grid direction perpendicular to the crack as shown in Figure C.4. The ideal position for the strain gauge is 5 mm away from the crack tip and aligned with it, when a/W ≈ 0,5. The background to this method is given in References [17] and [19].

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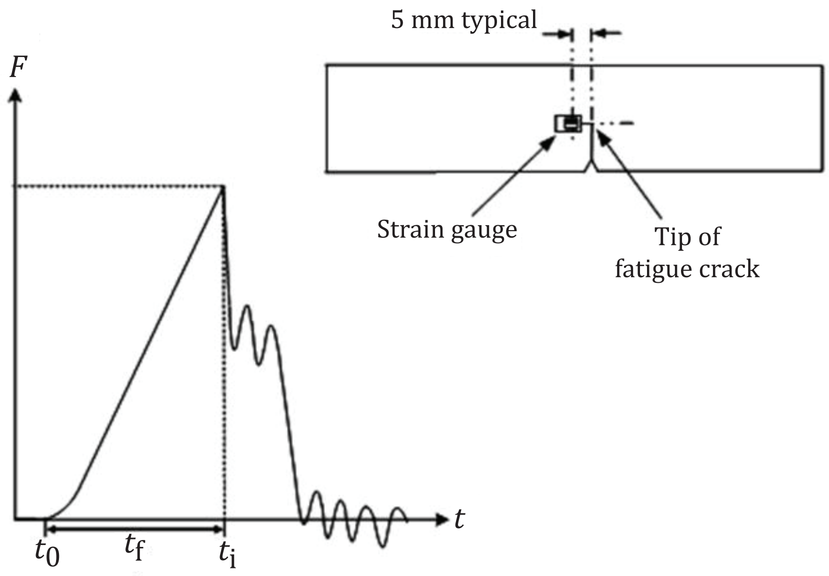

Figure C.4 — Typical force-time crack tip strain gauge record

C.3.2 The strain gauge shall have a grid size of not more than 1,5 mm × 1,5 mm and be bonded preferably using hot-cured solvent-thinned epoxy adhesive to obtain the thinnest possible glue line. The gauge is connected to a high frequency response amplifier using the three-wire quarter bridge configuration; the recommended frequency response is greater than or equal to 1 MHz. Gauge energization voltage shall be low enough to minimize thermal drift; 1 V to 4 V is usual.

C.3.3 The specimen is first loaded statically in bending to obtain a calibration record of the strain gauge amplifier output against applied force. At least six values of output voltage and force are required, up to the maximum precracking stress intensity factor, K_{fmax}. This calibration is preferably performed in the same testing machine as the impact test.

C.3.4 The impact test is performed and the strain gauge output signal is recorded. A typical force-time test record is shown in Figure C.4.

C.3.5 When there is a sufficiently long time to fracture, $t_f > 3\tau$,[4][5][6] crack initiation is defined as a sudden drop of at least 5 % of the force registered at the instrumented striker and a quasistatic evaluation is performed in accordance with Annex H.

C.3.6 If $t_f \leq 3\tau$, the time at fracture t_f is evaluated from the strain gauge force-time record and K_{Id} is then calculated from impact response curve method according to C.2.

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Annex D
(normative)

Determination of resistance curves at impact loading rates by multiple specimen methods

D.1 General

These methods make it possible to determine fracture toughness parameters in those cases where stable crack extension occurs, Figure 1, types III and IV. The multi-specimen procedure involves loading a series of nominally identical specimens to selected displacement levels, resulting in corresponding amounts of stable crack extension. Each specimen tested provides one point on the resistance curve. Six or more favourably positioned data points are required to generate one resistance curve in accordance with ISO 12135, making it possible to determine fracture toughness near the onset of physical crack initiation.

NOTE Loading the first specimen to a point just beyond maximum force will help to determine the energy levels needed to position the points in subsequent tests. The choice of a test temperature sufficiently far above the transition from cleavage to ductile fracture will avoid brittle fracture and thus the loss of some specimens.

D.2 Low-blow test

D.2.1 This test procedure is intended to limit the available impact energy W_0 of a pendulum hammer or a drop weight such that it is sufficient to produce a certain stable crack extension, but not sufficient to fully break the specimen. By selecting different energy levels $W_{0,i}$ in a series of tests on nominally identical specimens, a series of different crack extensions Δa_i are obtained. From the corresponding J_d values, J_d-Δa resistance curves are constructed.

NOTE Stop blocks can also be used to limit specimen deflection and avoid complete specimen fracture.

D.2.2 The following procedure shall be applied.

a) Precrack 7 to 10 specimens to nominally the same initial crack length a_0.

b) Perform a full blow instrumented impact test on one of the specimens. Evaluate the energy at maximum force and the total fracture energy, W_m and W_t, in accordance with ISO 14556.

c) Determine the energy spacing as $\Delta W_0 = 2W_m/N$, where N is the number of available specimens.

d) Perform an impact test by setting the release position of the pendulum hammer, or the height of the drop weight, such that $W_0 = 2W_m/N$. Avoid a second impact of the hammer.

e) Repeat the test on the remaining specimens, increasing the available fracture energy W_0 by the amount $\Delta W_0 = 2W_m/N$ at each test.

f) In order to mark the crack extension, fatigue cycling or heat tinting may be used.

g) Break the specimens open after testing. Care is to be taken to minimize post-test specimen deformation. Cooling metallic materials which exhibit a ductile-to-brittle transition may help to ensure brittle behaviour during specimen opening.

h) For each test, determine the final test force F_i and the corresponding absorbed energy W_i; measure a_0 and $\Delta a = \Delta a_i$ (where “i” is the test index, with $1 \leq i \leq N-1$) in accordance with 7.6.

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i) Calculate J_i using Formulae (H.1) to (H.8) with F_i, W_i, a_i, and Δa_i replacing F_s, U_{tot}, a, and Δa_s, respectively.

j) Plot the resulting N–1 pairs of values (J_i, Δa_i) in a J_d-Δa diagram and determine the J-R curve according to ISO 12135 and $J_{0,2Bd}$ according to Annex F.

k) Qualify the J_d-R curve and $J_{0,2Bd}$ according to the validity criteria of Annex G.

l) Report test results in accordance with Clause 9.

NOTE The differences in terms of impact velocity and loading rate between the various tests are small enough to have a negligible influence on the results and can be ignored.

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Annex E
(normative)

Estimation of J_d-Δa R-curves using the normalization method

E.1 The normalization method (NM), which is documented in Reference [20] is derived from the basic key-curve method. The procedure described below is adopted mainly from Reference [21].

E.2 The first step for the J_d-Δa R-curve determination is the measurement of initial and final crack lengths according to 7.6. Subsequently, each $F_{(i)}$ load value up to, but not including F_m, is normalized using Formula (E.1):

$$F_{N(i)} = \frac{F_{(i)}}{WB_e \left[\frac{W - a_{b(i)}}{W}\right]^{\eta}} \tag{E.1}$$

The value of η for a three-point bend specimen is 1,9. The effective thickness B_e is defined as

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

while $a_{b(i)}$ is the blunting corrected crack length, calculated as follows:

$$a_{b(i)} = a_0 + \frac{J_{d(i)}}{2R_{fd}} \tag{E.3}$$

$$J_{d(i)} = \frac{K_{d(i)}^2\left(1 - \nu^2\right)}{E} + J_{d,pl(i)} \tag{E.4}$$

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$$J_{\mathrm{d,pl(i)}} = J_{\mathrm{d,pl(i-1)}} + \left[\frac{2\left(W_{\mathrm{pl(i)}} - W_{\mathrm{pl(i-1)}}\right)}{\left(W - a_{\mathrm{(i-1)}}\right)B_{\mathrm{N}}}\right]\left[1 - \frac{a_{\mathrm{(i)}} - a_{\mathrm{(i-1)}}}{W - a_{\mathrm{(i-1)}}}\right] \quad \text{(E.5)}$$

R_{fd} is the dynamic flow stress, i.e. the average between dynamic yield strength [measured or given by Formula (G.2) or Formula (G.3)] and dynamic ultimate tensile strength (measured). $K_{\mathrm{d(i)}}$ is obtained from:

$$K_{\mathrm{d(i)}} = \frac{F_{\mathrm{i}}S}{\sqrt{BB_{\mathrm{N}}}W^{1,5}} f\left(\frac{a_{\mathrm{b(i)}}}{W}\right) \quad \text{(E.6)}$$

with:

$$f\left(\frac{a_{\mathrm{b(i)}}}{W}\right) = \frac{3\sqrt{\frac{a_{\mathrm{b(i)}}}{W}}}{2\left(1+2\frac{a_{\mathrm{b(i)}}}{W}\right)\left(1-\frac{a_{\mathrm{b(i)}}}{W}\right)^{1,5}}\left\{1,99 - \frac{a_{\mathrm{b(i)}}}{W}\left(1-\frac{a_{\mathrm{b(i)}}}{W}\right)\left[2,15 - 3,93\frac{a_{\mathrm{b(i)}}}{W} + 2,7\left(\frac{a_{\mathrm{b(i)}}}{W}\right)^2\right]\right\} \quad \text{(E.7)}$$

The normalized plastic displacement for each point is calculated from the specimen displacement $s_{\mathrm{(i)}}$ as follows:

$$s'_{\mathrm{pl(i)}} = \frac{s'_{\mathrm{pl(i)}}}{W} = \frac{s_{\mathrm{(i)}} - F_{\mathrm{(i)}}C_{\mathrm{(i)}}}{W} \quad \text{(E.8)}$$

where $C_{\mathrm{(i)}}$ is the elastic load-line compliance of the specimen based on the crack length $a_{\mathrm{b(i)}}$ and is given by:

$$C_{\mathrm{(i)}} = \frac{1}{EB_{\mathrm{e}}}\left(\frac{S}{W - a_{\mathrm{b(i)}}}\right)^2\left[1,193 - 1,98\left(\frac{a_{\mathrm{b(i)}}}{W}\right) + 4,478\left(\frac{a_{\mathrm{b(i)}}}{W}\right)^2 - 4,443\left(\frac{a_{\mathrm{b(i)}}}{W}\right)^3 + 1,739\left(\frac{a_{\mathrm{b(i)}}}{W}\right)^4\right] \quad \text{(E.9)}$$

E.3 In this manner, data points up to, but not including, the maximum force F_{m} are normalized. In order to obtain the final point, the same formulae are employed, but instead of the initial crack length, the final crack length is used. Normalized plastic displacement values above 0,001 up to maximum force, excluding the F_{m} value itself, and the point corresponding to the final crack length, shall be used for the normalization function fit. The normalization function may be analytically expressed in the form:

$$F_{\mathrm{N}} = \frac{C_1 + C_2 s'_{\mathrm{pl}} + C_3 s'^2_{\mathrm{pl}}}{C_4 + s'_{\mathrm{pl}}} \quad \text{(E.10)}$$

where C_1, C_2, C_3, and C_4 are fitting coefficients. After the fitting parameters are determined, an iterative procedure is further applied to force all $F_{\mathrm{N(i)}}$ data to lie on the fitted curve by adjusting the $a_{\mathrm{(i)}}$ values. After the crack lengths are determined, the J_{d}-Δa R-curve and the critical J-integral value, $J_{0,2\mathrm{Bd}}$, can be evaluated.

E.4 When the normalization method is applied, the following requirements, in addition to those of G.3, shall be satisfied: evenly distributed data points shall be within the fitting range, a minimum of 10 data points shall be available, all fitted points shall be within 1 % deviation from measured data, and the maximum permissible crack extension evaluated with the use of this procedure is 15 % of the initial uncracked ligament. Should any of these requirements not be fulfilled, the test cannot be analysed according to this International Standard.

E.5 In order to confirm the applicability of the normalization method for the material investigated, at least one additional specimen shall be tested. Using the previously obtained J_{d}-Δa R-curve, deflection of the specimen corresponding to 0,5 mm crack extension shall be determined. The additional specimen shall be loaded under identical conditions as previous specimens up to the calculated value of deflection and the crack extension optically measured shall be 0,5 mm ± 0,25 mm

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E.6 Report the results in accordance with Clause 9.

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Annex F
(normative)

Determination of characteristic fracture toughness value $J_{0,2Bd}$

F.1 General

From J_d-Δa R-curves determined according to Annex D or E, characteristic fracture toughness values can be determined in accordance with ISO 12135. In particular, $J_{0,2Bd}$ shall be obtained at the intersection of the J_d-Δa R-curve with the 0,2 mm-offset construction line, following the data points spacing requirements and the curve fitting procedure of ISO 12135. The 0,2 mm-offset construction line shall be adjusted to account for dynamic loading, as specified below.

The calculated value of $J_{0,2Bd}$ must fulfil the validity requirements specified in Annex G in order to qualify.

NOTE 1 $J_{0,2Bd}$ is regarded as an engineering estimate of the onset of stable crack extension. The use of $J_{0,2Bd}$ in safety assessments may result in non-conservative results. Nevertheless, $J_{0,2Bd}$ values can be used for research and development of materials, in quality control and service evaluation, and to establish the variation of properties with test temperature.

NOTE 2 In ISO 12135, the point of physical crack initiation at the end of crack tip blunting for a quasistatic test is denoted by J_i, the crack initiation toughness. J_i is regarded as a material property, insensitive to size and geometry of the test piece. The determination of J_i requires the use of a scanning electron microscope to measure the stretch zone width on the fracture surface. Dynamically tested specimens often exhibit a relatively rough fracture surface, where the stretch zone may be undistinguishable from other features or even become invisible. This International Standard does not include a procedure to determine a dynamic value of J_i, corresponding to the quasistatic value of ISO 12135.

F.2 Dynamic construction line for $J_{0,2Bd}$ evaluation

Adapting the definition of the construction line of ISO 12135 to dynamic testing gives:

$$J_d\left(\Delta a\right)=3{,}75\times R_{md}\times\Delta a \qquad \text{(F.1)}$$

where R_{md} is the dynamic ultimate tensile strength of the material, measured from dynamic tensile tests performed in accordance with ISO 26203-2.

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Annex G
(normative)

Validity criteria

G.1 General

Fracture toughness values determined according to this International Standard are considered to be valid if 0,30 $W \leq a_0 \leq$ 0,70 W and the following criteria are met.

G.2 Qualification of J_{cd} and J_{ud}

$$J_{cd}, J_{ud} \leq \frac{R_{fd}\left(W-a_0\right)}{100} \tag{G.1}$$

where R_{fd} denotes the dynamic flow stress at the test strain rate and temperature, i.e. the dynamic equivalent of the static flow stress used in ISO 12135. R_{fd} is obtained by averaging the values of the dynamic yield and ultimate tensile strengths, R_{pd} and R_{md}, respectively. If experimentally measured values of R_{pd} and R_{md} are not available, R_{pd} can be estimated using Formulae (G.3) and (G.3):[22]

$$R_{pd} = \frac{0{,}729 \times F_{gy} \times S}{\left(W-a_0\right)^2 B_N} \quad \text{for a 2 mm radius striker} \tag{G.2}$$

or

$$R_{pd} = \frac{0{,}683 \times F_{gy} \times S}{\left(W-a_0\right)^2 B_N} \quad \text{for a 8 mm radius striker.} \tag{G.3}$$

while R_{md} shall be experimentally measured by performing dynamic tensile tests.

NOTE J_{cd} and J_{ud} are size-sensitive parameters and as such characterize only the specimen thickness tested.

G.3 Qualification of J_d-Δa resistance curves

G.3.1 $J_{d,max}$ is calculated for each specimen tested as the smallest of:

$$J_{d,max} = a_0 \frac{R_{pd}+R_{md}}{20} \tag{G.4}$$

$$J_{d,max} = B \frac{R_{pd}+R_{md}}{20} \tag{G.5}$$

$$J_{d,max} = \left(W-a_0\right) \frac{R_{pd}+R_{md}}{20} \tag{G.6}$$

G.3.2 Δa_{max} is calculated for each specimen tested as:

$$\Delta a_{max} = 0{,}25\left(W-a_0\right) \tag{G.7}$$

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G.3.3 The value of J-integral at the intersection of the best-fit curve with either $J_{d,max}$ or Δa_{max} defines J_g, the upper limit to J-controlled crack extension behaviour.

G.3.4 A minimum of six data points shall be used to define the R-curve in the J_d-Δa space defined by the following exclusion lines:

— $J_d = J_g$;

— minimum crack-extension exclusion line, drawn parallel to the construction line [Formula (F.1)] at an offset equal to 0,10 mm;

— maximum crack-extension exclusion line, drawn parallel to the construction line [Formula (F.1)] at an offset equal to Δa_{max} [Formula (G.7)].

G.3.5 The limit of applicability of the J_d-R curve is set by J_g as defined in G.3.3.

G.4 Qualification of $J_{0,2Bd}$

G.4.1 $J_{0,2Bd}$ does not qualify if it exceeds $J_{d,max}$.

G.4.2 $J_{0,2Bd}$ does not qualify if the slope of the J_d-Δa curve at its intersection with the 0,2 mm construction line, $(\mathrm{d}J_d/da)_{0,2Bd}$, fails to meet the following criterion:

$$3{,}75 \times R_{md} > 2\left(\frac{\mathrm{d}J_d}{da}\right)_{0,2Bd} \quad \text{(G.8)}$$

G.4.3 If $J_{0,2Bd}$ qualifies, it is considered size insensitive. If it doesn't, the value shall be reported as size-sensitive $J_{0,2Bd(10)}$, where 10 mm is the nominal thickness of a precracked Charpy specimen.

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Annex H
(normative)

Determination of fracture toughness in terms of *J*-integral

H.1 If $0{,}30 \le a_0/W < 0{,}45$, the value of the dynamic *J*-integral, J_d, at a point on the force/displacement test record corresponding to an applied force F_s, a displacement s and a crack length a_0, is calculated as:

$$J_\mathrm{d} = \left(\frac{F_\mathrm{s} S}{\sqrt{B B_\mathrm{N}} W^{1{,}5}} f\left(\frac{a_0}{W}\right) \right)^2 \left(\frac{1-\nu^2}{E} \right) + \frac{2 W_\mathrm{p}}{B_\mathrm{N}(W-a_0)} \tag{H.1}$$

where

$$f\left(\frac{a_0}{W}\right) = \frac{3\sqrt{\frac{a_0}{W}}}{2\left(1+2\frac{a_0}{W}\right)\left(1-\frac{a_0}{W}\right)^{1{,}5}} \left\{ 1{,}99 - \frac{a_0}{W}\left(1-\frac{a_0}{W}\right)\left[2{,}15 - 3{,}93\frac{a_0}{W} + 2{,}7\left(\frac{a_0}{W}\right)^2\right] \right\} \tag{H.2}$$

and W_p, the plastic component of the area under the force-displacement test record, is given by:

$$W_\mathrm{p} = W_\mathrm{s} - \frac{C_0 F_\mathrm{s}^2}{2} \tag{H.3}$$

In Formula (H.3), W_s is the total area under the force-displacement test record up to displacement s, and C_0, the specimen elastic compliance, is calculated as:

$$C_0 = C_\mathrm{S} + C_\mathrm{M} \tag{H.4}$$

where C_S, the specimen theoretical compliance, is given by:

$$C_\mathrm{S} = \frac{1}{E B_\mathrm{e}} \left(\frac{S}{W-a_0} \right)^2 \left[1{,}193 - 1{,}98\left(\frac{a_0}{W}\right) + 4{,}478\left(\frac{a_0}{W}\right)^2 - 4{,}443\left(\frac{a_0}{W}\right)^3 + 1{,}739\left(\frac{a_0}{W}\right)^4 \right] \tag{H.5}$$

and C_M, the machine compliance, can be determined by performing an elastic low-blow test on an unnotched Charpy-size test bar, and using:[4]

$$C_\mathrm{M} = \frac{2\overline{W}}{\left(\overline{F_\mathrm{m}}\right)^2} - C_\mathrm{Scal} \tag{H.6}$$

with $\overline{W}$ = energy applied during the low-blow test, $\overline{F_m}$ = maximum force recorded, and C_{Scal} is, from standard beam theory:

$$C_\mathrm{Scal} = \frac{S}{4\times 10^9 EBW} \left[\frac{S^2}{W^2} + 2(1+\nu) \right] \tag{H.7}$$

In Formulae (H.6) and (H.7), C_M and C_{Scal} are in m/N, $\overline{W}$ in J, $\overline{F_m}$ in N, E in GPa, S, B, and W in m.

H.2 If stable crack extension from a_0 to $a = a_0 + \Delta a_s$ occurred during the loading up to s and $0{,}45 \le a_0/W \le 0{,}70$, Formula (H.1) shall be replaced by:

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$$J_{\mathrm{d}}=\left(\frac{F_{\mathrm{s}}S}{\sqrt{BB_{\mathrm{N}}}W^{1,5}}f\left(\frac{a_0}{W}\right)\right)^2\left(\frac{1-\nu^2}{E}\right)+\left[\frac{2W_{\mathrm{p}}}{B_{\mathrm{N}}\left(W-a_0\right)}\right]\left[1-\frac{\Delta a_{\mathrm{s}}}{2\left(W-a_0\right)}\right] \tag{H.8}$$

NOTE 1 For plain-sided specimens, $B_{\mathrm{N}} = B$.

NOTE 2 If $0{,}30 \leq a_0/W < 0{,}45$, J_{d} shall always be calculated using Formula (H.1).

H.3 Values of J_{cd} or $J_{0,2\mathrm{Bd}}$ calculated using Formula (H.1) or Formula (H.8) can be converted to values of stress intensity factor K_{Jcd} or $K_{\mathrm{J}0,2\mathrm{Bd}}$ using:

$$K_{\mathrm{Jd}}=\sqrt{\frac{EJ_{\mathrm{d}}}{1-\nu^2}} \tag{H.9}$$

Furthermore, values of dJ_{d}/dt calculated using Formula (5) can be converted to values of dK_{Jd}/dt using:

$$\frac{dK_{\mathrm{Jd}}}{\mathrm{d}t}=\sqrt{\frac{EJ_{\mathrm{d}}}{2\left(1-\nu^2\right)}\cdot\frac{d^2J}{\mathrm{d}t^2}} \tag{H.10}$$

K_{Jcd} and dK_{Jd}/dt values can be used to calculate the master curve reference temperature in accordance with Reference [2] provided all relevant requirements are met.

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Annex I
(informative)

Example test reports

NOTE It is the content and not the format of the test report that is important.

I.1 Specimen, material, and test environment

Specimen identifier:	**Operator:**	**Date:**

Specimen

Identification number

Orientation

Location within product

Material

Material designation

Material form/condition

Specimen dimensions

B	=	(mm)
B_N	=	(mm)
W	=	(mm)
a_0/W (nominal)	=	

Tensile properties – fatigue precracking temperature

Temperature	=	(°C)
	Referenced (R)	Measured (M)
E (Young's modulus)	=	(GPa)
ν (Poisson's ratio)	=	
$R_{p0,2}$ (quasistatic yield strength)	=	(MPa)
R_m (quasistatic tensile strength)	=	(MPa)

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Tensile properties – test temperature

Temperature	=	(°C)
	Referenced (R)	Measured (M)
E (Young's modulus)	=	(GPa)
ν (Poisson's ratio)	=	
R_p (quasistatic yield strength)	=	(MPa)
R_m (quasistatic tensile strength)	=	(MPa)
R_p (dynamic yield strength)	=	(MPa)
R_m (dynamic tensile strength)	=	(MPa)

Precracking

Fatigue temperature	=	(°C)
Final K_f	=	(MPa√m)
Final F_f	=	(kN)
Final K_f/E	=	(√m)

Test information

Striker impact velocity		(m/s)
Available potential energy		(J)
Test temperature		(°C)

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I.2 Data qualification

Measured crack length information Specimen identifier ______________________________

Table I.1 — Crack measurement table

Point	**Position** mm	**Precrack length** mm	Δa mm
1			
2			
3			
4			
5			
6			
7			
8			
9			

a_0 Average initial crack length (mm)

$a_0 - a_m$ Average fatigue precrack length (mm)

Δa Average crack extension (mm)

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

Fracture surface appearance

Record occurrence of cleavage (yes/no)

Record any unusual features on the fracture surface below:

Table I.2 — Resistance curve data

Specimen identifier:			Date:		
R-curve method:					
Test record information:			Operator:		
Data point	F kN	s mm	a_0 mm	Δa mm	J_d MJm^{-2}

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I.3 Qualification of J_d-R curve

a_0	(mm)
B	(mm)
$W - a_0$	(mm)
Coefficients of power law fit to data $J_d = \alpha + \beta \Delta a^\gamma$	α =
	β =
	γ =
$J_{d,max}$	(kJ/m^2)
Δa_{max}	(mm)
J_g	(kJ/m^2)

Requirements (see Annex G):

a) The data shall be qualified in accordance with G.3;

b) The limit of applicability of the J_d-R curve is set by J_g.

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

I.4 Qualification of $J_{0,2Bd}$

R_{md}	(MPa)
$(dJ_d/da)_{0,2Bd}$	(MPa)
$J_{d,max}$	(kJ/m^2)
Number of data points used:	
Coefficients of power law fit to data $J_d = \alpha + \beta \Delta a^\gamma$	α =
	β =
	γ =

Requirements (see Annex G):

a) The data shall be qualified in accordance with G.4;

b) The slope of the power law regression line, dJ_d/da, evaluated at the 0,2 mm-offset construction line; shall be less than 1,875 R_{md};

c) $J_{0,2Bd} \leq J_{d,max}$.

If all requirements are met:	$J_{0,2Bd}$ =	(MJ/m^2).
If all requirements are not met:	$J_{0,2Bd(10)}$ =	(MJ/m^2).

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ICS 77.040.10

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