# INTERNATIONAL STANDARD

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# 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*



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ISO copyright office
Ch. de Blandonnet 8 • CP 401
CH-1214 Vernier, Geneva, Switzerland
Tel. +41 22 749 01 11
Fax +41 22 749 09 47
copyright@iso.org
www.iso.org

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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)*.



 

## 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).

# 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.

**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 ($a_0$ + $\Delta a$) | mm |
| $a_m$ | Length of machined notch | mm |
| $a_0$ | Initial crack length | mm |
| $\Delta a$ | Crack extension ($a - a_0$) | mm |
| $\Delta a_{max}$ | Crack extension limit for $J$-controlled crack extension | mm |
| $\Delta a_s$ | 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 |
| $d\varepsilon/dt$ | 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) | $MJ/m^2$ |
| $dJ_d/dt$ | 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 | $MPa\ m^{0,5}$ |
| $dK_d/dt$ | 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 | — |

**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 |
| $t_0$ | Time at striker impact | s |
| $\tau$ | 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 |
| $W_0$ | Available impact energy | J |
| $\nu$ | 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.

**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, d$K_d$/d$t$, d$J_d$/d$t$) |
| Elastic-plastic, unstable fracture with $\Delta a$ < 0,2 mm | II | — | $J_{cd}$, $K_{Jcd}$ ($B$,d$J_d$/d$t$) |
| Elastic-plastic, unstable fracture with 0,2 mm ≤ $\Delta a$ ≤ 0,15 ($W - a_0$) | II | — | $J_{ud}$ ($B$,$\Delta a$,d$J_d$/d$t$) |
| Elastic-plastic, unstable fracture with $\Delta a$ > 0,15 ($W - a_0$) | III | $J_d$-$\Delta a$ | $J_{0,2Bd}$ (d$J_d$/d$t$) |
| Elastic-plastic; no unstable fracture | IV | $J_d$-$\Delta a$ | $J_{0,2Bd}$ (d$J_d$/d$t$) |

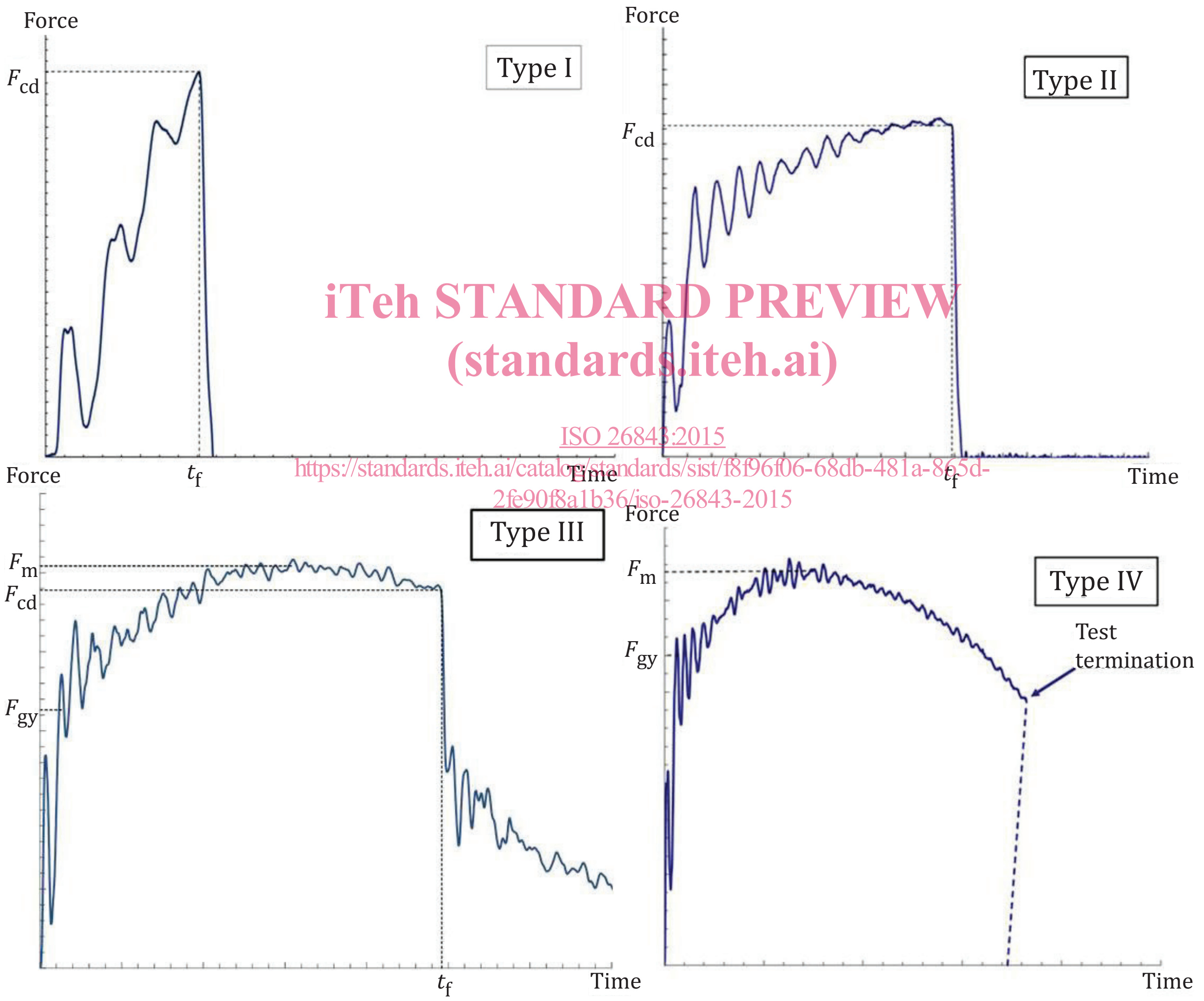




**Figure 1 — Typical force-time diagrams (schematic)**

 

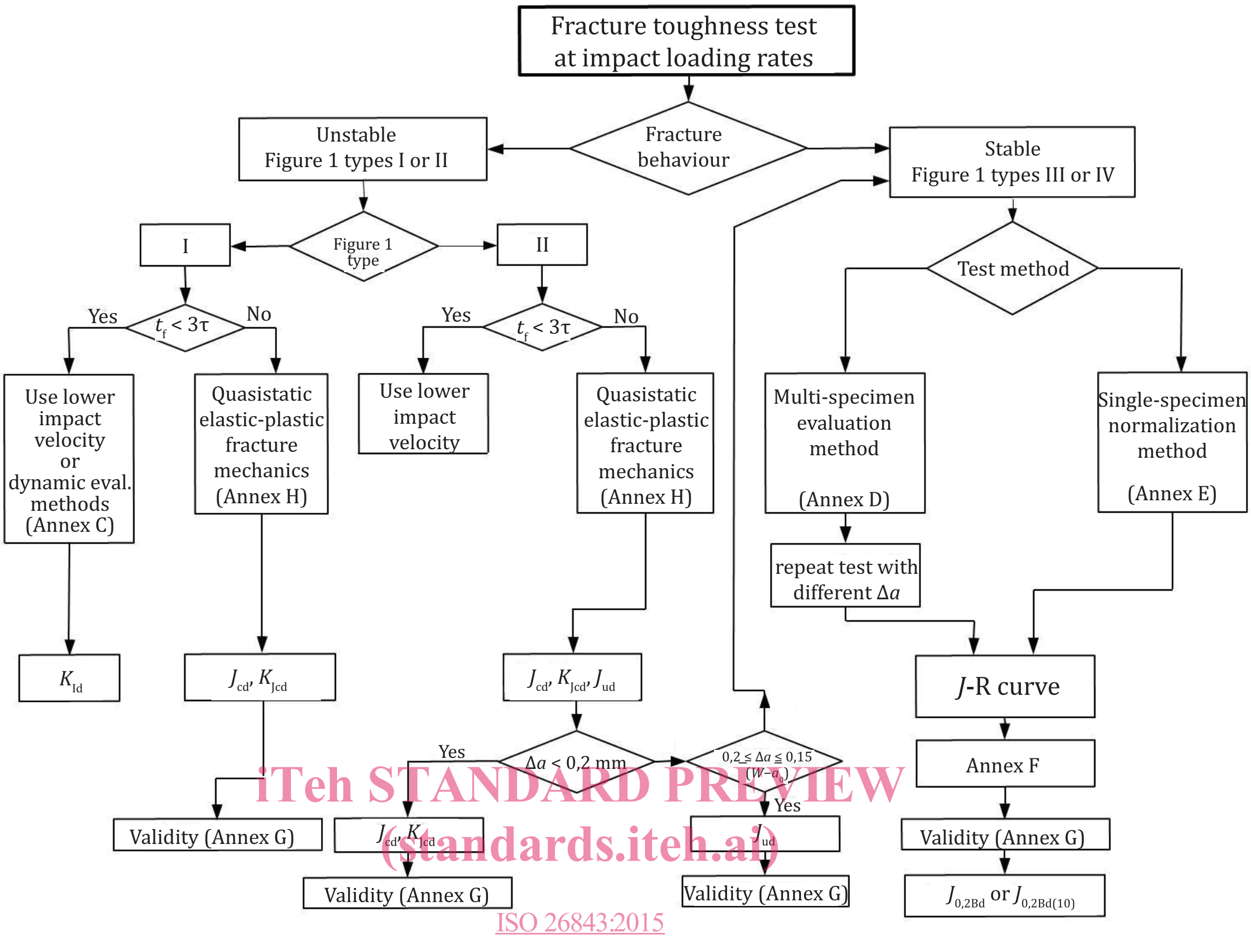




**Figure 2 — Flowchart for the application of the test method**

## 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:

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

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 $\xi = 1{,}6 \times 10^{-4}\ \mathrm{m}^{1/2}$ 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 $J_d$-$\Delta a$ 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.

 

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 $3\tau$, with $\tau$ 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 $\Delta a$ 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.

 