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Metallic materials — Measurement of fracture toughness of steels at impact loading rates using precracked Charpy specimens

Matériaux métalliques — Mesure de la ténacité à la rupture d'éprouvettes Charpy préfissurées en acier soumises à des charges dynamiques

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Foreword

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ISO 26843 was prepared by Technical Committee 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 “European Standards on Instrumented Precracked Charpy Testing” Working Party of the European Structural Integrity Society (ESIS) Technical Subcommittee on Dynamic Testing at Intermediate Strain Rates (TC 5).

Metallic materials — Measurement of fracture toughness of steels at impact loading rates using precracked Charpy specimens

1 Scope

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

This International Standard can be applied to other metallic materials by agreement. Dynamic fracture mechanics properties determined using this International Standard are comparable to 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 service evaluation 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 can 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. Additional information on the dependence of fracture toughness on loading (or strain) rate is given in Anderson [1]. In addition, it is generally acknowledged that fracture toughness also depends on test temperature. For these reasons, the user reports the actual test temperature and loading rate for each test performed.

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

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*

3 Symbols and definitions

For the purposes of this document, the symbols given in Table 1 apply.

Table 1 — Symbols used in this International Standard

Symbol	Definition	Unit
a	crack length	mm
a_o	initial crack length	mm
Δa	crack extension [$a - a_o$]	mm
Δa_s	crack extension corresponding to displacement s	mm
a_n	length of machined notch	mm
a_f	fatigue crack length	mm
B	specimen thickness	mm
B_e	specimen effective thickness as defined in Equation (E.7)	mm
B_N	specimen net thickness after side-grooving	mm
C_m	compliance of the test machine	m/N
δ	crack-tip opening displacement (CTOD)	mm
$\delta_{0,2Bd}$	dynamic equivalent of $\delta_{0,2BL}$ in ISO 12135	mm
$d\delta/dt$	rate of crack-tip opening displacement	$mm\ s^{-1}$
E	Young's modulus of elasticity	GPa
$d\varepsilon/dt$	strain rate	s^{-1}
f_g	output frequency limit	Hz
F	force	N
F_{cd}	applied force at onset of unstable crack extension in Figure 1 – Type I	N
F_f	maximum fatigue precracking force during the final precracking stage	N
F_{gy}	applied force at onset of yielding as defined in ISO 14556	N
F_m	maximum applied force as defined in ISO 14556	N
J	experimental equivalent of the J-integral	MJ/m^2
J_{cd}	dynamic equivalent of J_c in ISO 12135	MJ/m^2
J_{ud}	dynamic equivalent of J_u in ISO 12135	MJ/m^2
$J_{0,2Bd}$	dynamic equivalent of $J_{0,2BL}$ in ISO 12135	MJ/m^2
dJ/dt	rate of change of J-integral	$MJ/m^2\ s^{-1}$
K_I^{dyn}	dynamic stress intensity factor	$MPa\ m^{0,5}$
K_{Id}	dynamic plane strain fracture toughness	$MPa\ m^{0,5}$
dK/dt	rate of change of stress intensity factor	$MPa\ m^{0,5}\ s^{-1}$
KV	absorbed energy as defined in ISO 148-2	J
M	total mass of moving striker	kg
n	strain hardening exponent of the Ramberg-Osgood material law	—
N	number of available test specimens	—
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	displacement (calculated in accordance with ISO 14556)	mm
s_{pl}	plastic component of displacement	mm
S	span between outer loading points	mm

Table 1 (*continued*)

Symbol	Definition	Unit
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 of striker impact	s
τ	period of force oscillation	s
v_o	striker impact velocity	m s^{-1}
W	specimen effective width	mm
W_m	energy at maximum force defined in ISO 14556	J
W_s	actual total fracture energy (area under the force-displacement diagram up to displacement s)	J
W_{sp}	non-recoverable fracture energy corresponding to force F_s and displacement s	J
W_t	calculated energy from area under complete force-displacement curve to $F = 0{,}02\ F_m$ as defined in ISO 14556	J
W_o	available impact energy	J
z	initial distance of the notch opening gauge measurement position from the notched edge of the specimen [see ISO 12135:2002, Figure 8b)]	mm
ν	Poisson's ratio	—

4 Principle

This International Standard prescribes impact bend tests which may be performed on fatigue precracked Charpy notch specimens to obtain dynamic fracture mechanics properties of materials. This International Standard extends the procedure for V-notch impact bend tests in accordance with ISO 148, and may be used for evaluation of the Master Curve in accordance with ASTM E 1921[2]. 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 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
Essentially linear-elastic	I	—	K_{Id} ($\mathrm{d}K_I/\mathrm{d}t$)
Elastic-plastic, unstable fracture without significant stable crack extension ($\Delta a < 0{,}2$ mm)	II	—	J_{cd} (B,$\mathrm{d}J/\mathrm{d}t$)
Elastic-plastic, unstable fracture after significant stable crack extension [$0{,}2\ \mathrm{mm} \leqslant \Delta a \leqslant 0{,}15\ (W-a_o)$]	II	—	J_{ud} (B,Δa,$\mathrm{d}J/\mathrm{d}t$)
Elastic-plastic, unstable fracture after substantial stable crack extension [$\Delta a > 0{,}15\ (W-a_o)$]	III	J_d–Δa δ_d–Δa	$J_{0,2Bd}$ ($\mathrm{d}J/\mathrm{d}t$) $\delta_{0,2Bd}$ ($\mathrm{d}\delta/\mathrm{d}t$)
Elastic-plastic; no unstable fracture	IV	J_d–Δa δ_d–Δa	$J_{0,2Bd}$ ($\mathrm{d}J/\mathrm{d}t$) $\delta_{0,2Bd}$ ($\mathrm{d}\delta/\mathrm{d}t$)

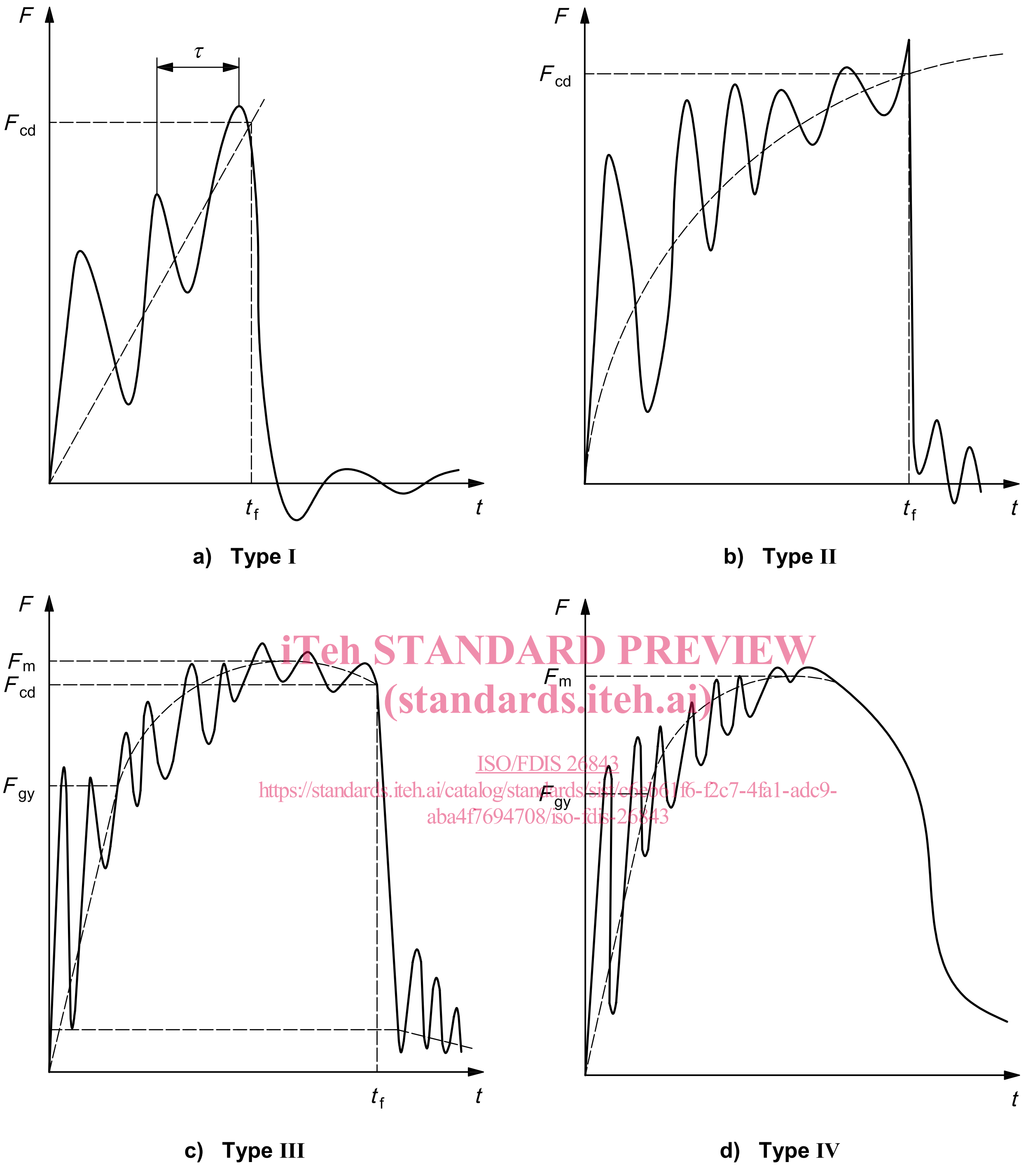

Figure 1 — Typical force-time diagrams — Schematic

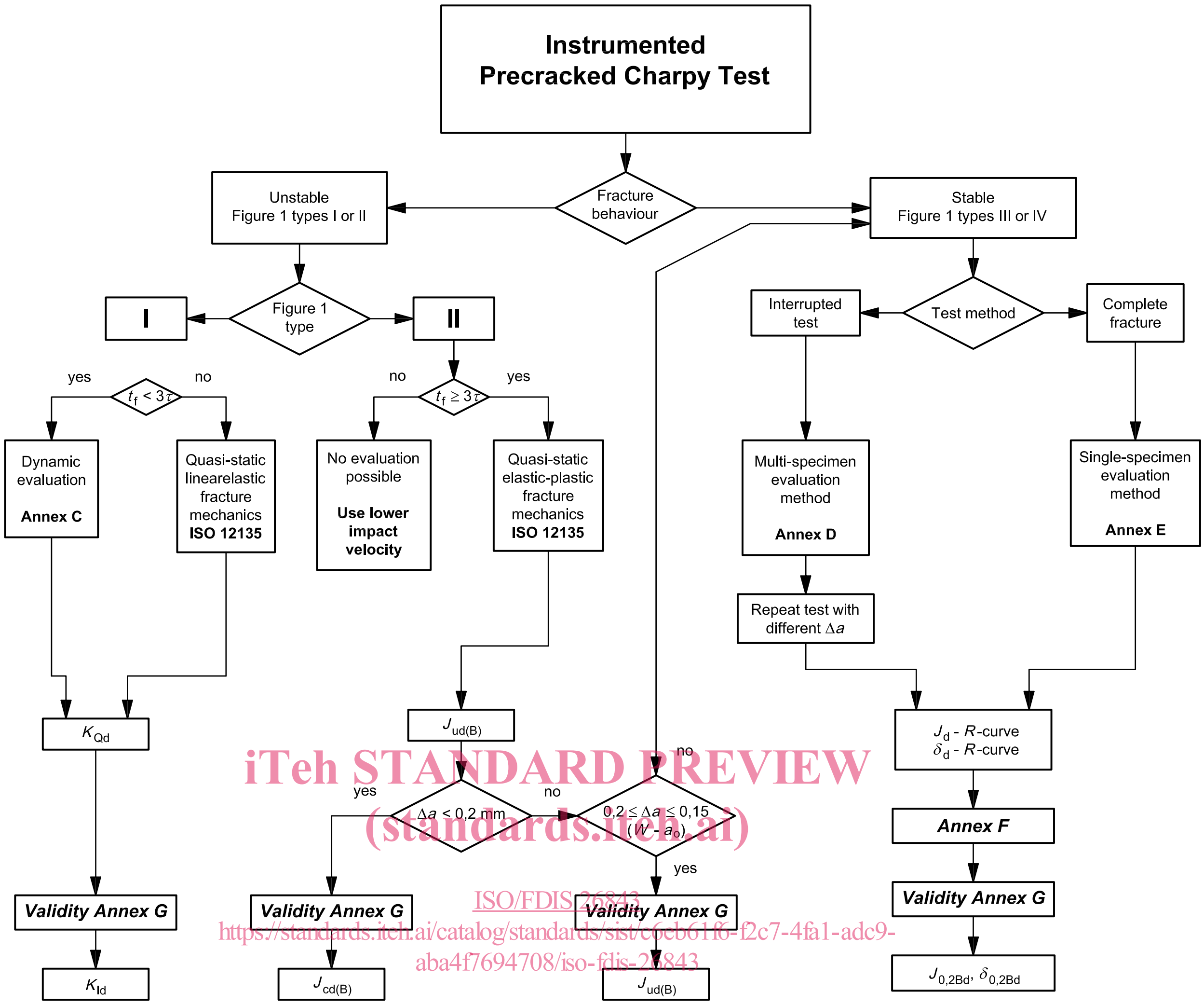

Figure 2 — Flow chart for selection of the test method

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. By agreement, alternative specimen dimensions may be used.

5.2 To initiate fatigue precracking, machine or spark erode a slot into the specimen to a depth of at least 1,0 mm less than the desired initial crack length, a_o. For specimens with an existing V-notch, fatigue precracking may initiate at the bottom of the notch.

5.3 During the final 1,3 mm or 50 % of precrack extension, whichever is less, the maximum fatigue precracking force shall be the lower of the value found using either Equation (1) or (2):

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

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

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

The ratio of minimum to maximum fatigue pre-cracking 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, $B_N = B$.

5.4 When fatigue precracking is performed at temperature T_1 and testing is done at temperature T_2, F_f in Equation (2) shall be factored by the ratio R_p [T_1]/R_p [T_2], where R_p [T_1] is the yield strength at temperature T_1 and R_p is the yield strength at temperature T_2. In addition, F_f determined from Equation (1) shall be evaluated using the lowest value between R_p [T_1] and R_p [T_2].

NOTE Experience has shown for a wide variety of steels that a fatigue precrack can be initiated in a Charpy specimen with an initial mean force of 2 kN and a range of ±1 kN at a/W of 0,3 which are both progressively reduced by equal amounts to a level of 0,7 kN over the final 0,5 mm of crack extension. Small 10 % progressive reductions in the force levels as crack extension progresses are made in order to avoid retardation effects during crack extension.

5.5 Specimens are fatigue precracked in three-point or pure bending to produce an initial crack length, a_o, normally in the range of $0{,}3 < a_o/W < 0{,}55$.

If the results in terms of J or δ are to be directly comparable to full-size standard fracture toughness values such as $J_{0,2BL}$ or $\delta_{0,2BL}$ (as defined in ISO 12135), a_o/W shall be in the range $0{,}45 < a_o/W < 0{,}55$. Otherwise, shorter crack lengths may be more advantageous.

NOTE An impact response curve for $0{,}28 < a_o/W < 0{,}32$ can be established[3][5].

5.6 Specimens may be side grooved 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-Δa R-curve tests. For details of crack length measurement, see 7.7.

6 Testing machines

6.1 The tests may be carried out using testing machines of the general types specified in Annex A. Other machines which comply with the calibration and other requirements are not excluded. Not all machines can perform all types of test (see Annex A). 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. until the force returns to the baseline), the difference between KV and W_t shall be within ±15 % of KV or ±1 J, whichever is the greater. If this requirement is not met, but the difference does not exceed ±25 % of KV or ±2 J, whichever is the greater, force values may be adjusted until $KV = W_t$[6]. 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 in this subclause shall be demonstrated by testing at least five non-precracked Charpy specimens of similar absorbed energy level.

7 Test procedures and measurements

7.1 General

Tests are performed in a manner similar to the standard Charpy impact test of ISO 148-1, especially with regard to the pendulum hammer and the handling of pre-cooled or pre-heated specimens.

7.2 Key data

The force-displacement diagram is recorded in accordance with ISO 14556, from which the key data values F_m, F_{cd}, W_m and W_t are determined. Additional to the procedures of ISO 14556 are the procedures for striking velocity, available energy and measurement of crack lengths, which are specified in this clause. These data form the basis for evaluation of toughness parameters according to Annexes C to G.

7.3 Impact velocity

This International Standard applies to any impact velocity, v_o, typically in the range from 1 ms^{-1} to 5,5 ms^{-1}.

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

NOTE 2 The reduced impact velocity, v_o, can be determined:

— releasing the pendulum from the appropriately reduced height, without a specimen on the specimen's supports;

— reading the energy KV_o (in J) indicated by the pointer on the analogue scale;

— from this, the reduced impact velocity is calculated for a 300 J pendulum using Equation (3):

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

If the pendulum capacity is different than 300 J, replace 300 in Equation (3) with the actual pendulum capacity. A reduced velocity (1 m/s to 2 m/s) can be advantageous, especially for brittle materials, since it reduces the effect of oscillations by lowering their relative amplitude and by increasing their number within the fracture time, t_f (see 8.2).

7.4 Time to fracture

When the time, t_f, to initiate unstable fracture is less than 3τ [7][8][9], the instant of crack initiation is not detectable in the force signal with adequate accuracy because of oscillations (see Type I of Figure 1) and an independent measurement of t_f is required as described in Annex C.

7.5 Multiple specimen tests

To determine dynamic R-curves by multi-specimen techniques, the fracture process is interrupted at a certain stable crack extension Δa. This procedure is described in Annex D.

7.6 Single-specimen tests

It is possible to estimate dynamic R-curves by single-specimen techniques, as described in Annex E.