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Metallic materials — Fatigue testing — Fatigue crack growth method

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Foreword

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

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

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For an explanation on the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 164, *Mechanical testing of metals*, Subcommittee SC 4, *Fatigue, fracture and toughness testing*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

This third edition cancels and replaces the second edition (ISO 12108:2012), which has been technically revised. The main changes compared to the previous edition are as follows:

— The document has been reorganized to move the formulae and drawings for each of the test specimens from the main body of the document into a separate normative annex for each specimen.

— Guidance on the effects of residual stress on fatigue crack growth rate data has been expanded.

Introduction

This document is intended to provide specifications for generation of fatigue crack growth rate data. Test results are expressed in terms of the fatigue crack growth rate as a function of crack-tip stress-intensity factor range, ΔK, as defined by the theory of linear elastic fracture mechanics[15][16][17][18][19][20]. Expressed in these terms, the results characterize a material's resistance to subcritical crack extension under cyclic force test conditions. This resistance is independent of specimen planar geometry and thickness, within the limitations specified in Clause 6.

This document describes a method of subjecting a precracked notched specimen to a cyclic force. The crack length, a, is measured as a function of the number of elapsed force cycles, N. From the collected crack length and corresponding force cycles relationship, the fatigue crack growth rate, $\mathrm{d}a/\mathrm{d}N$, is determined and is expressed as a function of stress-intensity factor range, ΔK.

Materials that can be tested by this method are limited by size, thickness and strength only to the extent that the material remains predominantly in an elastic condition during testing and that buckling is precluded.

Specimen size can vary over a wide range. Proportional planar dimensions for six standard configurations are presented. The choice of a particular specimen configuration can be dictated by the actual component geometry, compression test conditions or suitability for a particular test environment.

Specimen size is a variable that is subjective to the test material's 0,2 % proof strength and the maximum stress-intensity factor applied during test. Specimen thickness can vary independently of the planar size, within defined limits, so long as large-scale yielding is precluded and out-of-plane distortion or buckling is not encountered. Any alternate specimen configuration other than those included in this document can be used, provided there exists an established stress-intensity factor calibration expression, i.e. stress-intensity factor geometry function, $g\,(a/W)$[21][22][23].

Residual stresses[24][25], crack closure[26][27], specimen thickness, cyclic waveform, frequency and environment, including temperature, can markedly affect the fatigue crack growth data but are in no way reflected in the computation of ΔK, and so should be recognized in the interpretation of the test results and be included as part of the test report. All other demarcations from this method should be noted as exceptions to this practice in the final report.

For crack growth rates above 10^{-5} mm/cycle, the typical scatter in test results generated in a single laboratory for a given ΔK can be in the order of a factor of two[28]. For crack growth rates below 10^{-5} mm/cycle, the scatter in the $\mathrm{d}a/\mathrm{d}N$ calculation can increase to a factor of 5 or more. To ensure the correct description of the material's $\mathrm{d}a/\mathrm{d}N$ versus ΔK behaviour, a replicate test conducted with the same test parameters is highly recommended.

Service conditions can exist where varying ΔK under conditions of constant K_{max} or K_{mean} control[29] can be more representative than data generated under conditions of constant force ratio; however, these alternate test procedures are beyond the scope of this document.

Metallic materials — Fatigue testing — Fatigue crack growth method

WARNING — This document does not address safety or health concerns, should such issues exist, that can be associated with its use or application. The user of this document has the sole responsibility to establish any appropriate safety and health concerns.

1 Scope

This document describes tests for determining the fatigue crack growth rate from the fatigue crack growth threshold stress-intensity factor range, ΔK_{th}, to the onset of rapid, unstable fracture.

This document is primarily intended for use in evaluating isotropic metallic materials under predominantly linear-elastic stress conditions and with force applied only perpendicular to the crack plane (mode I stress condition), and with a constant force ratio, *R*.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

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

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
crack length
a
crack size
linear measure of a principal planar dimension of a crack from a reference plane to the crack tip

3.2
cycle
smallest segment of a force-time or stress-time function which is repeated periodically

Note 1 to entry: The terms “fatigue cycle”, “force cycle” and “stress cycle” are used interchangeably. The letter *N* is used to represent the number of elapsed cycles.

3.3
fatigue crack growth rate
d*a*/d*N*
extension in crack length

3.4
maximum force
F_{max}
force having the highest algebraic value in the cycle, a tensile force being positive and a compressive force being negative

3.5
minimum force
F_{min}
force having the lowest algebraic value in the cycle, a tensile force being positive and a compressive force being negative

3.6
force range
ΔF
algebraic difference between the maximum and minimum forces in a cycle

$$\Delta F = F_{max} - F_{min}$$

3.7
force ratio
R
stress ratio
algebraic ratio of the minimum force or stress to the maximum force or stress in a cycle

$$R = F_{min}/F_{max}$$

Note 1 to entry: R can also be calculated using the values of stress-intensity factors; $R = K_{min}/K_{max}$.

3.8
stress-intensity factor

K
magnitude of the ideal crack-tip stress field for the opening mode force application to a crack in a homogeneous, linear-elastically stressed body, where the opening mode of a crack corresponds to the force being applied to the body perpendicular to the crack faces only (mode I)

Note 1 to entry: The stress-intensity factor is a function of applied force, crack length, specimen size and geometry.

3.9
maximum stress-intensity factor
K_{max}
highest algebraic value of the stress-intensity factor in a cycle, corresponding to F_{max} and current crack length

3.10
minimum stress-intensity factor
K_{min}
lowest algebraic value of the stress-intensity factor in a cycle, corresponding to F_{min} and current crack length

Note 1 to entry: This definition remains the same, regardless of the minimum force being tensile or compressive. For a negative force ratio ($R < 0$), there is an alternate, commonly used definition for the minimum stress-intensity factor, $K_{min} = 0$. See 3.11.

3.11
stress-intensity factor range
ΔK
algebraic difference between the maximum and minimum stress-intensity factors in a cycle

$$\Delta K = K_{max} - K_{min}$$

Note 1 to entry: The variables ΔK, R and K_{max} are related as follows: $\Delta K = (1 - R)\, K_{max}$.

Note 2 to entry: For $R \leq 0$ conditions, see 3.10 and 10.6.

Note 3 to entry: When comparing data developed under $R \leq 0$ conditions with data developed under $R > 0$ conditions, it can be beneficial to plot the da/dN data versus K_{max}.

3.12
fatigue crack growth threshold stress-intensity factor range
ΔK_{th}
asymptotic value of ΔK for which da/dN approaches zero

Note 1 to entry: For most materials, the threshold is defined as the stress-intensity factor range corresponding to 10^{-7} mm/cycle. When reporting ΔK_{th}, the corresponding lowest decade of da/dN data used in its determination should also be included.

3.13
normalized *K*-gradient
$C = (1/K)\, dK/da$
fractional rate of change of K with increased crack length, a

$$C = 1/K\,(dK/da) = 1/K_{max}\,(dK_{max}/da) = 1/K_{min}\,(dK_{min}/da) = 1/\Delta K\,(d\Delta K/da)$$

3.14
***K*-decreasing test**
test in which the value of the normalized K-gradient, C, is negative

Note 1 to entry: A K-decreasing test is conducted by reducing the stress-intensity factor either by continuously shedding or by a series of steps, as the crack grows.

3.15
***K*-increasing test**
test in which the value of C is positive

Note 1 to entry: For standard specimens, a constant force amplitude results in a K-increasing test where the value of C is positive and increasing.

3.16
stress-intensity factor geometry function
$g\,(a/W)$
mathematical expression, based on experimental, numerical or analytical results, that relates the stress-intensity factor to force and crack length for a specific specimen configuration

3.17
crack-front curvature correction length
a_{cor}
difference between the average through-thickness crack length and the corresponding crack length at the specimen faces during the test

3.18
fatigue crack length
a_{fat}
length of the fatigue crack, as measured from the root of the machined notch

Note 1 to entry: See Figure 2.

3.19
notch length
a_n
length of the machined notch, as measured from the load line to the notch root

Note 1 to entry: See Figure 2.

3.20
specimen width
W
linear measure of a principal planar dimension of a specimen from a reference plane to the specimen edge

4 Symbols and abbreviated terms

4.1 Symbols

See Table 1.

Table 1 — Symbols and their designations

Symbol	Designation	Unit
Loading		
C	Normalized K-gradient	mm^{-1}
E	Tensile modulus of elasticity	MPa
F	Force	kN
F_{max}	Maximum force	kN
F_{min}	Minimum force	kN
ΔF	Force range	kN
K	Stress-intensity factor	$MPa{\cdot}m^{1/2}$
K_{max}	Maximum stress-intensity factor	$MPa{\cdot}m^{1/2}$
K_{min}	Minimum stress-intensity factor	$MPa{\cdot}m^{1/2}$
ΔK	Stress-intensity factor range	$MPa{\cdot}m^{1/2}$
ΔK_i	Initial stress-intensity factor range	$MPa{\cdot}m^{1/2}$
ΔK_{th}	Fatigue crack growth threshold stress-intensity factor range	$MPa{\cdot}m^{1/2}$
N	Number of cycles	cycle
R	Force ratio	kN/kN
R_m	Ultimate tensile strength at the test temperature	MPa
$R_{p0,2}$	0,2 % proof strength at the test temperature	MPa
Geometry		
a	Crack length or size measured from the reference plane to the crack tip	mm
a_{cor}	Crack-front curvature correction length	mm
a_{fat}	Fatigue crack length measured from the notch root	mm
a_n	Machined notch length	mm
a_p	Precrack length	mm
B	Specimen thickness	mm
D	Hole diameter for CT, SENT or CCT specimen, loading tup diameter for bend specimens	mm
$g(a/W)$	Stress-intensity factor geometry function	unitless
h	Notch height	mm
W	Specimen width measured from the reference plane to the specimen edge	mm
$(W - a)$	Uncracked ligament	mm
Crack growth		
da/dN	Fatigue crack growth rate	mm/cycle
Δa	Change in crack length, crack extension	mm

4.2 Abbreviated terms for specimen identification

CT	Compact tension
CCT	Centre cracked tension
SENT	Single edge notch tension
SEN B3	Three-point single edge notch bend
SEN B4	Four-point single edge notch bend
SEN B8	Eight-point single edge notch bend

5 Apparatus

5.1 Testing machine.

5.1.1 The testing machine shall have smooth start-up and a backlash-free force train if passing through zero force (tension – compression). Cycle to cycle variation of the peak force during precracking shall be less than ±5 % and shall be held to within ±2 % of the desired peak force during the test. ΔF shall also be maintained to within ±2 % of the desired range during test. A practical overview of test machines and instrumentation is available[36][37].

5.1.2 If a dynamic force calibration is appropriate or required (e.g. by the purchaser), it should be conducted according to ISO 4965-1. Dynamic force calibration is appropriate when inertial forces act on the force transducer or any dynamic errors occur in the electronics of the force indicating system, as described in ISO 4965-1. Test frequency and amplitude as well as grip mass can affect the inertial forces acting on the force transducer. Examples for which dynamic force calibration can be appropriate are configurations with the load cell on the moving piston or the part.

5.1.3 In terms of testing machine alignment, asymmetry of the crack front is an indication of misalignment. For tension-compression testing, the length of the force train should be as short and stiff as practical. Non-rotating joints should be used to minimize off-axis motion. It is important that adequate attention be given to alignment of the testing machine and during machining and installation of the grips in the testing machine. Regarding the relevance of alignment, a distinction shall be made between:

— Crack growth tests with rigid gripping and rigid load train which can also undergo compressive forces and stresses (e.g. corner crack test pieces): a sufficient alignment of the load train can be important for these test pieces to obtain correct and reproducible crack growth data, and

— Crack growth tests only with tensile load and fixed with bolts and using cardanic joints (e.g. CT-specimens): due to the use of cardanic or similar joints in the load train alignment checks are not necessary.

If an alignment check is appropriate (e.g. when using a rigid load train and grips) and required (e.g. by the purchaser), it should be conducted according to ISO 23788 and using an alignment class 5 according to ISO 23788. If alignment check is conducted, the results shall be reported.

5.1.4 Accuracy of the force measuring system shall be verified periodically in the testing machine. The calibration for the force transducer shall be traceable to a national organization of metrology. The force measuring system shall be designed for tension and compression fatigue testing and possess great axial and lateral rigidity. The indicated force, as recorded as the output from the computer in an automated system or from the final output recording device in a non-computer system, shall be within the permissible variation from the actual force. The force transducer's capacity shall be sufficient to cover the range of force measured during a test. Errors greater than 1 % of the difference between minimum and maximum measured test force are not acceptable.

The force measuring system shall be temperature compensated, not have zero drift greater than 0,002 % of full scale, nor have a sensitivity variation greater than 0,002 % of full scale over a 1 °C change. During elevated and cryogenic temperature testing, suitable thermal shielding/compensation shall be provided to the force measuring system so it is maintained within its compensation range.

5.2 Cycle-counter.

An accurate digital device is required to count elapsed force cycles. A timer is to be used only as a verification check on the accuracy of the counter. It is preferred that individual force cycles be counted. However, when the crack velocity is below 10^{-5} mm/cycle, counting in increments of 10 cycles is acceptable.

5.3 Crack length measurement apparatus.

Accurate measurement of crack length during the test is very important. There are a number of visual and non-visual apparati that can be used to determine the crack length. A brief description of a variety of crack length measurement methods is included in Reference [14]. The required crack length measurements are the average of the through-thickness crack lengths, as covered in 9.1.

6 Specimens

6.1 General

The proportional dimensions, formulae and procedures for the six standard specimen configurations shall be as defined in Annexes A to D:

CT	Compact tension	Annex A
CCT	Centre cracked tension	Annex B
SENT	Single edge notch tension	Annex C
SEN B3	Three-point single edge notch bend	Annex D
SEN B4	Four-point single edge notch bend	Annex D
SEN B8	Eight-point single edge notch bend	Annex D

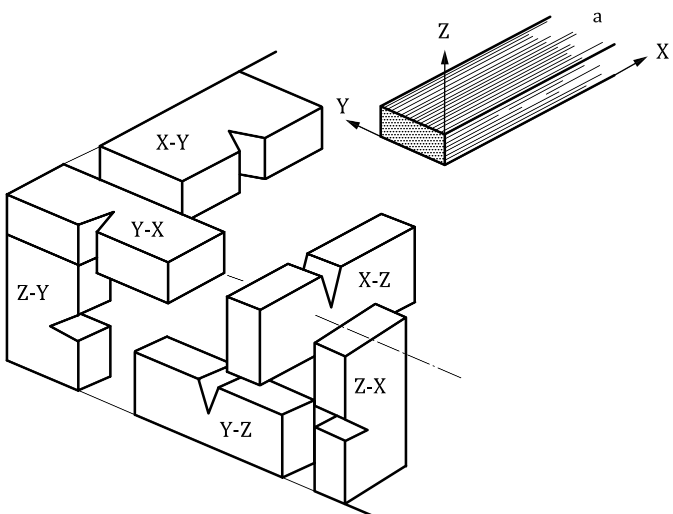
This variety of specimen configurations is presented to accommodate the component geometry available, test environment and force application conditions during a test. Machining tolerances and surface finishes are also given in Figures 7 to 10. The CT, SEN B3 and SEN B4 specimens are recommended for tension-tension test conditions only.

The specimen shall have the same metallurgical structure as the material for which the crack growth rate is being determined. The test specimen shall be in the fully machined condition and in the final heat-treated state that the material will see in service.

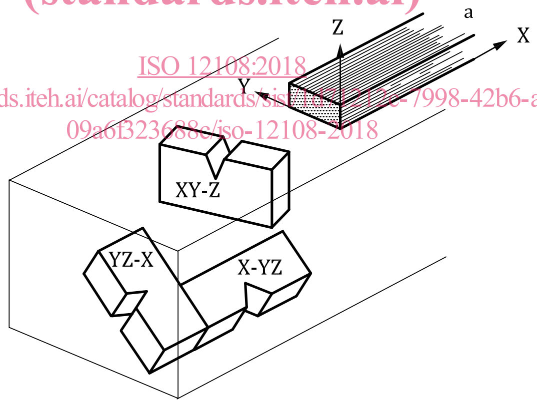
6.2 Crack plane orientation

The crack plane orientation, as related to the characteristic direction of the product, is identified in Figure 1. The letter(s) preceding the hyphen represent the force direction normal to the crack plane; the letter(s) following the hyphen represent the expected direction of crack extension. As specified in ISO 3785 for wrought metals, the letter X always denotes the direction of principal processing deformation, Y denotes the direction of least deformation and the letter Z is the third orthogonal direction. If the specimen orientation does not coincide with the product's characteristic direction, then two letters are used before and/or after the hyphen to identify the normal to the crack plane and/or expected direction of crack extension.

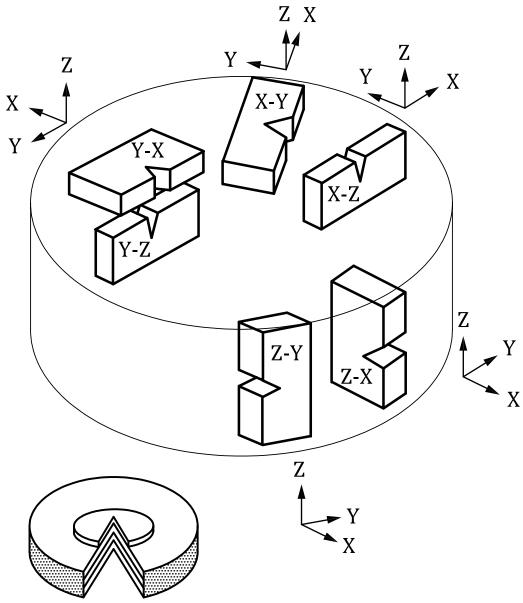
NOTE For rectangular sections of wrought metals, a commonly used alternative designation system uses the letters L to denote the direction of principal processing deformation (maximum grain flow), T to denote the direction of least deformation and S for the third orthogonal direction.



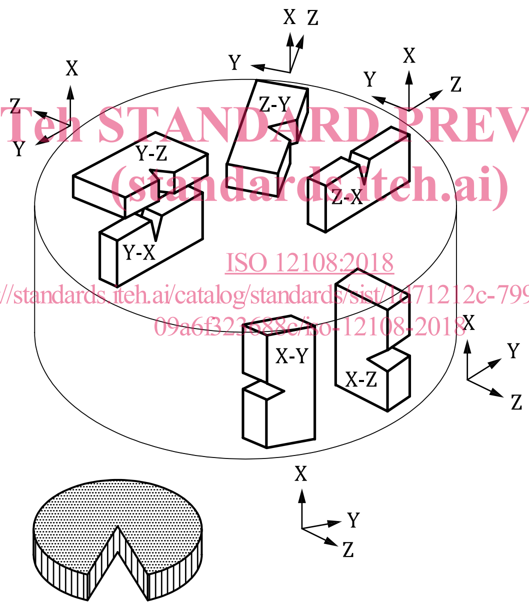
a) Basic identification, longitudinal grain flow



b) Non-basic identification, longitudinal grain flow



c) Axial working direction, radial grain flow



d) Radial working direction, axial grain flow

a Grain flow.

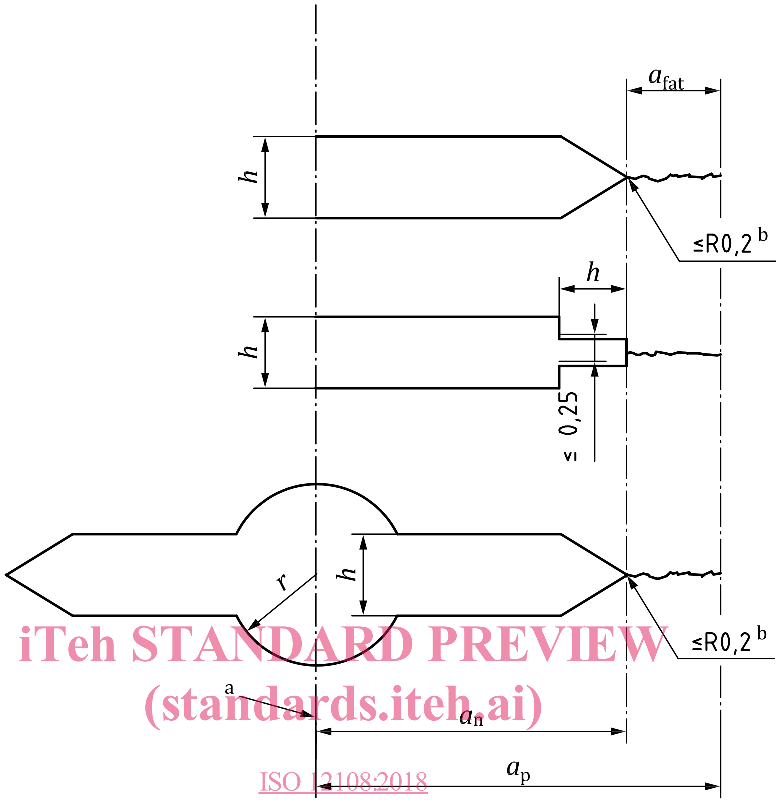
Figure 1 — Fracture plane orientation identification

6.3 Starter notch precracking details

The envelope and various acceptable machined notch configurations and precracking details for the specimens shall be as specified in Figure 2.

Notch length, a_n, shall meet the requirements defined in each respective specimen annex. The machined notches in the SENB and CCT specimens are determined by practical machining limitations; the *K*-calibration does not have a notch size limitation.

The starter notch for the standard specimens can be made via electrical discharge machining (EDM), milling, broaching or saw cutting. To facilitate precracking, the notch root radius should be as small as practical, typically less than 0,2 mm. For aluminium, saw cutting the final 0,5 mm starter notch depth with a jeweller's saw is acceptable.



Crack length shall be measured from the reference plane.

Notch height, h, should be minimized and shall be less than or equal to the maximum notch height.

A hole of radius $r < 0{,}05W$ is allowed for ease of machining the notch in a CCT specimen.

a Reference plane.

b Root radius.

Maximum notch height h	**Minimum precrack length** a_p
≤1 mm for $W \leq 25$	$a_p \geq a_n + h$, or
$W/16$ for $W > 25$	$a_p \geq a_n + 1$ mm, or
	$a_p \geq a_n + 0{,}1B$, whichever is greater
	$a_p \geq 0{,}2W$ for CT only

Figure 2 — Notch detail and minimum fatigue precracking requirements