BS ISO 12108:2012

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Metallic materials — Fatigue testing — Fatigue crack growth method

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National foreword

This British Standard is the UK implementation of ISO 12108:2012. It supersedes BS ISO 12108:2002, which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee ISE/101/6, Fatigue testing of metals and metal matrix composites.

A list of organizations represented on this committee can be obtained on request to its secretary.

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Published by BSI Standards Limited 2012

ISBN 978 0 580 66453 3

ICS 77.040.10

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This British Standard was published under the authority of the Standards Policy and Strategy Committee on 31 August 2012.

Amendments issued since publication

Date	Text affected

INTERNATIONAL STANDARD

ISO 12108

Second edition
2012-08-15

Metallic materials — Fatigue testing — Fatigue crack growth method

Matériaux métalliques — Essais de fatigue — Méthode d'essai de propagation de fissure en fatigue

Reference number
ISO 12108:2012(E)

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Published in Switzerland

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Foreword

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ISO 12108 was prepared by Technical Committee ISO/TC 164, *Mechanical testing of metals*, Subcommittee SC 5, *Fatigue testing*.

This second edition cancels and replaces the first edition (ISO 12108:2002), which has been technically revised.

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Introduction

This International Standard 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 [1]-[6]. 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. All values are given in SI units [7].

This International Standard 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 must remain predominantly in an elastic condition during testing and that buckling is precluded.

Specimen size may vary over a wide range. Proportional planar dimensions for six standard configurations are presented. The choice of a particular specimen configuration may 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 may vary independent 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 International Standard may be used, provided there exists an established stress-intensity factor calibration expression, i.e. stress-intensity factor geometry function, $g(a/W)$. [9]-[11]

Residual stresses[12],[13], crack closure[14],[15], specimen thickness, cyclic waveform, frequency and environment, including temperature, may 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[16]. For crack growth rates below 10^{-5} mm/cycle, the scatter in the $\mathrm{d}a/\mathrm{d}N$ calculation may 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 may exist where varying ΔK under conditions of constant K_{max} or K_{mean} control [17] may be more representative than data generated under conditions of constant force ratio; however, these alternate test procedures are beyond the scope of this International Standard.

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Metallic materials — Fatigue testing — Fatigue crack growth method

1 Scope

This International Standard 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 International Standard 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 stress ratio, R.

2 Normative references

The following normative 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 4965-1, *Metallic materials — Dynamic force calibration for uniaxial fatigue testing — Part 1: Testing systems*

3 Terms and definitions

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

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

NOTE This is also called crack size.

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

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

3.3
fatigue crack growth rate
da/dN
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

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

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

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

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

NOTE 1 R is also called the stress ratio.

NOTE 2 R may also be calculated using the values of stress-intensity factors; $R = K_{\text{min}}/K_{\text{max}}$.

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 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 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, $K_{\text{min}} = 0$. See 3.11.

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

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

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

NOTE 2 For $R \leq 0$ conditions, see 3.10 and 10.6.

NOTE 3 When comparing data developed under $R \leq 0$ conditions with data developed under $R > 0$ conditions, it may 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 For most materials, the threshold is defined as the stress-intensity factor range corresponding to 10^{-8} mm/cycle. When reporting ΔK_{th}, the corresponding lowest decade of da/dN data used in its determination should also be included.

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3.13
normalized K-gradient
$C = (1/K)\ \mathrm{d}K/\mathrm{d}a$
fractional rate of change of K with increased crack length, a

$$C = 1/K\ (\mathrm{d}K/\mathrm{d}a) = 1/K_{\mathrm{max}}\ (\mathrm{d}K_{\mathrm{max}}/\mathrm{d}a) = 1/K_{\mathrm{min}}\ (\mathrm{d}K_{\mathrm{min}}/\mathrm{d}a) = 1/\Delta K\ (\mathrm{d}\Delta K/\mathrm{d}a)$$

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

NOTE 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 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 See Figure 12.

3.19
notch length
a_{n}
length of the machined notch, as measured from the load line to the notch root

NOTE See Figure 12.

4 Symbols and abbreviated terms

4.1 Symbols

See Table 1.

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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	1
R	Force ratio or stress ratio	1
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	1
h	Notch height	mm
W	Specimen width, distance from reference plane to edge of specimen	mm
$(W-a)$	Minimum 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

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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 General

The testing machine shall have smooth start-up and a backlash-free force train if passing through zero force. See ISO 4965-1. 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 [33], [34].

5.1.2 Testing machine alignment

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.

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.

Asymmetry of the crack front is an indication of misalignment; a strain gauged specimen similar to the test article under investigation can be used in aligning the force train and to minimize nonsymmetrical stress distribution and/or bending strain to less than 5 %.

5.1.3 Force measuring system

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 noncomputer 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 Grips and fixtures for CT specimens

Force is applied to a CT specimen through pinned joints. The choice of this specimen and gripping arrangement necessitates tension-tension test conditions only. Figure 1 shows the clevis and mating pin assembly used at both the top and bottom of a CT specimen to apply the force perpendicular to the machined starter notch and crack plane. Suggested dimensions are expressed as a proportion of specimen width, W, or thickness, B, since these dimensions can vary independently within the limits specified in Clause 6. The pin holes have a generous clearance over the pin diameter, 0,2W minimum, to minimize resistance to specimen and pin in-plane rotation which has been shown to cause nonlinearity in the force versus displacement response [35]. A surface finish,

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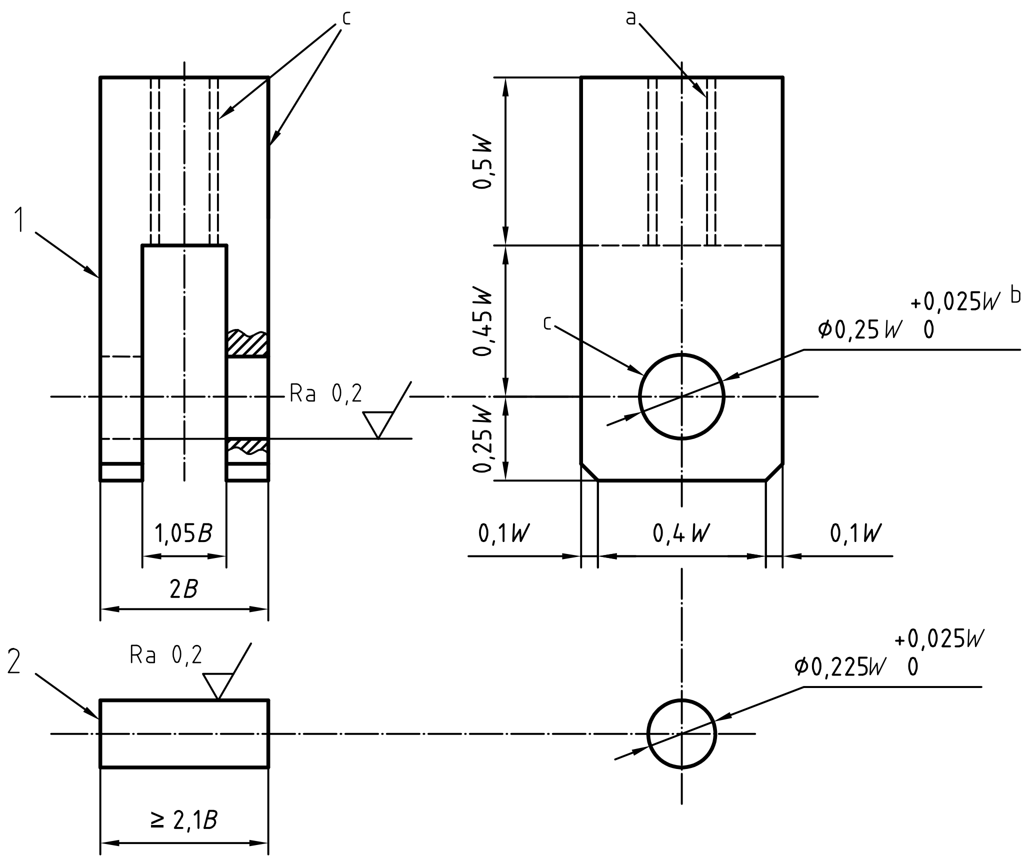
Ra, range of 0,8 μm to 1,6 μm is suggested for grip surfaces. With this grip-and-pin arrangement, materials with low proof strength may sustain plastic deformation at the specimen pin hole; similarly, when testing high strength materials and/or when the clevis displacement exceeds 1,05*B*, a stiffer force pin, i.e. a diameter greater than 0,225*W*, may be required. As an alternative approach to circumvent plastic deformation, a flat bottom clevis hole may be used along with a pin diameter equaling 0,24*W*. Any heat treatable steel thermally processed to a 0,2 % proof strength of 1 000 MPa used in fabricating the clevises will usually provide adequate strength and resistance to fretting, galling and fatigue.

In addition to the generous pin hole clearance, the mating surfaces shall be prepared to minimize friction which could invalidate the provided *K*-calibration expression. The use of high viscosity lubricants and greases has been shown to cause hysteresis in the force versus displacement response and is not recommended if compliance measurements are required.



Key

1 clevis

2 pin

NOTE For high strength materials or large pin displacements, the pin may be stiffened by increasing the diameter to 0,24*W* along with using D-shaped flat bottom holes.

[a] Loading rod thread.

[b] Through diameter.

[c] These surfaces are perpendicular and parallel as applicable to within 0,05*W*.

Figure 1 — Clevis and pin assembly for gripping a CT specimen

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5.4 Grips and fixtures for CCT/SENT specimens

5.4.1 General

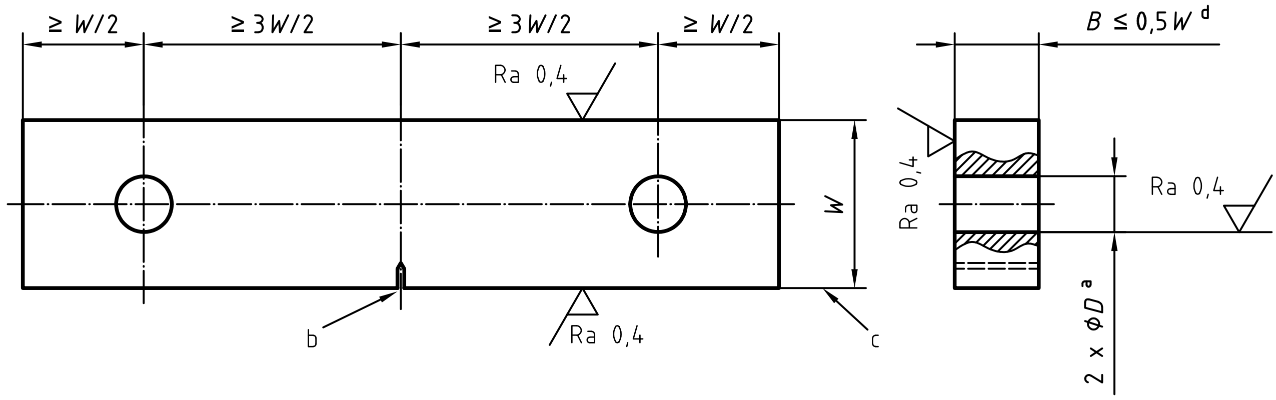
Force can be applied to CCT and SENT specimens through pinned joints and/or through frictional clamping grips. Gripping for the CCT and SENT specimens depends on specimen width and whether the test condition is to be tension-tension or tension-compression. The minimum CCT specimen gauge length varies with gripping arrangement and shall provide a uniform stress distribution in the gauge length during the test.

Under certain conditions, the CCT specimen can be prone to general and localized buckling. The use of buckling constraints is recommended.[49]

Formula (6) is applicable only for a single pinned end SENT specimen, as shown in Figure 2. The SENT pinned end specimen (Figure 2) is appropriate for tension-tension test conditions only.

Formula (7) is applicable for a SENT specimen with clamped ends and is appropriate for both tension and compression force conditions. For the clamped-end SENT specimen, the grips must be sufficiently stiff to circumvent any rotation of the specimen ends or any lateral movement of the crack plane; the presence of either condition introduces errors into the stress-intensity factor calculation [29].

Surface roughness values in micrometres



NOTE 1 The machined notch is centred to within ± $0{,}005W$ (TIR[e]).

NOTE 2 The surfaces are parallel and perpendicular to within ± $0{,}002W$.

NOTE 3 The crack length is measured from the reference loading plane containing the starter V-notch.

NOTE 4 This specimen is recommended for notch root tension at a force ratio $R > 0$ only.

a $D = W / 3$.

b See Figure 12 for notch detail.

c Reference plane.

d Recommended thickness: $B \leq 0{,}5W$.

e Total indicated reference value.

Figure 2 — Standard single edge notch tension, SENT, specimen

5.4.2 Tension-tension testing of a CCT specimen

For tension-tension testing of a specimen with a width $2W$, less than 75 mm, as shown in Figure 3, a clevis with single force pin is acceptable for gripping provided the specimen gauge length, defined here as the distance between the pin hole centrelines, be at least $6W$. Shims may be helpful in circumventing fretting fatigue at the specimen's pin hole. Another step that can be taken to prevent crack initiation at the pin holes is the welding or adhesive bonding of reinforcement plates or tabs to the gripping area, especially when testing very thin materials. Cutting the test section down in width to form a “dog bone” shaped specimen design is another

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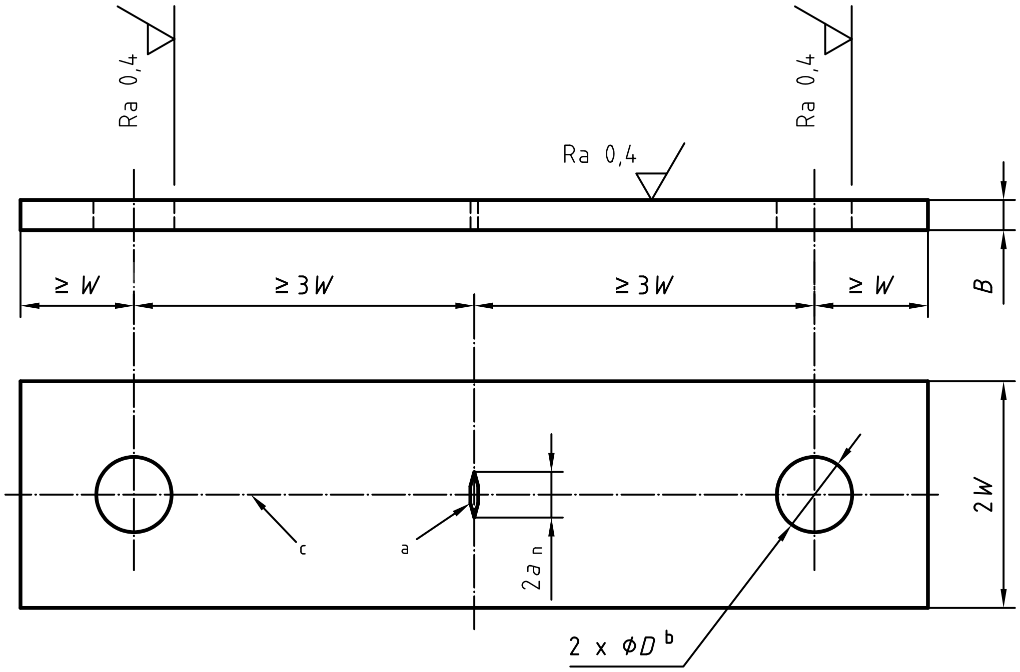
measure that can be adopted to circumvent failure at the pin holes; here the gauge length is defined as the uniform width section and it shall be at least 3,4W in length.

For tension-tension testing of a specimen with a width greater than 75 mm, distributing the force across the specimen width with multiple pin holes is recommended. A serrated grip surface at the specimen-grip interface increases the force that can be transferred. With this force application arrangement, the gauge length between the innermost rows of pin holes must be at least 3W.

Surface roughness values in micrometres



NOTE 1 The machined notch is centred to within ± 0,002W.

NOTE 2 The faces are parallel to ± 0,05 mm/mm.

NOTE 3 The two faces are not out-of-plane more than 0,05 mm.

NOTE 4 The crack length is measured from the reference plane of the longitudinal centreline.

NOTE 5 The clevis and pin loading system is not suitable for a force ratio $R < 0$.

NOTE 6 Special gripping systems may be used for a force ratio $R < 0$ such as shown in Figure 4.

a See Figure 12 for notch detail.

b $D = 2W/3$.

c Reference plane.

Figure 3 — Standard pinned end centre cracked tension, CCT, specimen for $2W \leq$ 75 mm

5.4.3 Tension-compression testing of a CCT specimen

A backlash-free gripping arrangement shall be used for tension-compression testing of the CCT specimen. Various commercially available pneumatic and hydraulic wedge grips that provide adequate clamping force may be used. The minimum gauge length for a clamped CCT specimen is 2,4W.

For tension-compression testing of a CCT specimen, Figure 4 presents a design that affords a simple backlash free grip that provides improved force transfer through multiple pins plus frictional force transfer via specimen clamp-up with the serrated gripping surfaces. The compressive condition between the pins and the specimen's end surfaces, induced by drawing the wedges together, affords large reverse force excursions

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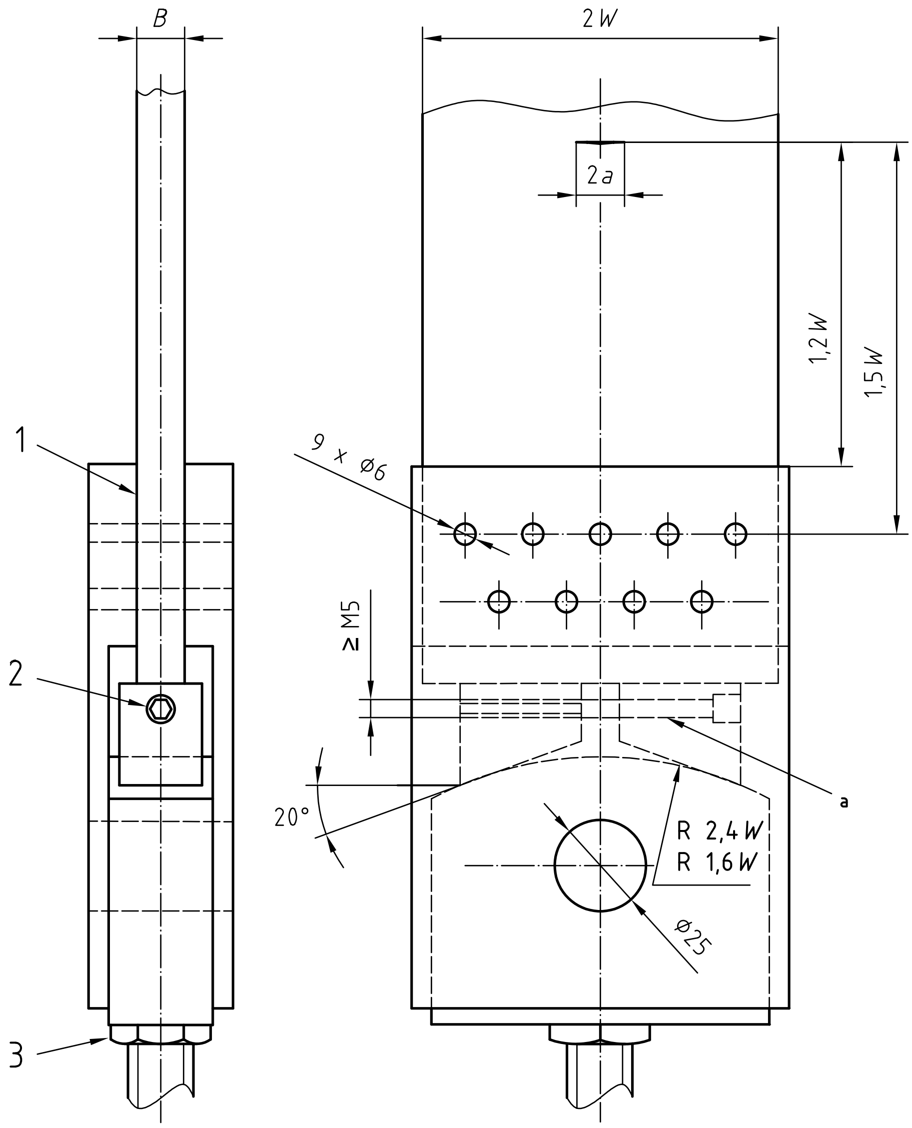
while circumventing elongation of the pin holes. The minimum gauge length for this specimen is 2,4W between the grip end surfaces and 3W between the inner rows of pins, as stated above.

Dimensions in millimetres



Key

1 Serrated sideplate surface

2 Countersunk cap screw

3 Lock nut

NOTE 1 Made of hardened steel, e.g. ≥ 40 HRC.

NOTE 2 Serrated side plates vary in thickness to accommodate approximately 2 mm to 3 mm, range in thickness B.

[a] Body drilled.

Figure 4 — Example of backlash free grip for a CCT specimen

5.4.4 Alignment of CCT specimen grips

The CCT specimen is sensitive to misalignment and nonsymmetrical force application, especially in tension-compression testing where gimbaled connections are not used, which can readily lead to violation of the through thickness crack curvature and/or symmetry validity criteria. It is recommended that bending strain

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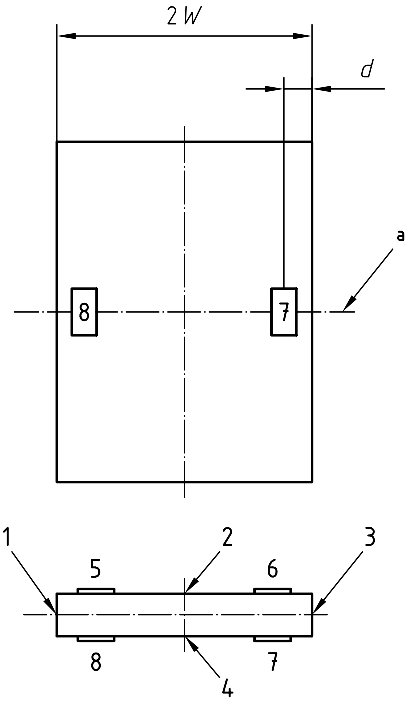
be checked periodically with a panel specimen similar to the one being tested and instrumented with strain gauges, as shown in Figure 5 [22]. This technique can be used to minimize the bending strain. See 5.1.2.



1 to 4 locations indicating faces on the specimen

5 to 8 locations indicating strain gauges applied to the specimen.

a Plane A.

Figure 5 — Strain gauge arrangement for an instrumented panel alignment specimen [22]

5.4.5 Bending strain calculation for the arrangement shown in Figure 5 [22]:

The average axial strain, ε_a , for the flat panel calibration specimen is calculated using:

$$\varepsilon_a = \frac{(\varepsilon_5 + \varepsilon_6 + \varepsilon_7 + \varepsilon_8)}{4}$$

where ε_5, ε_6, ε_7 and ε_8 are the measured strains.

The equivalent strain at the centre of the four faces 1 to 4 is calculated using:

$$\varepsilon_1 = \varepsilon_a - \left[\varepsilon_a - (\varepsilon_5 + \varepsilon_8)/2\right]\left[2W/(2W - 2d)\right];$$

$$\varepsilon_3 = \varepsilon_a - \left[\varepsilon_a - (\varepsilon_6 + \varepsilon_7)/2\right]\left[2W/(2W - 2d)\right];$$

$$\varepsilon_2 = (\varepsilon_5 + \varepsilon_6)/2 \; ; \; \varepsilon_4 = (\varepsilon_7 + \varepsilon_8)/2 .$$

The local bending strains at the centre of each of the four faces are calculated using:

$$b_1 = \varepsilon_1 - \varepsilon_a \; ; \; b_2 = \varepsilon_2 - \varepsilon_a \; ; \; b_3 = \varepsilon_3 - \varepsilon_a \; ; \; b_4 = \varepsilon_4 - \varepsilon_a \; .$$

The maximum bending strain percentage in plane A can then be calculated as follows:

$$\beta\% = \left[(b_1 - b_3)/2 + (b_2 - b_4)/2\right]100/\varepsilon_a \le 5\%$$

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5.5 Grips and fixtures for the SENB specimens

5.5.1 Tension-compression grips for the SEN B8 specimen

The eight-point bend specimen is also suited for tension-compression testing. In gripping the eight-point bend specimen, the top and bottom tups are rigidly tied together with a line-to-line fit to the specimen's surfaces. Precautions shall be taken to eliminate backlash and secondary moments.

5.5.2 Tension-tension testing of SENB specimens

The general principles of the bend test fixture suitable for tension-tension testing of the SENB specimen are illustrated in Figure 6. The fixture is designed to minimize frictional effects by allowing the support rollers to rotate and move apart slightly as force is applied to the specimen, hence permitting rolling contact. Thus, the support rollers are allowed limited motion along plane surfaces parallel to the notched side of the specimen, but are initially positively positioned against stops that set the span length and are held in place by low-tension springs (such as rubber bands). Fixtures and rollers shall be made of high hardness (>40 HRC) steel [23].

5.6 Crack length measurement apparatus

5.6.1 General

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 [26]. The required crack length measurements are the average of the through-the thickness crack lengths, as covered in 9.1.

5.6.2 Non-visual crack length measurement

There are a number of non-visual measurement techniques. Most lend themselves to automated data acquisition and determine the average crack length, reflecting the crack-front curvature, if it exists. Crack-opening-displacement compliance [36]-[38], AC and DC electric potential difference (EPD) [39]-[41], back face strain [36], [42], and side face foil crack gauges [43]- [45] are all acceptable techniques, provided the resolution requirements covered in 8.1 be met. (Information on the methodology of crack length determination through the use of EPD is provided in Annex A.)

5.6.3 Visual crack length measurement

In the past, the most common visual crack length measurement technique used a micrometer thread travelling microscope with low magnification (×20 to ×50). This technique measures the surface crack length during the test and may need to be corrected to the actual through-thickness crack size upon test completion, as covered in 9.1.

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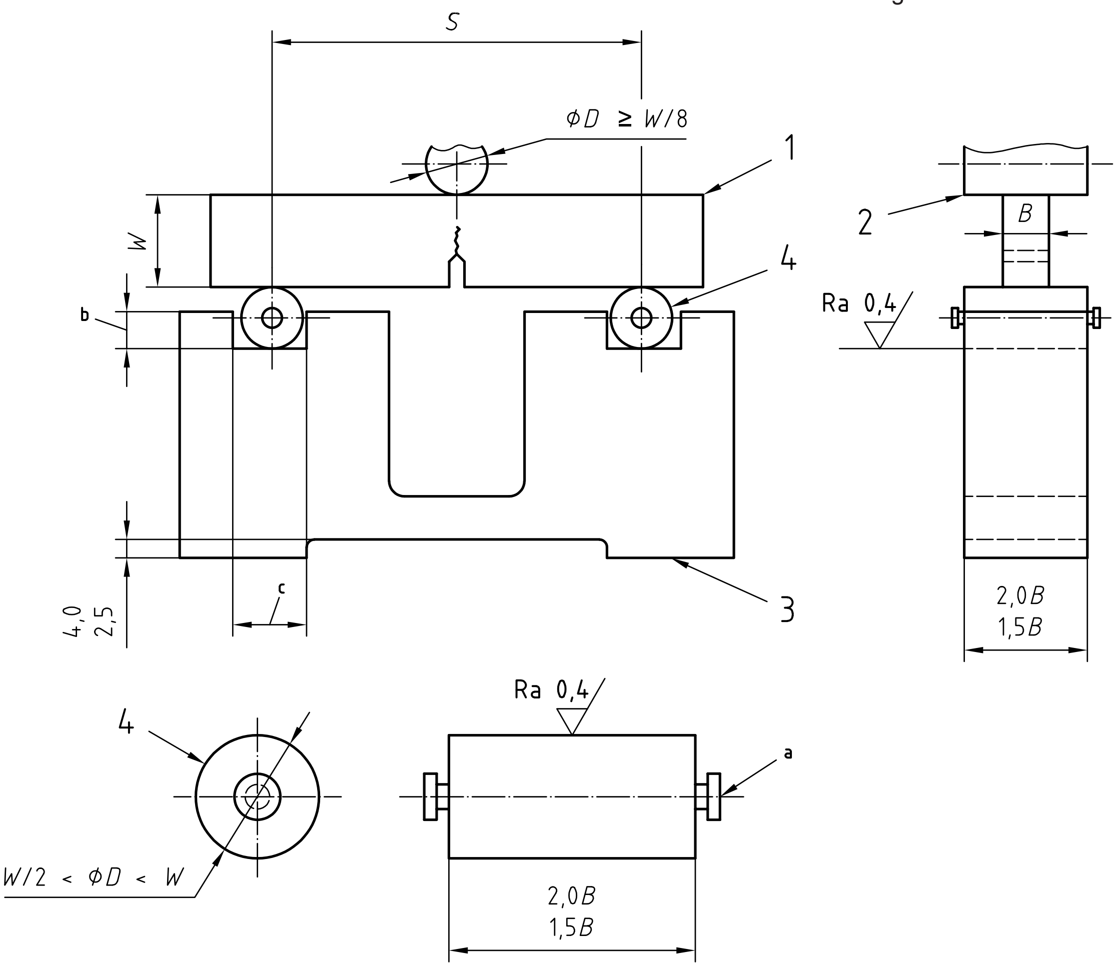
Dimensions in millimetres
Surface roughness values in micrometres



Key

1 test specimen
2 loading rod
3 test fixture
4 support rollers

NOTE Support rollers and specimen contact surface of loading rod should be parallel to each other to $\pm$ 0,002W (TIR).

a Bosses for springs or rubber bands.
b 0,6x support roller diameter.
c 1,1x support roller diameter.

Figure 6 — Fixture for tension-tension forcing of a SEN B3 specimen

6 Specimens

6.1 General

Proportional dimensions of six standard specimens: a compact tension (CT); a centre cracked tension (CCT) and three-, four- and eight-point single edge notch bends [(SEN B3), (SEN B4) and (SEN B8)]; and single edge notch tension (SENT) are presented in Figures 7, 3, 8, 9, 10 and 2, respectively. A variety of specimen configurations is presented to accommodate the component geometry available and test environment and/or 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.

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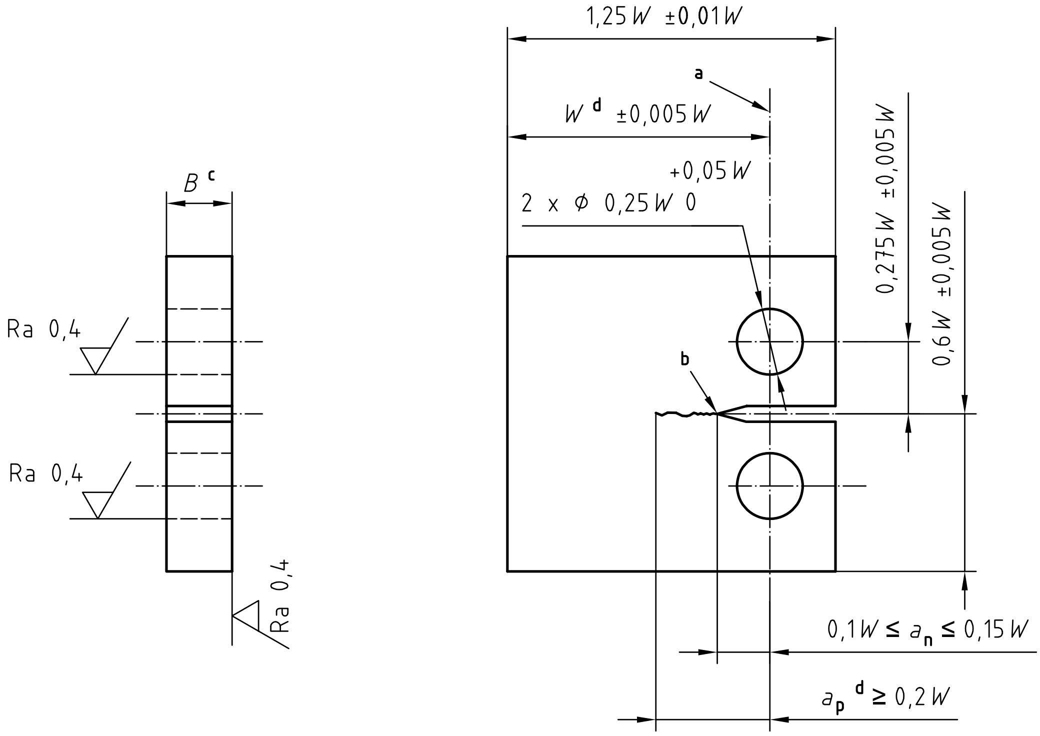
The specimen shall have the same metallurgical structure as the material for which the crack growth rate is being determined. The test specimen shall be in the fully machined condition and in the final heat-treated state that the material will see in service.

Surface roughness values in micrometres



NOTE 1 The machined notch is centred to within ± 0,005W.

NOTE 2 The surfaces are perpendicular and parallel to within ± 0,002W (TIR).

NOTE 3 The crack length is measured from the reference plane of the loading pin holes centerline.

NOTE 4 This specimen is recommended for notch root tension at a force ratio $R > 0$ only.

a Reference plane.

b See Figure 12 for notch detail.

c Recommended thickness: $W / 20 \leq B \leq W / 2$.

d The suggested minimum dimensions are $W = 25$ mm and $a_p = 0{,}2W$.

Figure 7 — Standard compact tension, CT, specimen for fatigue crack growth rate testing

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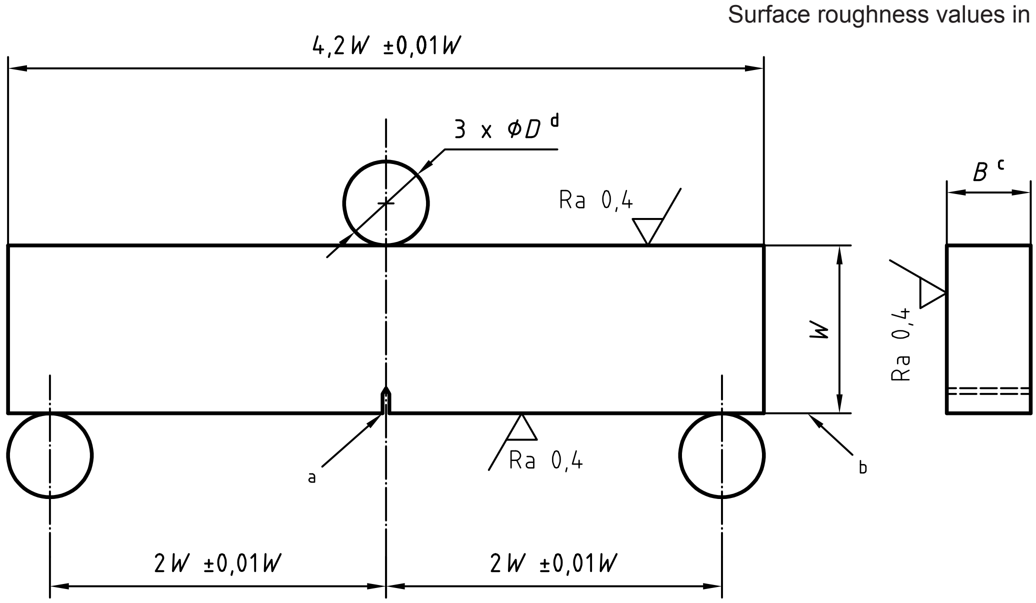
Surface roughness values in micrometres



NOTE 1 The machined notch is centre to within $\pm$ 0,005W (TIR).

NOTE 2 The surfaces are parallel and perpendicular to within $\pm$ 0,002W.

NOTE 3 The crack length is measured from the reference loading plane containing the starter V-notch.

NOTE 4 This specimen is recommended for notch root tension at a force ratio $R > 0$ only.

a See Figure 12 for notch detail.

b Reference plane.

c Recommended thickness: 0,2$W \leq B \leq W$.

d $D \geq W/8$.

Figure 8 — Standard three-point single edge notch bend, SEN B3, specimen

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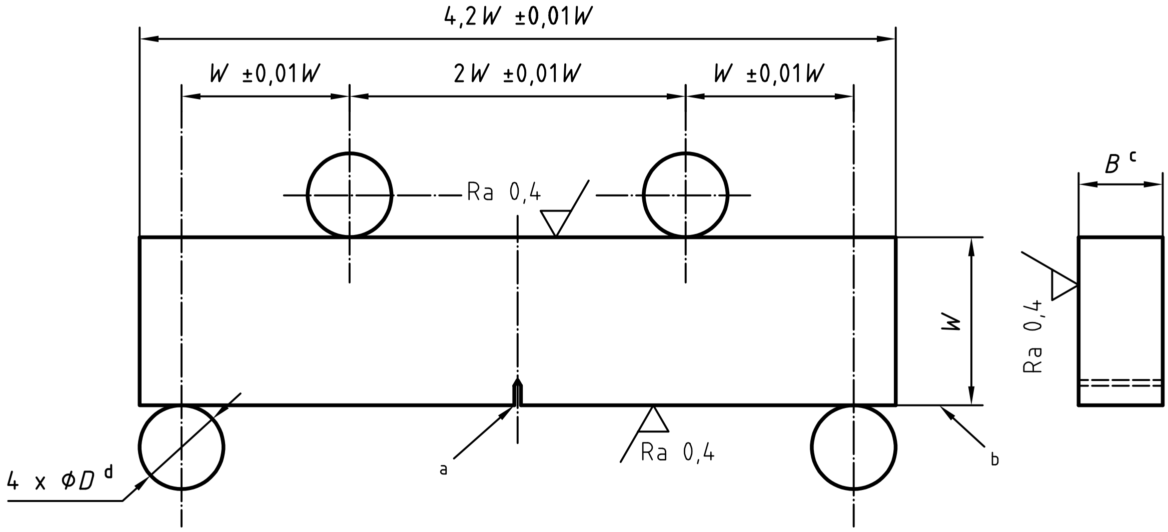
Surface roughness values in micrometres



NOTE 1 The machined notch is centred to within ± 0,005W.

NOTE 2 The surfaces are parallel and perpendicular to within ± 0,002W (TIR).

NOTE 3 The crack length is measured from the reference loading plane containing the starter V-notch.

NOTE 4 This specimen is recommended for notch root tension at a force ratio $R \geq 0$ only.

[a] See Figure 12 for notch detail.

[b] Reference plane.

[c] Recommended thickness: $0,2W \leq B \leq W$.

[d] $D \geq W/8$.

Figure 9 — Standard four-point single-edge-notch bend, SEN B4, specimen

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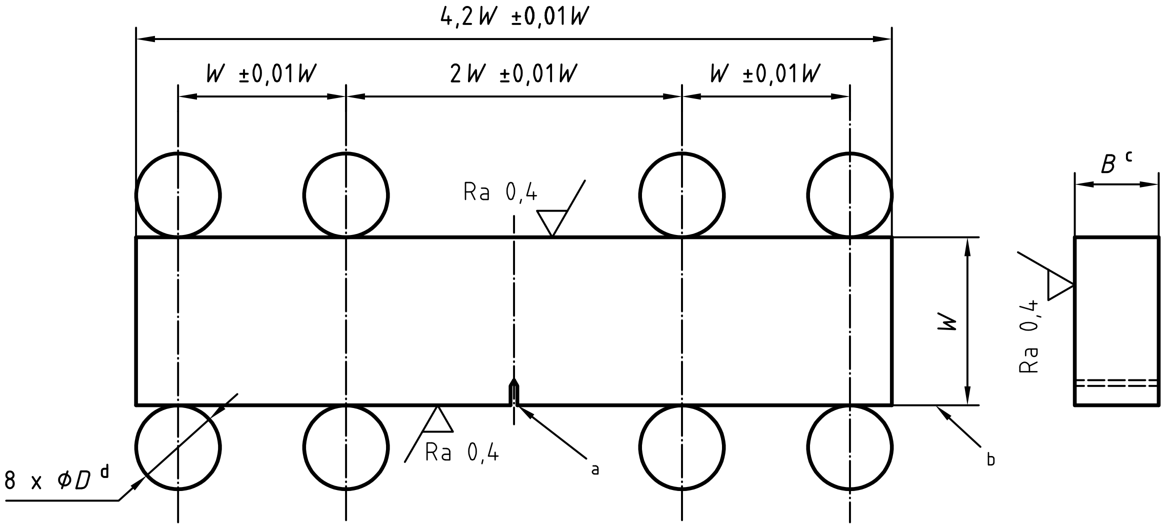
Surface roughness values in micrometres



NOTE 1 The machined notch is centred to within ± 0,005*W*.

NOTE 2 The surfaces are parallel and perpendicular to within ± 0,002*W* (TIR).

NOTE 3 The crack length is measured from the reference loading plane containing the starter V-notch.

NOTE 4 Specimen suitable for $R \leq 0$, provided backlash and secondary moment loading by grips be avoided.

a See Figure 12 for notch detail.

b Reference plane.

c Recommended thickness: $0,2W \leq B \leq W$.

d $D \geq W/8$.

Figure 10 — Standard eight-point single edge notch bend, SEN B8, specimen

6.2 Crack plane orientation

The crack plane orientation, as related to the characteristic direction of the product, is identified in Figure 11. The letter(s) preceding the hyphen represent(s) the force direction normal to the crack plane; the letter(s) following the hyphen represent the expected direction of crack extension. 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 letter 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.

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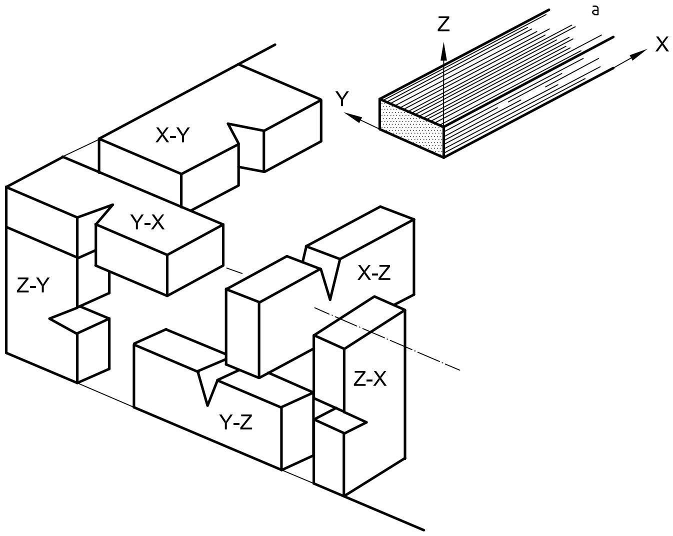
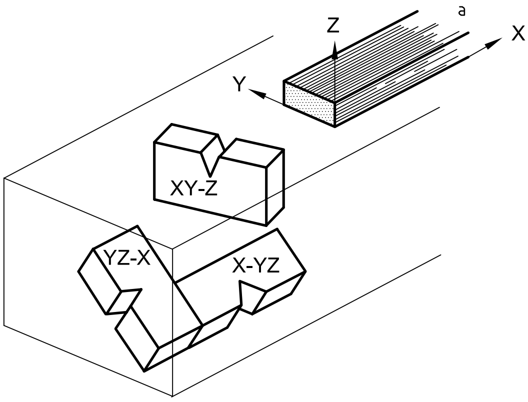
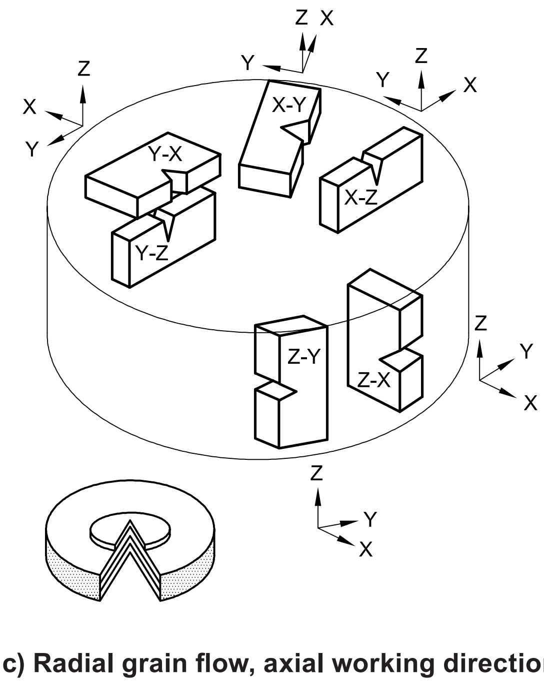


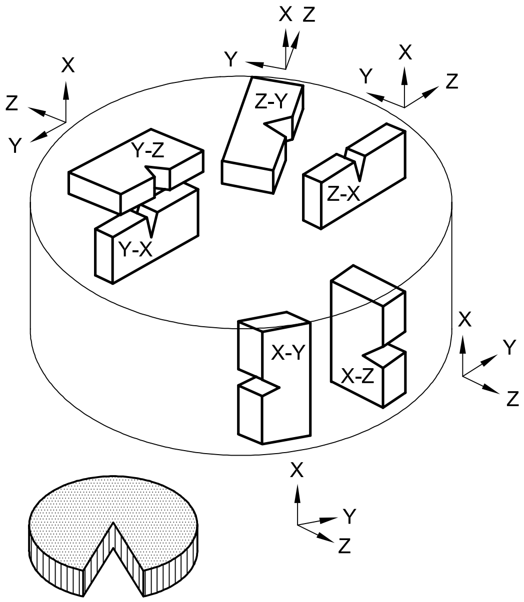
a) Basic identification



b) Non-basic identification



c) Radial grain flow, axial working direction



d) Axial grain flow, radial working direction

[a] Grain flow.

Figure 11 — Fracture plane orientation identification

6.3 Starter notch precracking details

The envelope and various acceptable machined notch configurations and precracking details for the specimens are presented in Figure 12.

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. However, a CCT specimen's minimum notch length, $2a_{\text{n}}$, of at least 0,2W is required when using the compliance method for crack length determination to ensure accurate crack length measurements.

The starter notch for the standard specimens may 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 jeweler's saw is acceptable.

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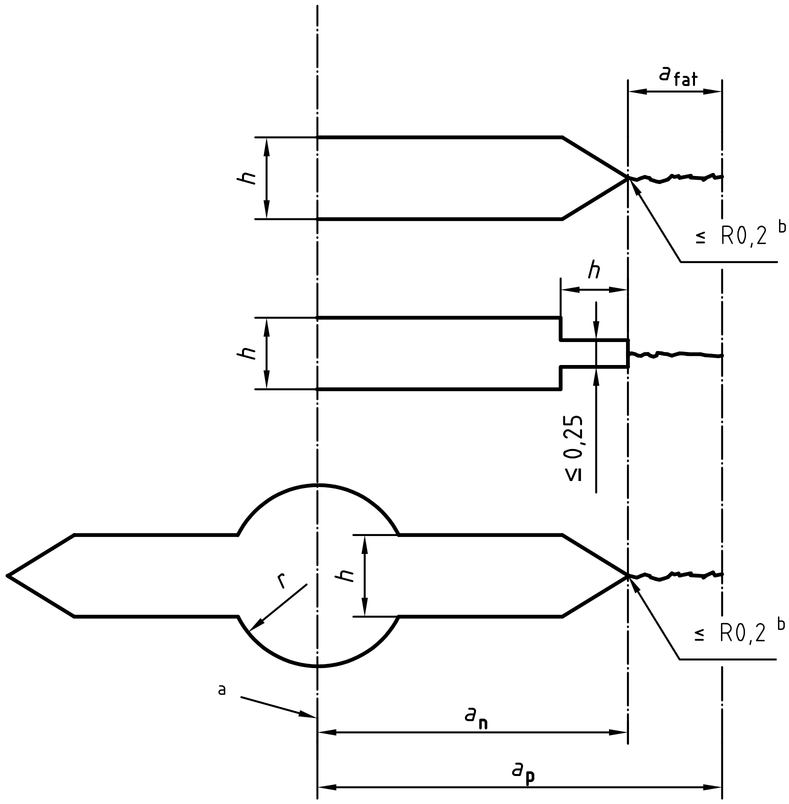

NOTE 1 Crack length is measured from reference plane.

NOTE 2 Notch height, h, should be minimized.

NOTE 3 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.

Specimen type	Notch length a_n	Maximum notch height h	Minimum precrack length a_p
CT CCT	$0{,}1W \le a_n \le 0{,}15W$	$\le$ 1 mm for $W \le 25$ $W/16$ for $W > 25$	$a_p \ge a_n + h$, or $a_p \ge a_n + 1$ mm, or $a_p \ge a_n + 0{,}1B$, whichever is greater. $a_p \ge 0{,}2W$ for CT only

Figure 12 — Notch detail and minimum fatigue precracking requirements

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6.4 Stress-intensity factor

6.4.1 General

The stress-intensity factor for all standard specimen configurations is calculated using the following relationship:

$$K = \frac{F}{BW^{1/2}} g(\frac{a}{W}) \tag{1}$$

The stress-intensity factor geometry function, $g(a/W)$, for each standard specimen configuration is calculated using the following expressions.

6.4.2 Compact tension, CT, specimen

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

where $\alpha = a/W$; the expression is valid for $0,2 \le a/W \le 1,0$. See Figure 7.

6.4.3 Centre cracked tension, CCT, specimen

For the centre cracked tension specimen, CCT, the stress-intensity factor geometry function is given by [24]-[26]:

$$g(\frac{a}{W}) = (\frac{\theta}{\cos\theta})^{1/2}(0,707\ 1-0,007\ 2\theta^2+0,007\ 0\theta^4) \tag{3}$$

where $\theta = \pi a / 2W$ radians; the expression is valid for $0 < \alpha = 2a / 2W < 1,00$. Here, it is recommended that the crack length, a, be the average of the four measurements from the centreline reference plane to the crack tips on both the front and back surfaces. See Figure 3.

6.4.4 Single edge notch three-point bend, SEN B3, specimen

$$g(\frac{a}{W}) = \frac{6\alpha^{1/2}}{[(1+2\alpha)(1-\alpha)^{3/2}]}[1,99-\alpha(1-\alpha)(2,15-3,93\alpha+2,7\alpha^2)] \tag{4}$$

where $\alpha = a/W$; the expression is valid for $0 \le \alpha \le 1,0$. See Figure 8.

6.4.5 Single edge notch four-point bend, SEN B4, specimen

For the four-point bend specimen, SEN B4, with the distance between external supports minus the distance between internal supports equaling 2*W*, the stress-intensity factor geometry function is given by [10]:

$$g(\frac{a}{W}) = 3(2\tan\theta)^{1/2}\left[\frac{0,923+0,199(1-\sin\theta)^4}{\cos\theta}\right] \tag{5}$$

where $\theta = \pi a / 2W$ radians; the expression is valid for $0 \le a/W \le 1,0$. See Figure 9.

For the four-point bend specimen, where the difference between the major and minor span does not equal 2*W*, the value for $g(1/W)$ is proportional to the ratio of the major span minus the minor span divided by 2*W*,

i.e. $\dfrac{\text{major span} - \text{minor span}}{2W}$

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6.4.6 Single edge notch eight-point bend, SEN B8, specimen

For the eight-point bend specimen, SEN B8, with the distance between external supports minus the distance between internal supports equaling 2W, the stress-intensity factor geometry function is given by [10]:

$$g(\frac{a}{W}) = 3(2\ \tan\theta)^{1/2}\left[\frac{0{,}923 + 0{,}199(1 - \sin\theta)^4}{\cos\theta}\right]$$

where $\theta = \pi a / 2W$ radians; the expression is valid for $0 \le a / W \le 1{,}0$. See Figure 10.

For the eight-point bend specimen, where the difference between the major and minor span does not equal 2W, the value for $g(a / W)$ is proportional to the ratio of the major span minus the minor span divided by 2W.

i.e. $\frac{\text{major span} - \text{minor span}}{2W}$

6.4.7 Single edge notch tension, SENT, specimen

For the single edge notch pinned end tension specimen, SENT, the stress-intensity factor geometry function is given by [10]:

$$g\left(\frac{a}{W}\right) = \sqrt{2\ \tan\theta}\left[\frac{0{,}752 + 2{,}02\alpha + 0{,}37(1 - \sin\theta)^3}{\cos\ \theta}\right] \tag{6}$$

where $\theta = \pi a / 2W$; the expression is valid for $0 < a / W < 1{,}0$. See Figure 2.

For the single edge notch clamped-end tension specimen, with the clear span between the grips equaling 4W, the stress-intensity factor geometry function is given by [28]:

$$g\left(\frac{a}{W}\right) = (1 - \alpha)^{-3/2}\left[1{,}987\ 8\alpha^{1/2} - 2{,}972\ 6\alpha^{3/2} + 6{,}950\ 3\alpha^{5/2} - 14{,}447\ 6\alpha^{7/2} \right. \tag{7}$$

$$\left. + 10{,}054\ 8\alpha^{9/2} + 3{,}404\ 7\alpha^{11/2} - 8{,}714\ 3\alpha^{13/2} + 3{,}741\ 7\alpha^{15/2}\right]$$

where $\alpha = a / W$; the expression is valid for $0 < a / W \le 0{,}95$. See Figure 2.

Stress-intensity factor functions, for clamped-end SENT specimens with spans between the grips other than 4W, are available [29]-[31].

6.5 Specimen size

6.5.1 General

For the test results to be valid, it is required that the specimen remain predominantly in a linear-elastic stress condition throughout the test. The specimen width, W, and thickness, B, may be varied independently within the limits covered in 6.6. The smallest specimen to meet these criteria, based on experimental results, varies with each specimen configuration [32].

The minimum uncracked ligament that circumvents large scale yielding varies with specimen configuration and is a function of the material's 0,2 % proof strength.

6.5.2 CT specimen minimum uncracked ligament

For the CT specimens the minimum uncracked ligament for producing valid data are given by:

$$(W - a) \ge \left(\frac{4}{\pi}\right)\left(\frac{K_{\text{max}}}{R_{\text{p0,2}}}\right)^2 \tag{8}$$

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6.5.3 CCT specimen minimum uncracked ligament

For the CCT specimen, the minimum size of the uncracked ligament, based upon large scale net section yielding of the material, is given by:

$$(W-2a) \geq \frac{1{,}25F_{\max}}{BR_{\mathrm{p0,2}}} \tag{9}$$

6.5.4 SENB specimen minimum uncracked ligament

For all of the bend SENB specimens, the minimum size of the uncracked ligament is given by:

$$(W-a) \geq \left(\frac{3\lambda F_{\max}}{2BR_{\mathrm{p0,2}}}\right)^{0{,}5} \tag{10}$$

This criterion is based upon large scale net section yielding of the material and $\lambda = 4W$, the distance between external supports for a three-point bend specimen; $\lambda = 2W$ for a four and eight-point bend specimen or, if a nonstandard four or eight-point bend specimen is used, λ equals the distance between external supports minus the distance between internal supports.

6.5.5 SENT specimen minimum uncracked ligament

The minimum size of the uncracked ligament for the SENT specimen depends on the gripping technique: for a tensile stress, e.g. the ends embedded in hydraulic wedge grips, the minimum uncracked ligament is given by:

$$(W-a) \geq \frac{1{,}25F_{\max}}{BR_{\mathrm{p0,2}}} \tag{11}$$

This criterion is based upon large scale net section yielding of the material.

For a bending stress, e.g. clevis and pinned end grips, the minimum uncracked ligament is given by Formula (8).

6.6 Specimen thickness

6.6.1 General

Specimen thickness, B, may be varied independent of specimen width, W, for the specimen configurations, within the limits for buckling and through-thickness crack-front curvature considerations. It is recommended that the selected specimen thickness be similar to that of the product under study.

6.6.2 CT specimen

For a CT specimen, it is recommended that the thickness, B, be within the range $W/20 \leq B \leq W/4$. A thickness up to $W/2$ is permitted. For a specimen, this thick, a through-thickness crack-front curvature correction length, a_{cor}, may often be required; also, difficulties may be encountered in meeting the through-thickness crack straightness requirements covered in 9.1.

6.6.3 CCT specimen

For the CCT specimen, it is recommended that the upper limit for thickness be within the range $2W/8 \leq B \leq 2W/4$. The minimum thickness for circumventing out-of-plane deflection or buckling in the CCT specimen is dependent on the test material's elastic modulus, E, gauge length, gripping, grip alignment and force ratio, R.

6.6.4 SENB specimen

For the single edge notch bend specimen, it is recommended that the thickness be within the range

$0{,}2W \leq B \leq W$.

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6.6.5 SENT specimen

For the single edge notch tension specimen, the maximum recommended thickness equals 0,5W.

6.7 Residual stresses

Residual stresses in a material that has not been stress relieved can influence the crack propagation rate considerably [12], [13]. This influence can be minimized by choosing a symmetrical specimen configuration like the standard CCT specimen and reducing the B/W ratio to minimize crack-front curvature caused by variation in residual stresses through the thickness [13].

7 Procedure

7.1 Fatigue precracking

The purpose of precracking is to provide a straight and sharp fatigue crack of sufficient length so that the K-calibration expression is no longer influenced by the machined starter notch and that the subsequent fatigue crack growth rate is not influenced by a changing crack front shape or precracking force history.

One practice is to initiate the fatigue crack at the lowest possible maximum stress-intensity factor, K_{max}, that is practical. If the test material's critical stress-intensity factor, which will cause fracture, is approximately known, then the initial K_{max} for precracking can range from 30 % to 60 % of that value. If crack initiation does not occur within a block 30 000 to 50 000 load cycles, then K_{max} can be increased by 10 % and the block of load cycles repeated. The final K_{max} for precracking shall not exceed the initial K_{max} for which test data are to be generated.

Frequently, a stress-intensity factor, greater than the K_{max} used in the test, needs to be used for crack initiation. In this case, the maximum force shall be stepped down to meet the above criteria. When manually controlling precracking, the recommended stress-intensity factor drop for each step is less than 10 % of K_{max}. In addition, it is recommended that between each stress-intensity factor reduction, the crack extend by at least the value given in Formula (12) [18]:

$$\Delta a_j = \frac{3}{\pi}\left[\frac{K_{max(j-1)}}{R_{p0,2}}\right]^2 \quad (12)$$

where $K_{max(j-1)}$ is the maximum terminal stress-intensity factor of the previous step.

When test data are to be generated for a high force ratio, it may be more convenient to precrack at a lower K_{max} and force ratio than the initial test conditions.

The precracking apparatus shall apply the force symmetrical to the specimen's notch and accurately maintain the maximum force to within 5 %. A centre cracked panel shall also be symmetrically stressed across the width, 2W. Any frequency that accommodates maintaining the force accuracy specified in 5.1 is acceptable.

The precrack shall meet the symmetry and out-of-plane cracking requirements as described in 7.2.

7.2 Crack length measurement

The requirements for measurement accuracy, frequency and validity are covered in Clauses 8 and 9 for the various specimen configurations and test procedures that follow. When surface measurements are used to determine the crack length, it is recommended that both the front and back surface traces be measured. If the front to back crack length measurements vary by more than 0,25B and, for a CCT specimen, if the side-to-side symmetry of the two crack lengths vary in length by more than 0,025W then the precrack is not suitable and test data would be invalid under this test method. In addition, if the precrack departs from the plane of symmetry beyond the corridor, defined by planes 0,05W on either side of the specimen's plane of symmetry containing the notch root(s), the data would be invalid. See Figure 13.

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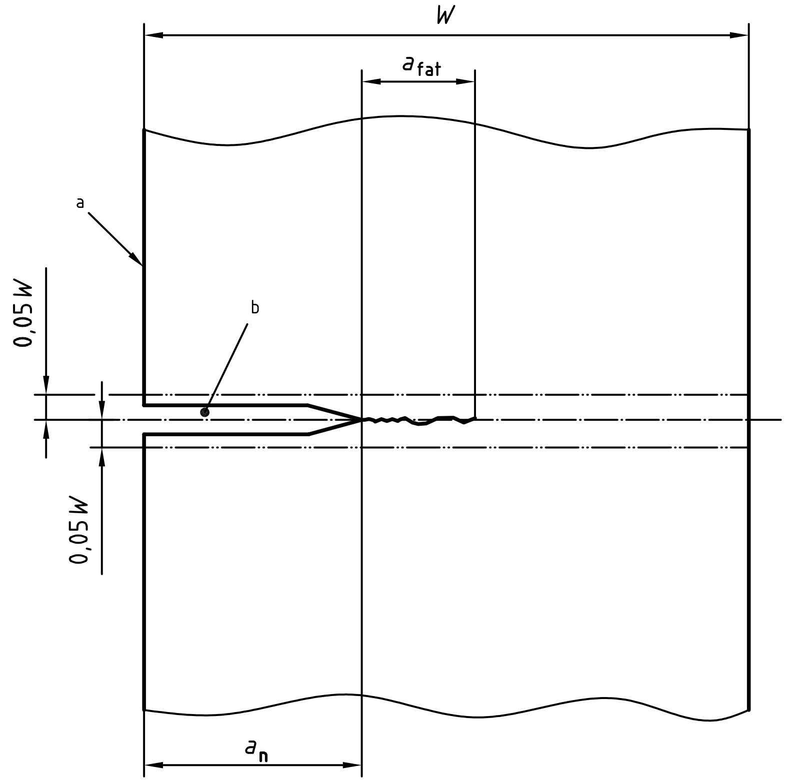

a Reference plane.

b Machined notch, a_n.

Figure 13 — Out-of-plane-cracking validity corridor

7.3 Constant-force-amplitude, K-increasing, test procedure for $da/dN > 10^{-5}$ mm/cycle

This procedure is appropriate for generating fatigue crack growth rate data above 10^{-5} mm/cycle. After stepping the maximum precracking force down to be equal or less than that corresponding to the lowest K_{max} in the range over which fatigue crack growth rate data will be generated, it is preferred that the force range be held constant as is the stress ratio and frequency. The maximum stress-intensity factor will increase with crack extension and should be allowed to increase to equal or exceed the greatest K_{max} in the range over which data will be generated. Several suggestions, aimed at minimizing transient effects while using this K-increasing procedure, follow. If test variables are to be changed, K_{max} shall be increased rather than decreased in order to preclude the retardation effects attributable to the previous force history. Transient effects can also occur following a change in K_{min} or the stress ratio. An increase of 10 % or less in K_{max} and/or K_{min} will usually minimize the transient effect reflected in the fatigue crack growth rate. Following a change in force conditions, sufficient crack extension shall be allowed to occur in order to re-establish a steady-state crack growth rate before the ensuing test data are accepted as valid under this test practice. The amount of crack extension required is dependent on many variables, e.g. percentage of force change, the test material and heat treatment condition. When environmental effects are present, the amount of crack extension required to re-establish the steady-state growth rate may increase beyond that required in a benign environment.

Test interruptions shall be kept to a minimum. If the test is interrupted, a change in growth rate may occur upon resumption of cycling. The test data immediately following the interruption shall be considered invalid if there is a significant demarcation in the crack velocity from the steady-state growth rate immediately preceding the suspension of cycling. The sphere of influence of the transient effect may increase with the steady-state force applied to the specimen during the suspension of dynamic force cycling.

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7.4 K-decreasing procedure for $\mathrm{d}a/\mathrm{d}N < 10^{-5}$ mm/cycle

This K-decreasing procedure may result in different crack growth rates dependent on the test K-gradient, C. It is the user's responsibility to verify that the crack growth rates are not sensitive to the test K-gradient, C.

Testing starts at a K_{max} or stress-intensity factor range, ΔK, equal to or greater than that used for the final crack extension while precracking. Following crack extension, the stress-intensity factor range is stepped down, or continuously shed, at a constant rate until test data have been recorded for the lowest stress-intensity factor range or fatigue crack growth rate of interest. The rate of force shedding with increasing crack size shall be small enough to prevent anomalous data resulting from the reduction in stress-intensity factor.

The K-decreasing test may be controlled by a stepped stress-intensity factor following a selected crack extension at a constant ΔF, as shown in Figure 14. Alternately, the stress-intensity factor gradient per increment of crack extension may be held constant, $1/\mathrm{d}a\ (\mathrm{d}K/K) =$ constant, called continuous stress-intensity factor shedding, by using a computer-automated test control procedure [46]; the constant, C, is called the normalized K-gradient. Typically, $C \geq -0{,}1\ \mathrm{mm}^{-1}$. However, research has shown that this value may be material- and specimen-geometry dependent [47],[48].

This value usually provides a gradual enough force shed to preclude a transient in the crack growth rate. The relationship between K and crack length for a constant-C test can be rewritten for convenience in the integrated form as:

$$\Delta K_{i(j)} = \Delta K_{i(j-1)} e^{C \Delta a_{(j-1)}} \tag{13}$$

where

$\Delta K_{i(j)}$ and $\Delta K_{i(j-1)}$	are the initial stress-intensity factor range at step j and j–1, respectively;
$\Delta a_{(j-1)} = [a_{(j)} - a_{(j-1)}]$	is the crack extension at the preceding constant force range $\Delta F_{(j-1)}$.

The stress ratio, R, and the normalized K-gradient, C, should be kept constant throughout the K-decreasing test. It is recommended that K-decreasing be followed by K-increasing test procedure, as covered in 7.3.

When using the stress-intensity factor stepped drop procedure, the reduction of K_{max} shall not exceed 10 % of the previous maximum stress-intensity factor and a minimum crack extension $\Delta a \geq 0{,}50$ mm at each stress intensity step is recommended.

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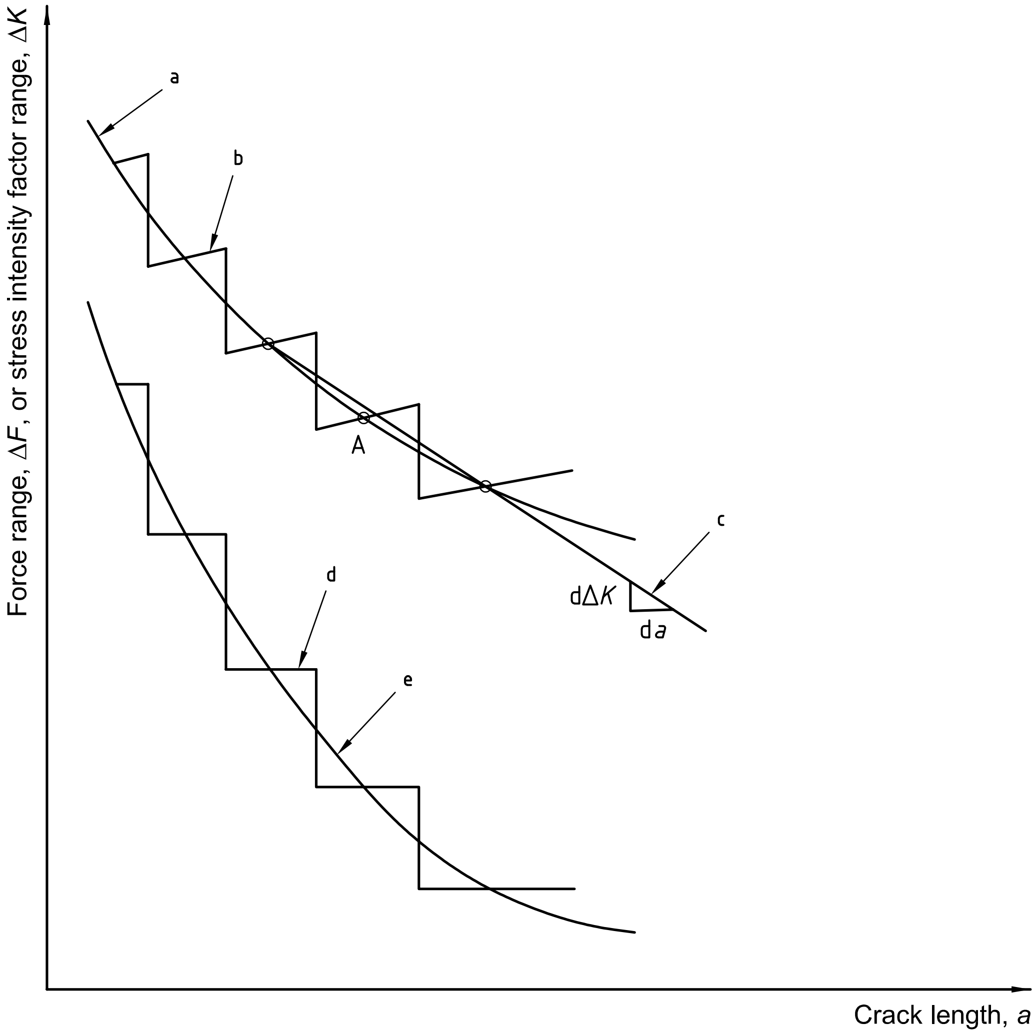

a ΔK nominal.

b ΔK actual.

c Slope approximately nominal $\frac{d\Delta K}{da}$ at point A.

d ΔF actual.

e ΔF nominal.

Figure 14 — Typical K-decreasing test by stepped force reduction method

When using a continuous stress intensity shedding procedure, the above requirement is inoperative. It is better to keep the force range constant for a very small crack extension, $\Delta a_{(j-1)}$. Here, continuous stress-intensity factor shedding is defined by the drop in initial stress-intensity factor range, $\Delta K_{i\,(j)}$, with each step, j, which may not exceed 2 % of the preceding initial stress-intensity factor range, corresponding to:

$$\left[\frac{\Delta K_{i(j-1)} - \Delta K_{i(j)}}{\Delta K_{i(j)}}\right] \leq 0{,}02 \qquad (14)$$

For example, if the common value $C = -0{,}1\ \text{mm}^{-1}$ is used, along with the maximum 2 % drop in each initial stress intensity range, then the exponent $C = \Delta a_{(j-1)}$ and the crack extension for each constant force range equals $\Delta a_{(j-1)} = 0{,}2$ mm:

$$\frac{\Delta K_{i(j)}}{\Delta K_{i(j-1)}} = e^{C\Delta a_{(j-1)}} \qquad (15)$$

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$$0{,}980 = e^{(-0{,}1)(0{,}2)} = \frac{1}{2{,}718\ 3^{0{,}02}} = \frac{1}{1{,}020\ 2}$$

8 Crack length measurement

8.1 Resolution

The fatigue crack length measurements made as a function of elapsed force cycles may be made by techniques outlined in 5.6. The resolution for crack length should be equal to or better than $0{,}002W$.

When making visual crack length measurements, it is recommended that the surface in the area of the crack plane be polished and indirect lighting be used to enhance the visibility of the crack tip. It is highly recommended that crack length measurements be made on both the front and back faces of the specimen, to ensure that crack symmetry requirements specified in 8.5 are met. The average of the surface crack length measurements, two for a CT, SENT and SENB specimens, and four for the CCT specimen, shall be used in calculating the crack growth rate and stress-intensity factor range. If crack length is not measured on both faces for every crack length measurement, then the interval between both front and back face measurements shall be reported. It is good practice to make regular comparisons between visual and non-visual measurement methods.

8.2 Interruption

Suspension of force cycling while making crack length measurements, although permitted, is discouraged and shall be avoided when possible. The duration and frequency of any interruptions should be kept to a minimum. Test interruption for making visual crack length measurements can be avoided by using strobe light illumination.

8.3 Static force

A static force may be maintained to enhance the resolution of the crack length measurements. A static force equal to or less than the fatigue mean force is usually acceptable. In corrosive or elevated-temperature environments, the mean force may introduce transient creep or blunting effects. In no case shall the applied static force exceed the maximum fatigue force. See 7.3.

8.4 Measurement interval

Crack length measurement shall be made so that $\mathrm{d}a/\mathrm{d}N$ data are uniformly distributed over the range of ΔK of interest. The following measurement intervals are recommended to provide a uniform data distribution:

— for the CT and SENB specimens,

$$\Delta a \le 0{,}04W \text{ for } 0{,}25 \le a/W < 0{,}40$$

$$\Delta a \le 0{,}02W \text{ for } 0{,}40 \le a/W < 0{,}60$$

$$\Delta a \le 0{,}01W \text{ for } a/W \ge 0{,}60;$$

— and for the CCT specimen,

$$\Delta a \le 0{,}03W \text{ for } 2a/2W \le 0{,}60$$

$$\Delta a \le 0{,}02W \text{ for } 2a/2W > 0{,}60.$$

However, a minimum Δa of 0,25 mm is recommended. The above limits may need to be reduced in order to obtain multiple crack length measurements in the near threshold region. The minimum crack measurement interval in all cases must exceed 10 times the crack length measurement precision. Here, precision is defined as the standard deviation from the mean value crack length determined for a set of repeat measurements.

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8.5 Symmetry

As in 7.2, for any crack length measurement, the data are invalid if

a) for a given crack front, the front and back crack length measurements differ by more than 0,25B, and

b) for a CCT specimen, the symmetry of the two crack fronts differs by more than 0,05W. In this case, the crack is not suitable and the data are invalid by this test method.

When using a nonvisual method for crack length measurement, the crack length should be visually checked for symmetry at the test start and finish, and at least three additional, evenly spaced, intermediate measurements are recommended.

8.6 Out-of-plane cracking

If the crack deviates from the theoretical crack plane by more than the 0,05W corridor, as covered in 7.2, the ensuing data are invalid. See Figure 13. Large-grained or single-crystal materials can commonly violate this requirement for out-of-plane cracking.

8.7 Crack tip bifurcation

Crack front splitting or branching can be a source of variability in the measured fatigue crack growth rate data since it is not compensated for in the stress-intensity factor calculation. When crack tip branching or bifurcation is present, it shall be noted in the final report.

9 Calculations

9.1 Crack-front curvature

After completion of the test, the fracture faces shall be examined for through-thickness crack-front curvature. If a crack contour is visible, calculate an average through-thickness crack length using either three or five-points equally spaced across the specimen. The difference between the average through-thickness crack length and the corresponding crack length recorded during the test is the crack curvature correction length, a_{cor}. It is desirable to make the crack curvature correction calculation at more than one location on the fracture face where the fatigue crack front is clearly marked. If the crack curvature correction results in a more than 5 % difference in the calculated stress-intensity factor at any location, then this correction must be included when analysing the recorded test data, and the effective crack length becomes:

$$a = a_{\text{n}} + a_{\text{fat}} + a_{\text{cor}} \tag{16}$$

When the magnitude of the crack curvature correction varies with crack length, a linear interpolation is used to determine the correction for the intermediate data.

9.2 Determining the fatigue crack growth rate

9.2.1 General

The fatigue crack growth rate is determined from the test record data pairs of crack length and corresponding elapsed force cycles. Two common methods used for calculating the crack growth rate, the secant method and incremental polynomial method, are suggested here. Other mathematical techniques for calculating the crack growth rate are possible; the procedure used in calculating the growth rate shall be specified in the test report. The observed scatter in the fatigue crack growth rate data are influenced by the method of data reduction.

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9.2.2 Secant method

Calculating the crack growth rate via the secant method entails computing the slope of a straight line connecting two adjacent data pairs of crack length and elapsed cycle count and represents an average velocity:

$$\frac{\mathrm{d}a(j)_{\mathrm{avg}}}{\mathrm{d}N} = \frac{(a_j - a_{j-1})}{(N_j - N_{j-1})} \tag{17}$$

for the incremental crack extension, $a_j - a_{j-1}$.

The stress-intensity factor range is calculated using the average crack length over the increment of crack extension:

$$a(j)_{\mathrm{avg}} = \frac{(a_j + a_{j-1})}{2} \tag{18}$$

9.2.3 Incremental polynomial method

Calculating the crack growth rate by the incremental polynomial method (K-increasing only) requires fitting a polynomial to a segment of the data pairs: crack length, a_j, as a function of elapsed cycles, N_j. The data segment consists of an odd number of elements (3, 5 or 7), which are consecutive a_j versus N_j data pairs. The growth rate equals the slope of the polynomial, $\mathrm{d}a/\mathrm{d}N_j$, for the data segment's centremost element, e.g. for a data segment consisting of seven data pairs, the slope would be calculated as the derivative at the fourth element. The stress-intensity factor range associated with the data segment is determined by using the fitted crack length of the centremost element of the data segment. For a data segment consisting of 3, 5 or 7 elements, the fitted crack length corresponding to the second, third or fourth element, respectively, would be used in determining the stress-intensity factor range for the data segment.

9.3 Determination of the fatigue crack growth threshold

The crack growth threshold, ΔK_{th}, generally refers to the asymptotic value of ΔK for which the corresponding $\mathrm{d}a/\mathrm{d}N$ approaches zero. It is commonly defined as being the value of ΔK corresponding to a crack growth rate equal to 10^{-8} mm/cycle [25],[48]. The fatigue crack growth rate corresponding to the threshold stress-intensity factor range shall be reported. A common way to determine the threshold is to use a straight line fitted to a minimum of five, approximately equally spaced, log $\mathrm{d}a/\mathrm{d}N$ versus log ΔK data pairs between 10^{-7} mm/cycle and 10^{-8} mm/cycle; here, log ΔK is the dependent variable of the best fir straight line. Using this linear regression technique, the value of ΔK is defined by this test method, as the threshold stress-intensity factor range, ΔK_{th}, at a fatigue crack growth rate equal to 10^{-8} mm/cycle.

In the case where data are generated within different fatigue crack growth rate ranges, the above procedure may be used with the lowest decade of the $\mathrm{d}a/\mathrm{d}N$ test data.

10 Test report

10.1 General

The test report shall include a reference to this International Standard, i.e. ISO 12108, and the test date(s), plus the following information.

10.2 Material

All relevant available material details shall be reported, including the following:

a) standard alloy designation;

b) thermal/mechanical conditioning;

c) product form;

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d) chemical composition, if available;

e) heat and lot number, if available;

f) 0,2 % proof stress used to evaluate specimen size criteria;

g) ultimate tensile strength;

h) modulus of elasticity (required when compliance crack length measurements are used).

10.3 Test specimen

The following information regarding the test specimen shall be reported:

a) specimen configuration;

b) crack plane orientation (see Figure 11);

c) specimen location;

d) width, W;

e) thickness, B;

f) notch height, h;

g) stress-intensity factor expression as a function of crack length and force;

h) specimen drawing and the reference source for specimen configurations not included in this International Standard.

10.4 Precracking terminal values

The following information shall be reported:

a) elapsed cycles at final stress intensity range;

b) final crack extension;

c) final crack length, a_p;

d) final stress-intensity factor range;

e) final maximum stress-intensity factor;

f) force ratio;

g) cyclic waveform;

h) precracking method (constant force, K-decreasing, constant K_{max}, etc.);

i) environmental conditions (temperature, humidity, etc.);

j) crack symmetry and out-of-plane cracking checks.

10.5 Test conditions

All of the test variables, including the following, shall be reported:

a) testing machine force capacity;

b) measurement cell force range;

c) initial stress-intensity factor range, ΔK_i;

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d) force ratio;

e) forcing frequency;

f) cyclic waveform;

g) test procedure used (K-increasing or K-decreasing);

h) test environment;

i) test temperature;

j) laboratory relative humidity;

k) crack curvature correction, a_{cor};

l) K-gradient, if the K-decreasing procedure is used;

m) method of crack length measurement.

10.6 Test analysis

Information that describes the analysis methodologies used shall be reported, and at a minimum should include:

a) analysis method for converting the crack length, a, and elapsed force cycles, N, data to crack growth rate da/dN, i.e. the secant method, incremental polynomial method, etc.;

b) definition of ΔK for negative force ratio ($R < 0$) conditions, i.e. full-range or truncated;

c) remaining ligament size criteria used to ensure predominant elastic loading in a non-standard test specimen configuration;

d) report ΔK_{th} and the lowest decade of near threshold crack growth rate data used in its determination, if applicable;

e) exceptions to this test method;

f) anomalies that could affect test results, e.g. test interruptions or changing the loading variables;

g) identification of invalid data points to include both precracking and test data (i.e. symmetry, crack plane, etc.).

10.7 Presentation of results

The results of the fatigue crack growth test shall be tabulated including a_{fat}, a, N, ΔK and da/dN, as presented in Figure 15. Figure 15 can be expanded, as necessary, to include all measured crack lengths and forcing conditions. See Figure 17.

In addition, the results shall also be presented in a log-log plot with log(ΔK) plotted on the abscissa and log(da/dN) on the ordinate. For optimum data comparison, it is recommended that the size of the log(ΔK) cycle be two to three times larger than that of the log(da/dN) cycle, as shown in Figure 16. For both the plot and the table, data violating the validity criteria shall be clearly identified. An example of the presentation of fatigue crack growth data are shown in Figures 17 and 18. When a negative force ratio ($R < 0$) is used, the method of calculating the stress-intensity factor range, $\Delta K = (1 - R)\ K_{max}$ or $\Delta K = K_{max}$, shall be clearly identified on both the table and optional figure; also see 3.11 stress-intensity factor range, ΔK.

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FATIGUE CRACK GROWTH TEST RESULTS [REFERENCE ISO/TC 164/SC 5/WG 6]

Date………………………….. Specimen I.D. Mark………………………. Page 1 of………………......

MATERIAL………………………………………………. Product form………………………………………………...
Thermal/mechanical conditioning………………………………………………………………………………………
Chemical composition…………………………………………………………………………………………………..

MECHANICAL PROPERTIES AT TEST TEMPERATURE
Ultimate tensile strength……………………..MPa 0,2 % Proof strength…………………………….MPa
Modulus of elasticity…………………………MPa

SPECIMEN
Dimensions: Thickness, B…………mm Width, W…………mm Machined notch length, a_n……………mm
Crack plane orientation…………………. Notch, h…………..mm Specimen location…………………………
Stress-intensity factor reference……………………………………………………………………………………..

PRECRACK TERMINAL VALUES
Final crack extension, Δa…………………….mm Preceding K_{max} (j–1)………………………………..MPa·m$^{1/2}$
Final crack length, a_p………………………..mm Force ratio……………………………………………………..
Final K_{max} (j)………………………….. MPa·m$^{1/2}$ Final load cycles………………………………………………
Final ΔK (j)…………………………...MPa·m$^{1/2}$ Cyclic waveform………………………………………………

TEST CONDITIONS
Test machine capacity………………………….. Environment……………………………………………………..
Force transducer range…………………………. Temperature…………………………………………………°C
Measurement interval of a, Δa……………...mm Relative humidity………………………………………………%
Force frequency……………………………Hz Force ratio……………………………………………………..
Test procedure…………………………………. K-gradient……………………………………………...m^{-1}
Crack correction……………………………..mm Cyclic waveform………………………………………………
Initial ΔK_i……………………………..MPa·m$^{1/2}$ Initial force range……………………………………………kN
Crack measurement method………………………………………………………………………………………

TEST ANALYSIS
Threshold stress-intensity factor range, ΔK_{th}…………………………………………………………...MPa·m$^{1/2}$
Threshold crack growth rate decade…………………………………………………………………mm/cycle
Analysis method…………………………………………………………………………………………………
Remaining size criteria Ref:……………………………………………………………………………………….

EXCEPTIONS, ANOMALIES AND COMMENTS

Figure 15 — Test report

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Page ……. of …….

MATERIAL:……………………… SPECIMEN I.D.:…………………...…… DATE:…………………………….

Measurement number	a_{fat} (mm)	N (cycles)	a (mm)	$a_{(j)avg.}$ (mm)	$g(a/W)$	ΔK (MPa√m)	da/dN (mm/cycle)	

Figure 15 — Test report *(continued)*

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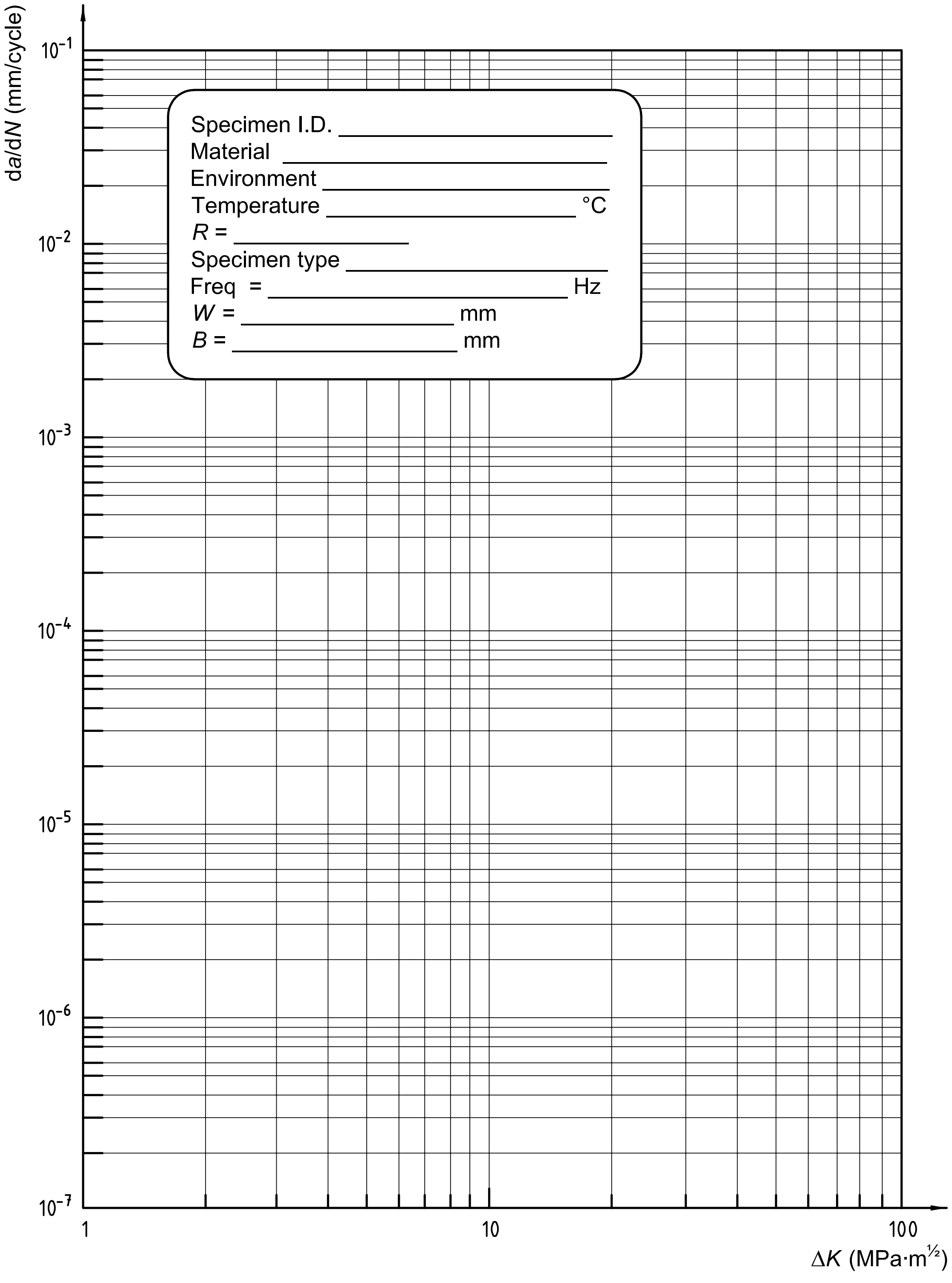

Figure 16 — Example axis for plotting log (da/dN) versus log (ΔK) test data

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FATIGUE CRACK GROWTH TEST RESULTS [REFERENCE ISO/TC 164/SC 5/WG 6]

Date…………1/9/90………….. Specimen I.D. Mark………N410………. Page 1 of………2……......

MATERIAL………………16MND5…………………… Product form………………forging……………………..

Thermal/mechanical conditioning……………………………………………………………………………………

Chemical composition……………………………………………………………………………………………...

MECHANICAL PROPERTIES AT TEST TEMPERATURE

Ultimate tensile strength………………..611 MPa 0,2 % Proof strength………………………423 MPa

Modulus of elasticity…………………………MPa

SPECIMEN

Dimensions: Thickness, B………25 mm Width, W……...50 mm Machined notch length, a_n………..10 mm

Crack plane orientation……………Y-Z Notch, h………..1 mm Specimen location…………1/4 thickness

Stress-intensity factor reference………ISO/TC 164/SC 5/WG 6……………………………………………………..

PRECRACK TERMINAL VALUES

Final crack extension, Δa…………………….mm Preceding K_{max} (j–1)………………………………….MPa·m$^{1/2}$

Final crack length, a_p………………...12,50 mm Force ratio…………0,1………………………………………..

Final K_{max} (j)………………………….. MPa·m$^{1/2}$ Final load cycles…………………………………………………

Final ΔK (j)…………………………..…MPa·m$^{1/2}$ Cyclic waveform………sinusoidal..……………………………

TEST CONDITIONS

Test machine capacity………………………….. Environment…………air………………………………………...

Force transducer range……………………….. Temperature……………………………………………300°C

Measurement interval of a, Δa…………1,2 mm Relative humidity………………………………………………%

Force frequency……………………………1 Hz Force ratio……………………………………………………..0,1

Test procedure……………………..K-increasing K-gradient……………………..…………………………mm^{-1}

Crack correction……………………………0 mm Cyclic waveform…………sinusoidal………………………….

Initial ΔK_i…………………………18,07 MPa·m$^{1/2}$ Initial force range……………………………………19,620 kN

Crack measurement method……………………compliance……………………………………………………………

TEST ANALYSIS

Threshold stress-intensity factor range, ΔK_{th}…………………………………………………………...MPa·m$^{1/2}$

Threshold crack growth rate decade……………………………………………………………………mm/cycle

Analysis method…………secant………………………………………………………………………………………….

Remaining size criteria Ref:…………………………………ISO 12108

EXCEPTIONS, ANOMALIES AND COMMENTS

[1] Crack-front curvature correction, a_{corr} = 0 mm [2] Data violates remaining ligament size criteria

Figure 17 — Example of a test report

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Page 2 of 2

MATERIAL:…16 MND 5………….. SPECIMEN I.D.:……N410……………… DATE:………1/9/90………...

Measurement number	a_{fat} (mm)	N (cycles)	a (mm)	$a_{(j)avg.}$ (mm)	$g(a/W)$	ΔK (MPa√m)	da/dN (mm/cycle)	
1	4,20	205 000	14,20					
2	5,60	237 080	15,60	14,90	5,59	19,62	4,36E-05	[1]
3	6,80	258 200	16,80	16,20	5,98	20,99	5,68E-05	
4	8,80	280 720	18,80	17,80	6,49	22,78	8,88E-05	
5	10,10	293 050	20,10	19,45	6,98	24,50	1,05E-04	
6	12,30	310 000	22,30	21,20	7,76	27,24	1,30E-04	
7	14,00	321 800	24,00	23,15	8,65	30,36	1,44E-04	
8	15,50	328 500	25,50	24,75	9,51	33,38	2,24E-04	
9	17,50	336 000	27,50	26,50	10,63	37,31	2,67E-04	
10	18,35	338 800	28,35	27,93	11,68	41,00	3,04E-04	
11	19,70	342 300	29,70	29,03	12,70	44,58	3,86E-04	
12	20,50	343 800	30,50	30,10	13,76	48,30	5,33E-04	[2]
13	21,40	345 380	31,40	30,95	14,74	51,74	5,70E-04	[2]
14	22,65	346 720	32,65	32,03	16,16	56,83	9,33E-04	[2]
15	23,80	347 730	33,80	33,23	18,03	63,43	1,14E-03	[2]
16	24,77	348 230	34,77	34,29	20,01	70,35	1,94E-03	[2]

Figure 17 — Example of a test report *(continued)*

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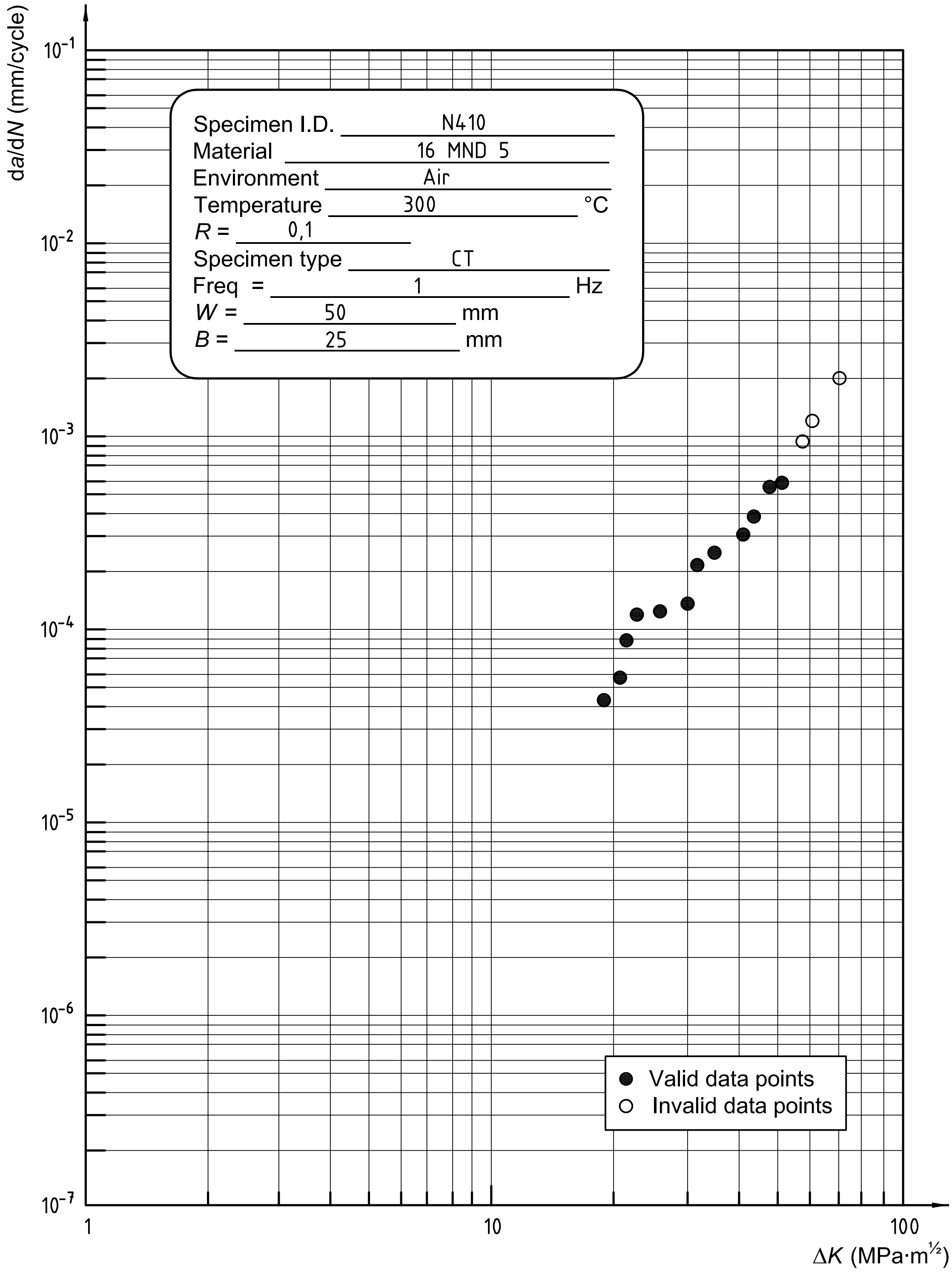

Figure 18 — Example plot of a fatigue crack growth test result

Annex A
(informative)

Non-visual crack length measurement methodology — Electric potential difference [18] [24] [33]

A.1 General principles

Crack length determination through the use of electric potential difference (EPD) is applicable to practically any electrically conductive material. This method involves the passing of an electric current of constant magnitude through the test specimen and measuring the change in the electric potential across the crack plane during propagation. As the crack length increases, the resulting electrical resistance increases due to the reduced cross sectional area remaining in the specimen. Through basic electrical principles, this change in resistance results in a change in the voltage measured between two points that span the crack plane. By monitoring this change in voltage, and comparing it with a reference voltage and reference crack length, a crack length measurement can be determined through the use of a relevant calibration curve for the particular test specimen geometry. This calibration will have been developed either experimentally, analytically, or numerically. Experimental validation is desirable for analytical or numerical solutions. It should be noted that for the direct current and low frequency alternating current systems, described below, the resultant crack length may be considered to be an average measurement across the thickness of the specimen. For materials that exhibit significant crack-front curvature, this average measurement may not correspond to optically measured surface crack lengths.

For non-conductive materials, the use of bonded foils or films is possible as long as the replicate matches the crack length in the specimen and doesn't affect the growth rate in the specimen. This replicate method can also be used on conductive materials as well. The biggest drawback to the use of these surface-affixed foils is that they will only replicate the surface crack length. For thicker specimens, or those that exhibit nonlinear crack fronts, there could possibly be significant differences between the physical crack length and that determined by electric potential.

A.2 Basic methods

A.2.1 General

Direct current (DC) and alternating current (AC) techniques have been used for the measurement of crack lengths during fatigue crack growth rate testing. Although the DC method is more commonly employed, both methods can provide a satisfactory level of performance. Regardless of the method used, care should be taken to understand possible sources of error that could occur. For example, as a crack grows and the two halves of the specimen come into contact with each other during cycling, there is a possibility of electrical shorting across the crack plane. This shorting can lead to an under-estimation of the physical crack length. However, most materials will develop an insulating layer of oxide during the formation of new fracture surfaces during propagation. This insulation will prevent the shorting from occurring during the test, provided the overall closure forces do not compromise this oxide layer.

Unless it can be demonstrated that shorting is not occurring in the specimen, voltage readings should be taken at or near the peak tensile force during loading. While this will not guarantee the absence of shorting, it should minimize the effect. Errors due to this effect can be resolved post-test using physical crack length measurements and using a simple linear interpolation comparison to correct the electric potential measurements. However, this correction cannot be employed for testing that requires an accurate crack length measurement for testing control (e.g. constant ΔK testing).

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Under both methods described herein, the test specimen needs to be electrically isolated from the test frame. Since the methods rely on the measurement of voltage based on a constant current magnitude, it is critical that there are no parallel paths for the applied current. The resistance of the test frame (between the specimen grips, without specimen in place) should be at least 10^4 greater than the resistance of the specimen alone. If necessary, specially-designed isolation grips should be used to achieve this resistance ratio.

A.2.2 Direct current method

The DC method is the more commonly used technique for measuring electric potential difference due to the readily available equipment typically found in most testing facilities. This method provides an average crack length across the thickness of the specimen and, as such, is well-suited for automated crack growth systems operating under K-control.

This method is subject to possible errors due to thermoelectric effects which can be a significant portion of the overall measured voltage. However, these effects can be minimized through

a) the use of voltage-probe-wire material similar to that of the test material,

b) maintaining current and voltage instrumentation at a constant temperature, and

c) maintaining a constant temperature for the specimen during the test.

It is possible to account for these effects by subtracting voltage measurements taken with the current off from the measurements made with the current on. An alternate method corrects for this by taking voltage measurements while reversing the direction of current flow. Corrected EPD measurements are then equal to one-half of the difference of the measured voltage readings taken at each current polarity.

A.2.3 Alternating current method

A.2.3.1 General

The AC method is typically sub-classified into low and high frequency systems. Although the principles behind both DC and AC methods are the same, the equipment used for the AC method tends to be more specialized, and as such this method is capable of providing a higher crack length resolution due in part to the specific amplifiers and filters utilized. Also, the AC method is not subject to thermoelectric effects as sometimes seen while using the DC method.

A.2.3.2 Low frequency systems

The low frequency AC method (typically operating in the range 10 Hz to 100 Hz) is similar to the DC method with the exception of the equipment necessary for producing the current and for measuring the resultant voltages. Care should be taken to ensure that the testing frequency is not producing crack plane bridging effects that exhibit themselves as unwanted signal components on the AC voltage frequency.

A.2.3.3 High frequency systems

The high frequency AC method (5 kHz to 8 kHz) takes advantage of the localization of the current flow to the “skin” of the specimen. This “skin effect” effectively reduces the specimen thickness to the surface layers, and since the output voltage is inversely proportional to the specimen thickness, the use of this method produces a higher crack length resolution for a given current input. However, if this effect is very pronounced, only surface crack lengths will be measured and any crack-front curvature will be ignored in the measurement. Also, with this method, extra diligence needs to be taken to prevent effects from induction and capacitance contributions from the current lead wires, specimen attachment points, and the crack itself. These effects can be significant in magnitude, making it difficult to relate the measured voltage to the actual crack length.

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These issues can be minimized by

a) keeping the current input and the voltage measurement leads away from each other,

b) keeping the voltage measurement leads as short as possible and twisting them to reduce stray voltages,

c) keeping the wires rigid during the test to prevent movement of the wires through magnetic fields,

d) keeping equipment that produce strong magnetic fields at a distance from the test equipment, and

e) using proper equipment grounding procedures.

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Bibliography

[1] GRIFFITH A.A. The Phenomena of Rupture and Flow in Solids. *Phil. Trans. Roy. Soc.* 1920, **A221** pp. 163–198

[2] IRWIN G.R. *Fracture Dynamics in Fracturing of Metals*. American Society of Metals, 1948, pp. 147–66

[3] IRWIN G.R. Proceedings from Ninth International Congress on Applied Mechanics, Univ. of Brussels, Vol. 8, 1957, pp. 245-251

[4] IRWIN G.R. ASME. *J. Appl. Mech.* 1957, **24** pp. 361–364

[5] PARIS P.C. *The Fracture Mechanics Approach to Fatigue*, Proceedings of the Tenth Sagamore Army Material Research Conference, Syracuse University Press, 1964, pp. 107-132

[6] RITTER, J.C., *Fracture Mechanics Principles*, Department of Defence Australian Defence Scientific Service, Materials Research Laboratories, Maribyrnong Victoria, Report 661, May 1976

[7] ASTM SI-10, *Standard for Use of the International System of Units (SI): The Modern Metric System*

[8] ISO 12737:1996, *Metallic materials — Determination of plane-strain fracture toughness*

[9] MURAKAMI Y. *Stress-intensity Factor Handbook*. Paragon Books Ltd, Oxford, UK, 1987

[10] TADA H., PARIS P.C. and IRWIN G.R. *Stress Analysis of Cracks Handbook*. Paris Production Inc, St. Louis, MO, Second Edition, 1985

[11] ROOKE D.P. and CARTWRIGHT D.J. *Stress-intensity Factors*. Her Majesty's Stationary Office, The Hillingdon Press, Uxbridge, UK, 1976

[12] PARKER A.P. Stress-intensity factors, Crack Profiles and Fatigue Crack Growth Rates in Residual Stress Fields. *Residual Stress Effects in Fatigue, ASTM STP*. 1982, **776** pp. 13–31

[13] BUCCI R.J. *Effect of Residual Stress on Fatigue Crack Growth Rate Measurement*, Fracture Mechanics (13th Conference), ASTM STP 743, 1981, pp. 28-47

[14] ELBER W. The Significance of Crack Closure. *Damage Tolerance in Aircraft Structures, ASTM STP*. 1971, **486** pp. 230–242

[15] ELBER W. Fatigue Crack Closure Under Cyclic Tension. *Eng. Fract. Mech.* 1970, **2** pp. 37–45

[16] CLARK, W.G. JR and HUDAK, S.J., Variability in Fatigue Crack Growth Rate Testing. *J. Test. Eval.* 1975, **3** (6) pp. 454–476

[17] HERMAN W.A., HERTZBERG R.W., NEWTON C.H. and JACCARD R. *A Re-evaluation of Fatigue Threshold Test Method*. Fatigue '87, Vol II, Third International Conference on Fatigue and Fatigue Threshold held at the University of Virginia, Charlottesville, VA, EMAS W. Midlands U.K., Editors R.O. Ritchie and E.A. Starke Jr., July 1987, pp. 819-828

[18] ASTM E 647, *Standard Test Method for Measurement of Fatigue Crack Growth Rates*

[19] ASTM E 4, *Standard Practices for Force Verification of Testing Machines*

[20] ASTM E 399, *Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials*

[21] ASTM E 616, *Terminology Relating to Fracture Testing (now withdrawn)*

[22] ASTM E 1012, *Standard Practice for Verification of Specimen Alignment Under Tensile Loading*

[23] ASTM E 1820, *Standard Test Method for Measurement of Fracture Toughness*

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[24] BSI BS 6835:1988, *Method for the determination of the rate of fatigue crack growth in metallic materials. Fatigue crack growth rates of above 10^{-8} m per cycle*

[25] BSI DD 186:1991, *Method for determination of threshold stress-intensity factors and fatigue crack growth rates in metallic materials*

[26] AFNOR A 03-404, *Metallic products fatigue crack growth testing*

[27] SRAWLEY J.E. Wide Range Stress-Intensity Factor Expressions for ASTM E 399 Standard Fracture Toughness Specimens, *Int. J. Fract.* 1976, **12** p. 475

[28] JOHN R., KALDON S.G., JOHNSON D.A. and COKER D. Cracked Geometry with Clamped Ends.*Int. J. Fract.* 1995, **72** pp. 145–158

[29] MARCHAND N., PARKS D.M. and PELLOUX R.M. Ki-Solutions for Single Edge Notch Specimens under Fixed End Displacements. *Int. J. Fract.* 1986, **31** pp. 53–65

[30] JOHN, R. and RIGLIN, B., *Engineering Fracture Mechanics*, Submitted for publication, 1997

[31] DAO, T.X. and METTU, S.R., *Analysis of an Edge-Cracked Specimen Subject to Rotationally-Controlled End Displacement*, NASA JSC32171, 1991

[32] HOEPPNER D.W., KRUPP W.E. Prediction of Component Life by Application of Fatigue Crack Growth Knowledge. *Eng. Fract. Mech.* 1974, **6** pp. 47–70

[33] Metals Handbook, Ninth Edition, Vol. 8, *Mechanical Testing*, J.R. Newby, Coordinator, American Society ofMetals, Metals Park. *OH*. 1987, (June) pp. 376–402

[34] ASM Handbook, Vol. 19. *Fatigue and Fracture*. ASM International, Materials Park, OH, 1996

[35] HARTMAN, G.A. and ASHBAUGH, N.E. *Load Pin Size Effects in the C(T) Geometry*, ASTM Research Report RR E24-1016, Oct. 1991

[36] BEEVERS C.J. *The Measurement of Crack Length and Shape During Fracture and Fatigue*. Engineering Materials Advisory Service LTD, West Midlands, UK, 1980

[37] HUDAK, S.J. Jr. and BUCCI, R.J. *Fatigue Crack Growth Measurement and Data Analysis*, ASTM STP 738, 1981

[38] SAXENA A. and HUDAK S.J. Review and Extension of Compliance Information for Common Crack Growth Specimens. *Int. J. Fract.* 1978, **14** (5) pp. 453–468

[39] BEEVERS C.J. *Advances in Crack Length Measurement*. Engineering Materials Advisory Board LTD, West Midlands, UK, 1982

[40] WILKOWSKI G.M. and MAXEY W.A. *Review and Application of the Electric Potential Method for Measuring Crack Growth in Specimens*, Flawed Pipe, and Pressure Vessels, Fracture Mechanics: Fourteen Symposium-Volume II, Testing and Applications, ASTM STP 791, Editors: J.C. Lewis and G. Sines, American Society of Testing and Materials, Philadelphia, PA, pp. II-266-II-294

[41] CATLIN W.R., LORD D.C., PRATER T.A. and COFFIN L.F. The Reversing D.C. Electrical Potential Method. *Automated Test Methods for Fracture and Fatigue Crack Growth, ASTM STP*. 1985, **877** pp. 67–85

[42] DEAN W.F. and RICHARDS C.E. A Simple and Sensitive Method of Monitoring Crack and Load in Compact Fracture Mechanics Specimens Using Strain Gages. *J. Test. Eval.* 1979 May, **7** (3) pp. 147–154

[43] PARIS P.C. and HAYDEN B.R. *A New System for Fatigue Crack Growth Measurement and Control*, ASTM Symposium on Fatigue Crack Growth, Pittsburgh, PA, October 1979

[44] LIAW P.K., HARTMANN H.R. and LOGSDON W.A. A New Transducer to Monitor Fatigue Crack Propagation. *J. Test. Eval.* 1983 May, **11** (3) pp. 202–207

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[45] LIAW P.K., LOGSDON W.A., ROTH L.D. and HARTMANN H.R. In: *Krak-Gages for Automated Fatigue Crack Growth Rates Testing: A Review, Automated Test Methods for Fracture and Fatigue Crack Growth, ASTM STP 877*. (CULLEN W.H., LANDGRAF R.W., KAISAND L.R., UNDERWOOD J.H., eds.). American Society for Testing and Materials, Philadelphia, 1985, pp. 177–96.

[46] SAXENA A., HUDAK S.J., DONALD J.K. and SCHMIDT D.W. Computer-Controlled Decreasing Stress Intensity Technique for Low Rate Fatigue Crack Growth Testing. *J. Test. Eval.* 1978, **6** (3) pp. 167–174

[47] HUDAK S.J., SAXENA A., BUCCI R.J. and MALCOLM R.C. *Development of Standard Methods of Testing and Analyzing Fatigue Crack Growth Rate Data — Final Report, AFML TR 78-40*. Air Force Materials Laboratory, Wright Patterson Air Force Base, OH, 1978

[48] DOKER H., BACHMANN V. and MARCI G. *A Comparison of Different Methods of Determination of the Threshold for Fatigue Crack Propagation, in Fatigue Threshold*, Proceedings of an International Conference held in Stockholm June 1-3, 1981, p. 45, Editors: J. Backlund, A.F. Blom and C.J. Beavers (Set 2 Volumes), 1982

[49] ASTM E 561, *Standard Test Method for K-R Curve Determination*

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ICS 77.040.10

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