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Aerospace series — Test methods for metallic materials — Determination of fatigue crack growth rates using Corner-Cracked (CC) test pieces

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National foreword

This British Standard is the UK implementation of EN 3873:2010.

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

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Série aérospatiale - Méthodes d'essais applicables aux matériaux métalliques - Détermination de la vitesse de propagation de fissure en fatigue à l'aide d'éprouvettes avec fissure en coin

Luft- und Raumfahrt - Prüfverfahren für metallische Werkstoffe - Ermittlung der Rißfortschritts- Geschwindigkeit an Cornercrackproben (Eckanris)

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COMITÉ EUROPÉEN DE NORMALISATION
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Foreword

This document (EN 3873:2010) has been prepared by the Aerospace and Defence Industries Association of Europe - Standardization (ASD-STAN).

After enquiries and votes carried out in accordance with the rules of this Association, this Standard has received the approval of the National Associations and the Official Services of the member countries of ASD, prior to its presentation to CEN.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by May 2011, and conflicting national standards shall be withdrawn at the latest by May 2011.

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Introduction

This standard and its parts belong to the general organization of the ASD collection of metallic material standards for aerospace applications

1 Scope

This standard specifies the requirements for determining fatigue crack growth rates using the corner-crack (CC) test piece. Crack development is measured using a potential-drop system, and the calculated crack depths can be corrected via marker bands created on the fracture surface during the test. Results are expressed in terms of the crack-tip stress-intensity range (ΔK), with crack depths and test stress level noted.

2 Normative references

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

EN 2002-002, *Aerospace series — Metallic materials — Test methods — Part 002: Tensile testing at elevated temperature*

EN ISO 7500-1, *Metallic materials — Verification of static uniaxial testing machines — Part 1: Tension/compression testing machines — Verification and calibration of the force-measuring system (ISO 7500-1:2004)*

EN ISO 3785, *Metallic materials — Designation of test specimen axes in relation to product texture (ISO 3785:2006)*

ASTM E 647-2008*, Standard test method for measurement of fatigue crack growth rates* 1)

ASTM E 1012-2005, *Verification of test frame and specimen alignment under tensile and compressive axial force application* 1)

3 Symbols and abbreviations

a	Crack depth. The crack depth a is the distance from the extrapolated original corner containing the notch to the centre of the crack front (45° position). For the calculation of stress-intensity factor, the crack length must be given in metres
a_e	Final crack depth (in millimetres)
a_i	Initial crack depth (in millimetres)
a_m	Measured crack depth (optical, post-test fracture surface micrography or with SEM)
	a_v Calculated (Potential) crack depth is the average crack depth due to the averaging nature of the potential measurement method. Calculation involving average lengths measured at several positions along the crack front are best for correlation with the potential measurements (in millimetres)
Δa	Crack growth increment (in millimetres)
da/dN	Fatigue crack growth rate (FCGR) (in metres per cycle)
W	Test piece width (in millimetres)

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1) Published by: American Society for Testing and Materials (ASTM), http://www.astm.org/.

a/W	Normalized crack depth (in millimetres/millimetres)
f	Frequency (in Hertz)
E	Young's modulus (in gigapascals)
K	Stress-intensity factor (general) The stress-intensity factor K is a load parameter which characterises the stress field at the crack tip. It is a function of load, crack depth and test piece geometry (in MPa $\sqrt{}$m)
$K_{max.}$	Maximum value of K during a loading cycle, corresponding to the maximum tensile force applied (in MPa $\sqrt{}$m)
$K_{min.}$	Minimum value of K during a loading cycle (in MPa $\sqrt{}$m)
ΔK	Range of K during a loading cycle $= K_{max.} - K_{min.} = (1 - R)*K_{max.}$ (in MPa $\sqrt{}$m)
ΔK_{eff}	Effective range of K, due to crack closure-induced reduction applied ΔK (in MPa $\sqrt{}$m)
ΔK_{th}	Fatigue crack growth threshold The asymptotic value of ΔK for which da/dN approaches zero. For most materials the operational threshold is defined as the ΔK corresponding to 10^{-7} m/cycle. When reporting ΔK_{th}, the corresponding lowest decade of near threshold data used in its determination must be given
C	Normalized K-gradient $C = (1/K \times dK/da)$. For load-shedding to attain a desired initial ΔK, C defines the fractional rate of change of K with increasing crack depth a. $C = 1/K \times dK/da = 1/K_{max.} \times dK_{max.}/da = 1/K_{min.} \times dK_{min.}/da = 1/\Delta K \times d\Delta K/da$, (in mm^{-1})
N	Number of loading cycles Stress cycle (fatigue cycle, load cycle) is the smallest segment of the loading waveform spectrum which is repeated periodically
N'	Number of stress cycles between two marker cycles
N_m	Number of stress cycles in a marker cycle
ΔN	Stress cycle difference
r	Notch radius (expressed in millimetres)
F_m	Mean force (expressed in kilonewtons)
$F_{max.}$	Maximum tensile force applied to the test piece during a cycle (expressed in kilonewtons)
$F_{min.}$	Minimum tensile force (in kilonewtons)
ΔF	Force range (in kilonewtons), $\Delta F = F_{max.} - F_{min.}$
q	Resolution of crack depth measuring system (expressed in millimetres)
R	Force ratio ($= F_{min.}/F_{max.} = K_{min.}/K_{max.}$)
R^*_m	Ratio $F_{min.}/F_{max.}$ during a marker cycle
R_p	0,2 % offset yield strength (Proof Stress $R_{p0,2}$) at test temperature (expressed in megapascals)

R_m	Tensile strength at test temperature (expressed in megapascals)
σ_f	Flow stress – here defined as the arithmetic mean of R_p and R_m (expressed in megapascals)
Z	Axial distance from crack plane to each wire used for potential measurement (expressed in millimetres) – ($2Z$ = wire separation distance)

4 General

4.1 The corner-crack (CC) test piece is useful in determining da/dN for components where the cracks usually appear at a corner, such as in holes in turbine disks. The determination involves the use of an axially-loaded test piece of square or rectangular cross-section. It may be loaded in tension and compression for positive and negative stress ratio testing if suitable end designs permit backlash-free loading.

A carefully defined and produced notch or a small arc strike enables cracking to be initiated at the centre of the reduced section. A fatigue crack is induced at the root of the notch by cyclic loading, and its growth is monitored by a suitable method, e.g. potential drop techniques. As the crack grows, the force range applied to the test piece is maintained or reduced in a controlled manner until the cracks are of sufficient depth for the influence of the notch and the crack initiation method to be negligible, and the ΔK has reached the lowest level of interest. The test is then carried out. The force range is maintained constant and the crack depth recorded as a function of elapsed cycles. These data are then subjected to numerical analysis, enabling da/dN to be determined as a function of ΔK.

4.2 The majority of metallic materials can be tested using the method described here, provided that the force applied is such as to ensure that the plastic zone in front of the crack tip is small in relation to the remaining cross section (linear-elastic criterion).

4.3 The test piece used here is a corner-crack (CC) test piece. See Figure C.1.

4.4 In the standard crack-growth test the load amplitude is assumed to be constant throughout the test, after the required ΔK level and R-ratio is reached. Another load range can be added if certain transient effects are to be investigated.

4.5 The range of the stress-intensity factor ΔK is:

$$\Delta K = K_{\text{max.}} - K_{\text{min.}} \tag{1}$$

where the ratio R

$$R = \frac{K_{\text{max.}}}{K_{\text{min.}}} \tag{2}$$

applies.

From Equations (1) and (2) it follows that, for $R > 0$, $\Delta K = (1 - R)\, K_{\text{max.}}$ (3)

4.6 The reference point for measuring the crack depth with CC test pieces is the original corner of the test piece, determined by the projections of the sides of the test piece on the fracture surface adjacent to the notch. Possible rounding of the corner during test piece manufacture will result in this reference point being no longer on the fracture surface. This rounding must be determined to obtain a “Zero-point offset” between the reference point and the rounded corner where the measurement wire is welded, which is used in the calibration of the potential-drop measurements.

4.7 The purpose of the crack propagation measurements is to allocate the relevant load cycles N to the crack depth a. The measurements (a-N points, see Figure C.2) are normally evaluated in the form of a da/dN versus ΔK curve (see Figure C.3). It is not always the case that the crack propagation can be described by the range of stress-intensity factor ΔK. If it cannot be so described, other laws can be applied, e.g. crack growth rate as a function of $K_{\max}$.

4.8 The crack growth behaviour depends on a number of parameters. The framework within which the test is to be carried out needs to be precisely defined in order to avoid undesired effects on the results.

The most important factors affecting the results are:

a) temperature and environment;

b) load spectrum.

The test parameters R, dwell time and loading frequency must be defined and recorded before testing commences. The results can also be affected by the loading history, including interruption times, e.g. stop and restart of cycling to check surface crack length or other parameters, work stoppage at weekends, etc. These should be recorded.

c) Residual stresses

Residual stresses are usually ignored, as they are difficult to determine, and a duplication of the residual stresses in a component is very difficult to obtain in a test piece. Their presence in a component will affect the life of the component, and should be regarded in the use of the crack growth data. The presence of unexpected residual stresses in the test piece may be witnessed in an asymmetry of the crack front.

4.9 Applicability of results

The crack-growth measurements are generally used for:

a) investigating the influence of fatigue-crack growth on the predicted life of a component, or for evaluating the crack-growth resistance of a material or heat-treat condition;

b) defining the requirements of NDT testing; and

c) macroscopic quantitative determination of various factors (e.g. load, microstructure, manufacture, etc.).

5 Resources

5.1 Test machine

5.1.1 General

Tests shall be performed with a feed-back load-controlled servohydraulic or electromechanical test system designed for smooth loading from first load cycle without exceeding the desired $F_{\max}$. The system should be capable of halting the cycling at desired intervals of cycles or crack depth, at a desired potential level, or at will, to enable measurements of the optical crack depth, potential or thermal potential, without stopping the test or causing overloads during the following restart.

5.1.2 Load control

The apparatus must satisfy the following requirements in accordance with EN ISO 7500-1:

a) accuracy of electronic force measurement: ± 0,5 % and ± 0,25 % of nominal range respectively;

b) accuracy of control throughout testing: better than 0,5 % of specified value of ΔF;

c) recording instrument voltage requirements (upper and lower stress range, cycles): digital recorder is recommended;

d) recording accuracy throughout testing: better than 0,25 %.

5.1.3 Load alignment

Good alignment in the load train is essential for ensuring loading symmetry. An alignment test should be carried out. The loading train should be rigid, to avoid loading eccentricity as the crack grows, which would influence the applied stress-intensity factor at the crack tip. Alignment should be carried out in accordance with ASTM E 1012.

5.2 Calibration

All instruments shall be calibrated at least once a year, as well as after every incident that may have affected the calibration accuracy. Multiplication factors (e.g. ×10 or ×100) shall not be used when counting the cycles, unless the factor is less than 10^{x-2}, where 10^{-x} mm/cycle is to be measured.

Thermocouples should be calibrated every six months in accordance with EN ISO 3785.

5.3 Temperature measurement and control

Temperature of the test piece shall be measured by a calibrated Platinum/ Rh (Type R) or Chromel-Alumel (Type K) thermocouple in adequate thermal contact with the test piece, at the centreline of one face adjacent to the notch, 2 mm to 4 mm above or below the crack plane. Shielding of the junction from radiation is not necessary if the difference in indicated temperature from an unshielded bead and a bead inserted in a hole in the test piece has been shown to be less than one-half the permitted variation shown below.

Throughout the test, the temperature shall not deviate from the specified values by more than the following:

For elevated temperature tests up to (1 000 ± 3) °C: (1 000 ± 4) °C to (1 100 ± 4) °C.

Temperatures shall be recorded and monitored, irrespective of the accuracy of temperature control, by each change of 1 °C.

The recording accuracy shall be better than 0,25 % of the specified value.

Room temperature variations; i.e. at night, over weekends, should be known and limited to ± 5 °C.

For tests at elevated temperatures, a three-zone furnace featuring electronic PID control shall be used. The grips must also be heated.

5.4 Gripping of test pieces

To compensate for the weight of the grips and fixtures, the load cell must be adjusted to ensure that the test piece is not under stress at zero indicated force.

6 Test pieces

6.1 Corner-crack (CC) test piece

The corner-crack (CC) test piece is illustrated in Figure C.1. CC test pieces may be used with positive or negative R-ratio loading, assuming the gripping system can transmit loads without backlash.

6.2 Stress-intensity − Factor calculation

The stress-intensity factor for the CC test piece is calculated as follows (Annex B describes this in more detail):

First, the geometry factor for the 45° position is calculated:

$$Y_{45°} = 0{,}574 + 1{,}199\ (1 - a/W) - 1{,}324\ (1 - a/W)^2 + 0{,}4845\ (1 - a/W)^3 \qquad (4)$$

Then, for crack depths $a \le 0{,}2\ W$:

$$Y = 1{,}143\ (1 + 0{,}6\ a/W)\ (1 + 0{,}7\ a/W)^2\ (2/\pi)\ Y_{45°} \qquad (5)$$

and for crack depths $a > 0{,}2\ W$:

$$Y = [0{,}1\ (a/W)^2 + 0{,}29\ (a/W) + 1{,}081] \times [0{,}75\ (a/W)^2 - 0{,}185\ (a/W) + 1{,}019] \times [(\ 0{,}9\ (a/W)^2 - 0{,}21\ (a/W) + 1{,}02\ )]\ 2/\pi \times Y_{45°} \qquad (6)$$

and

$$K = \frac{F \times Y}{W^2} \times \sqrt{\frac{\pi \times a}{10}} \qquad (7)$$

where

a is the crack depth (expressed in centimetres);

W is the test piece width (expressed in centimetres);

F is the force (expressed in kilonewtons);

K is the stress-intensity (expressed in MPa√m).

A check for this calculation may be made with the following input and results:

a 1 mm (0,1 cm);

W 0,8 cm;

F 32 kN.

here

Y 0,691;

K 19,365.

6.3 Test piece size requirements

For the results to be valid, the test pieces are to be subjected to a stress within the elasticity range of the material for all values of the applied load.

6.4 Crack plane orientation

The crack plane orientation, as related to the characteristic direction of the product is identified with a hyphenated letter code as in Figure C.4. The letter(s) preceding the hyphen represent the loading direction normal to the crack plane; the letter(s) following the hyphen represent the expected direction of crack extension. For wrought metals the letter *L* always denotes the direction of principal processing deformation, *T* denotes the direction of least deformation and the letter *S* is the third orthogonal direction. *C* denotes the circumferential direction and *R* the radial direction in a disk, while *L* denotes the direction along the longitudinal axis of the disk.

6.5 Residual stresses

In test pieces where stress relief has not been applied, or where forging may have introduced residual stresses which cannot be adequately relieved, the crack growth rate and/or crack symmetry may be affected, particularly at lower ΔK levels.

7 Procedures

7.1 Condition of test pieces

The test pieces shall be cleaned and measured before testing commences. Test pieces should be degreased and cleaned in accordance with the guidelines in Annex C. The notch depth and measurement wire spacing must be measured before the test, since the wire spacing cannot be determined after the test, and the notch depth is necessary to determine the initial stress-intensity levels.

7.2 Heating

The maximum heating rate shall be 1 K/s. After the specimen temperature reaches that specified, at least 30 min shall be allowed for stabilisation.

7.3 Number of tests

The number of tests depends on the use to which the data are to be put. In any case, at least two tests should be carried out for each set of tested parameters. As far as possible, the tests should be identical so that the scatter can be attributed to material effects. If this is not possible, all tests should be carried out within the same ΔK range, with similar number of measurement points and similar measurement intervals.

7.4 Testing, general

7.4.1 General

The test should be conducted at constant load amplitude (ΔF). However, crack growth measurements under variable load amplitude may be desired, especially when obtaining specific information from a limited number of test pieces. In this case the procedure must be such as to exclude undesired transient effects.

7.4.2 Measurement of crack depth

Crack-depth measurements are to be made using the potential-drop method:

The DC (direct current) potential-drop method determines the crack depth through the increase in potential (V), measured across the mouth of the crack, from an initial reference potential V_o measured at a known or estimated initial crack depth at test temperature, induced by a constant current (~ 10 A) passing through the plane of the crack. For a constant current flow, the electric potential or voltage drop across the crack plane will increase with increasing crack size due to modification of the electrical field and associated perturbation of the current streamlines. The relationship between potential and crack depth depends on the arrangement of the current- and measurement leads on the test piece. Appendix A gives information on the use of this method. An AC (alternating current) potential-drop method may instead be used, and also requires calibration.

7.5 Notch preparation

7.5.1 General

To facilitate crack initiation at low stress ratios, the notch root radius should be on the order of < 0,05 mm. The notch depth used depends on the initial K required for initiation. For nickel-based alloys, either the arc-strike technique with an effective notch depth of 0,1 mm or a diamond-sawed notch of 0,25 mm depth have proven effective. An EDM notch of 0,1 mm width or smaller and 0,1 mm depth can be effectively used for the initiation of the fatigue crack with titanium alloys.

7.5.2 Precracking

The condition of the test piece (e.g. heat treatment) when initiating the precrack shall be the same as that with which testing is carried out. No intermediate heat treatments between precracking and testing are allowed. The purpose of precracking is to provide sharp fatigue cracks of sufficient depth so that the K-calibration expression is no longer influenced by the starter notches and that the subsequent fatigue crack growth rate is not influenced by the precracking force history. Frequently a ΔK is required to initiate the crack that is larger than the ΔK desired as the starting point for the test. In this case, the forces must be stepped down to meet the desired starting criteria (see Figure C.9).

If $F_{\text{max.},j}$ and a_j are the maximum load and crack depth in one step j, and $F_{\text{max.},j+1}$ and a_{j+1} are the corresponding values in the next step $j + 1$, the following conditions must be met:

$$F_{\text{max.},\,j+1} \geq \frac{F_{\text{max.},\,j}}{1{,}2} \tag{8}$$

(a 10 % change is a good initial recommendation; later steps of only 5 % may be necessary to avoid excessive delays before crack growth resumes after each step)

$$a_{j+1} - a_j \geq \frac{1}{3\pi}\left(\frac{K_{\text{max.},\,j}}{R_\text{p}}\right)^2 \tag{9}$$

The best initial $K_{\text{max.}}$ should be determined for each material. But if this is not known, a value of 0,000 08*E √m may be initially used until experience is gained. A net section stress of 500 MPa to 600 MPa is recommended for high-strength nickel alloys.

Procedure

a) For the DC method, apply ~ 0,1·W^2 amperes direct current to produce an initial potential of ~ 1 mV.

b) A fatigue precrack of 0,03 mm should be produced using a stress intensity range of ~ 10 MPa√m to 15 MPa√m until a potential change of 0,005 mV to 0,01 mV is noted. This change represents approx. 0,01 mm to 0,04 mm crack extension, and usually indicates the crack is growing steadily. For some materials, small incremental increases in ΔK will be necessary to initiate a crack. Here it is useful to drop the minimum load used into the compressive range, as well as increasing the tensile maximum load, to avoid net section stresses too near to yield.

c) The loading should then be adjusted for the desired minimum ΔK for the test, while the precrack extends to $a = \sim 0{,}3$ mm. Figure C.6 shows a schematic of the load-shedding process typically recommended (ASTM E 647); the shedding process must be accelerated for CC test pieces due to the small test piece dimensions.

The temperature during precracking should be the same as during testing to avoid transient effects which tend to retard the initial crack growth after precracking. Precracking may be performed at room temperature, to enable monitoring the precrack length on the specimen sides. To save time during load shedding, higher frequencies than during testing may be used initially (e.g. 5 Hz to 20 Hz), but the final 0,05 mm of precrack growth should be performed using a waveform having similar loading rates as the waveform used during testing.

If hold times at maximum load are used during CGR testing at elevated temperatures, the initial 0,05 mm to 0,1 mm of growth data may be influenced by such transient effects, and should be considered as suspect, especially if a gradual transition to higher rates is evident after switching to a hold time.

NOTE If reduction of the frequency from precracking to test conditions allows $F_{\text{max.}}$ to increase, due to test machine control characteristics, then all frequency changes, including stops and restarts, should be immediately preceded by a precautionary 10 % reduction in $F_{\text{max.}}$ and $F_{\text{min.}}$ to avoid $F_{\text{max.}}$ overshoot, and later increased.

d) The potential at this reference crack depth and $F_{\text{min.}}$ is recorded and, if precracking was performed at RT the test piece is heated, still at $F_{\text{min.}}$, to the test temperature, if elevated temperature tests are required. If so, the potential at the test temperature is recorded and used to obtain the temperature correction coefficient

$$Y_{\text{TC}} = \frac{V_{\text{o}}(\text{RT})}{V_{\text{o}}(\text{Test Temp.})} \tag{10}$$

This coefficient may be used to correct the potentials measured, for use in the crack depth equation (see Annex A).

Optimally, the test piece should be precracked at the test temperature. The reference potential is taken at RT in the notched condition, or after heating, to obtain Y_{TC}. A different potential-drop calibration will be necessary, however, due to differences between potentials for notches and cracks of the same depths.

If the desired R-ratio is higher than 0,1, further cycling must now be performed to reach the desired R-ratio, reducing the loading range by 10 % after each 0,1 mm of crack extension by increasing the minimum load. For materials with R_{p} ~ 1 000 MPa, and for low R-ratios, reductions may be made after each 0,05 mm of extension, permitting the use of higher initial precracking stress-intensities, or enabling the possibility to reach lower stress-intensities for the initial testing conditions without excessive precrack depths.

This can also be achieved by initially cycling at the R-ratio desired for the test, with a ΔK of ~ 16 MPa $\sqrt{\text{m}}$, but the resulting higher $K_{\text{max.}}$ may require larger crack extension increments to avoid retardation, due to the larger crack tip plastic zone at elevated temperature.

The final transition to testing parameters involves changing to the test frequency, which may involve hold times. The choice of sinus or trapezoidal waveform depends partly on the ability to accurately measure the potential at the maximum load each cycle. If the test frequency is less than 2 Hz, the transient effects may require up to 0,2 mm of crack growth before constant growth rates are obtained. This frequency, and the possible transient zone sizes, depends on the material, test temperature and hold time. Switching the control mode to constant ΔK, with continuous decreasing control of $F_{\text{max.}}$ and $F_{\text{min.}}$ to maintain ΔK constant over the next 0,1 mm to 0,2 mm of growth, will show the size of this transient, as the crack growth rises to a stable rate. During data analysis, any transient data should be deleted if this transient was not the object of the test.

7.5.3 Increasing-K-test

At this point the control mode is switched to constant $F_{\text{max.}}$ and $F_{\text{min.}}$, and ΔK is allowed to increase with crack extension. The final crack depth, as determined from the potential drop (PD), should be limited to $a/W \leq 0,5$. Test interruptions should be kept to a minimum. If the test is interrupted, a change in growth rate may occur after resumption of cycling.

Measurements of the actual initial and final crack depths, taken from the actual post-test fracture surface, should be used to correct the calculated crack depths. For tests where the final crack depth is too large (e.g. > 0,5 W), the relationship between the crack depth and potential measured may no longer be linear, skewing the analysis. Inclusion of periodic “Marker loads” of a few thousand cycles, cycling at the same $K_{\text{max.}}$ as during testing, but with a significantly higher or lower R-ratio, can produce visible “beach marks” at known cycle counts and known potentials, which can be used to calibrate the crack depth calculations based on potential, using the measured crack depths at the beach marks (see Figure C.7). Thus any deviations from linearity can be determined and used to limit the range of data used. At slow crack growth rates, the stress-intensity factor range of the marker cycles may be below the threshold, in which case no propagation during the marker cycles can be expected, and the transition to and from the marker cycling may not be visible on the fracture surface. At moderate temperatures, the markers may also be difficult to observe. Dark-field microscopy or post-test oxidation of the fracture surface may be of advantage.

7.5.4 Measurement intervals

The interval should be large in relation to the accuracy of the measurement method, but small compared to the K-gradient of the test piece.

For potential drop methods, crack-depth potential should be recorded at least every 15 min. For low growth rates, longer intervals may be used, and the stability of the measurements over time should be ensured. The interval chosen should permit adequate sampling of the crack depth at short crack depths, but should not be less than ten times the measurement accuracy. Crack depth must be recorded every ~ 0,1 mm. An interval of 1/20$^{\text{th}}$ of the initial potential is recommended (0,05 mV when $V_{\text{o}} = 1$ mV). The resulting da/dN data should present at least ten points in each growth rate decade.

7.6 End of test

Avoid breaking the test piece during the fatigue test. Stop the test at or before the normalised crack depth $a/W = 0{,}5$, and before the net section stress reaches the yield level at the test temperature. The potential must be measured and recorded immediately before the stop (one cycle to three cycles) to enable accurate post-test correction of the calculated crack depths. The test piece should be heat-tinted as necessary to enable a clearly-defined final crack depth to be measured on the fracture surface. For elevated temperature tests, it is recommended that the test piece should be cooled to at least room temperature and that additional cycling at the previous stress levels be performed to extend the fatigue crack beyond the test end, before loading in tension to failure. The fracture surfaces of both halves should be protected from further damage, or contact with each other.

8 Health and safety

Exposure limits as given in EC regulation 93/72/EWG for cleaning solvents and for artificial mineral fibres used for sealing furnace gaps shall be observed.

9 Evaluation of results

9.1 Test piece measurement

If the crack front is visually recognisable, the depth of the precracks and the final depths of the fatigue cracks are to be measured at the end of the test. The actual crack depths are then used to correct the individual crack depth measurements by a linear adjustment method.

9.2 Determination of crack growth rate

The crack growth rate da/dN can be calculated as follows:

a) Polynomial method

In this method, a polynomial of the second degree is fitted to (2 n + 1) consecutive points in the $a_{\text{average}} - N$ diagram.

The following applies:

$$a_{\text{i}} = b_0 + b_1\,(N_{\text{eff}}) + b_2\,(N_{\text{eff}})^2 \tag{11}$$

where

$$N_{\text{eff}} = \frac{N_i - C_1}{C_2} \tag{12}$$

and

$$C_1 = \frac{N_{i-n} + N_{i+n}}{2} \tag{13}$$

$$C_2 = \frac{N_{i+n} + N_{i-n}}{2} \tag{14}$$

The coefficients b_0, b_1 and b_2 are determined by the least squares method over the range $a_{i-n} \leq a_i \leq a_{i+n}$. The recommended value for n is 5.

The crack growth rate at point N_i is determined with the aid of the following relation:

$$\left(\frac{\text{da}}{\text{dN}}\right) = \frac{b_1}{C_2} + 2\,b_2\left(\frac{N_i - C_1}{C_2^2}\right) \tag{15}$$

The stress-intensity factor K is calculated for the value a_i corresponding to N_i.

In generating the best fit for the $a - N$ data, the polynomial regression should use the minimum residual of the x- and y-residuals for the best fit. At the start of the test, the flat progression of the $a - N$ curve lends itself better to a regression based on a least squares fit of the y-residuals, while at the end of the test the steep curve progression lends itself better to a regression based on the x-residuals.

A modification of this method is useful at slow growth rates (< 10^$^{-5}$ mm/cycle). The data points used are not individually incremented, but rather a, N points within a selectable Δa interval, usually five times to ten times the crack depth measurement resolution.

b) Secant method (Recommended)

In this method, the slope of the line between two adjacent points in the $a - N$ diagram is calculated (see Figure C.2).

The following applies:

$$\left(\frac{\text{da}}{\text{dN}}\right)_i = \left(\frac{a_{1+i} - a_i}{N_{i+1} - N_i}\right) \tag{16}$$

This method results in large data scatter if the Δa interval is small.

The geometric mean value

$$a_i = \sqrt{a_i \cdot a_{i+1}} \tag{17}$$

is used for determining the corresponding stress intensity factor ΔK_i.

9.3 Crack closure correction – ΔK_eff

At low or negative R-ratios, the flanks of the crack surface usually come into contact before the minimum load is reached during unloading. Thus the crack tip does not experience the full $\Delta K_\mathrm{applied}$ and the CGR is lower than it would be for the same ΔK at higher R-ratios. If it is necessary to distinguish $\Delta K_\mathrm{applied}$ from the effective ΔK (ΔK_eff), compliance measurements may be used to determine the minimum force required to fully open the crack, F_op, and the corresponding K_op. The ΔK_eff is then given by:

$$\Delta K_\mathrm{eff} = \Delta K - K_\mathrm{op} \tag{18}$$

and may be used instead of ΔK as the abscissa for the da/dN vs ΔK plot. It is desirable to be able to determine this closure, but for the CC test piece this requires a high degree of measurement accuracy (~ nm) and is difficult to achieve.

10 Test record

10.1 The test report (see Figure C.8) shall include the following information for each test piece investigated:

- reference to this standard;
- material specification and heat treatment, with identification of the part or half-finished;
- product from which the test pieces are taken;
- test piece identity, drawing number, and reference to a documented method of preparation;
- tabulated results and curves of fatigue crack growth and fatigue crack growth rate;
- including model coefficients and model used, where determined (see 10.10 and 10.11);
- initial and final crack depth used for the analysis;
- temperature of the test plus any deviation from the specified limits;
- waveform and stress or strain ratio;
- frequency for precracking and testing, or cycle period with hold times;
- environmental details, including temperature, medium, pressure and relative humidity.

The following information is often of importance, and should be kept on file:

10.2 A brief description of the test machine and furnace, if used, and the method used for measuring the crack depth, including details describing the accuracy of the method.

10.3 Test piece type, including the width W. Drawings showing the test piece and fixturing system used, if test pieces other than as in Figure C.1 are used.

10.4 Parameters for potential (calculated) crack depth measurement, if used, including measurement lead spacing, current, and initial potential at room temperature and test temperature at the initial precrack depth.

10.5 Material details concerning the laboratory test record number, material identification code, heat treatment, composition, mechanical properties (yield strength at room temperature and test temperature, and tensile strength at test temperature), size and form (sheet, forging, etc.). All these details must be obtained from the requestor, so that the data can be correlated with the other necessary material properties, and so that necessary calculations involving R_p may be made to determine test parameters prior to testing.

10.6 Orientation of crack front relative to the original component, and notch location in relation to the component geometry.

10.7 Brief description of precracking, with details of notch depth and width, method of obtaining the notch, and sharpness (tip radius); ΔK, ΔF, R and potential crack depth "a" at the beginning and end of precracking, load-shedding rate C, and the final precracking frequency. Include number of cycles to initiation.

10.8 Test parameters including ΔF and $F_\mathrm{max.}$

10.9 Fracture surface optical measurements. Reporting form showing average a_K measurements, notch depth and final crack depths at the 10°, 45°, and 80° (or others as used) positions (see Figure C.7).

10.10 Tabulated results. The desired format is: N, a_average, da/dN, ΔK, K_max. Units used for a, N, da/dN, ΔK and $K_\mathrm{max.}$ must be reported.

10.11 The most popular presentation of data is via a graphical da-dN diagram. Its construction involves plotting the number of cycles as the abscissa and the crack depth as the ordinate, with linear scales. This is termed the crack growth, or a-N curve. From this curve, the derivative is taken at equal increments of crack extension (Δa), creating the more familiar Crack Growth Rate curve (da/dN), using logarithmic scales. Plotted results should be given, with ΔK as two log decades between 1 and 100, and da/dN in metres per cycle over the range 10^{-9} to 10^{-5}.

10.12 Details of any additional occurrences during the test which might affect the results, e.g. crack irregularity, asymmetry, out-of-plane cracking, crack branching, shear lips, or interruptions.

10.13 Microstructure description and/or micrographs; and drawings or photos showing precise position and orientation of each test piece.

10.14 Fractographic examination of the two fracture surfaces to identify the initiation site and to determine any unusual causes of failure that might invalidate the test result.

Annex A
(normative)

Information on measuring crack depths in corner-crack test pieces with the direct-current − Potential-drop method

A.1 General

Information on measuring crack depths in corner-crack test pieces with the direct-current − Potential-drop method

For corner-crack test pieces where the current can be introduced uniformly through the top and bottom ends of the piece, as it is mounted in the test fixture, the relationship is described by the Pickard formula:

$$\frac{V}{V_{\text{rg}}} = 4a/\pi + z - 2z/\pi \times \sin^{-1} [(a\text{^}2 - z\text{^}2) / (a\text{^}2 + z\text{^}2)] \tag{19}$$

where

a is the crack depth, millimetres from contact point on rounded corner (a, meas. - zero-pt. offset);

V is the corresponding measured potential;

V_{rg} is the reference potential;

$2z$ is the separation between potential measurement points, in millimetres,

and current flow is uniform across the crack plane. This formula is basically a linear relationship at crack depths greater than the wire spacing. Thus the wire spacing should be kept small; 0,2 mm spacing of 50 µm wire across a 100 µm wide notch allows linearity at crack depths relevant for highly stressed components such as turbine disks (> 0,3 mm). For slightly shorter crack depths, the non-linear Pickard formula is essential. The effective wire spacing can only be estimated by optical measurements; for exact determination, especially at a small spacing (~ 0,2 mm), the potential vs. optical crack depth data must be compared to the Pickard curve generated using various wire spacings and reference potentials, and the curve with the best fit to the observed data indicates the optimal, effective wire spacing to be used in calculations.

In place of an analytically derived expression, it is possible to empirically develop relationships for virtually any type of test piece geometry used in fatigue crack growth rate testing. Such empirical relationships can be advantageous when wire placement must be altered. In any event, analytical or empirical relationships should be experimentally verified using alternative measurements at various crack sizes in the range of interest (optical surface measurements or post-test fracture surface measurements). Such measurements should be reported and may be used for correcting crack depths inferred from equations.

A.2 Electrical shorting

Unless it can be shown that electrical shorting does not occur during the entire load cycle, the voltage measurements should be taken at or near the peak tensile load. It should be noted that measurement of the electrical potential at maximum load does not always guarantee the absence of electrical shorting errors. The maximum potential does not necessarily occur at maximum load.

The response time of the voltage measurement system must be sufficient to resolve changes in potential drop as a function of applied load, if fracture surface shorting occurs. The time integration period for the potential measurement must be short, relative to the time during which test conditions are stable, either with respect to hold times at maximum load (a recommended method) or to the crack growth rate for cases where the measurements must be made at the maximum stress, averaged over many cycles.

The fracture surface shorting effect can be accounted for after the test using post-test fracture surface crack size measurements. One approach is to compute offset and scaling factors to match the initial and final crack sizes from electric potential measurements and fracture surface measurements. A simple linear interpolation technique is the used to correct the intermediate electric potential values.

Elastic and plastic deformation can, in principle, affect material resistivity. While unlikely to be an important source of error for the stress intensities typical of fatigue crack growth under small scale yielding, the user should document any load dependence of the potential for constant crack size without surface shorting, and assess the importance of associated errors in calculated crack size. The correction method for shorting errors will generally account for deformation effects on the electrical properties of the material.

A.3 Reference potential measurements

Some materials exhibit time-dependent conductivity changes while at elevated temperatures. Variations in the gain of amplifiers or calibration of voltmeters may also result in a proportional scaling of the measured voltages.

To compensate for these effects, voltage measurements can be normalised using additional voltage measurements taken at a reference location. The reference location may be either on the test piece or on a separate piece of the same material in the same environment. If the reference measurements are made directly on the test piece, the location must be chosen so that the reference voltage is not affected by crack size. Since all material and instrument variations are also included in the reference measurements, the normalisation process should eliminate them. Use of reference voltage measurements can significantly increase crack size resolution.

A.4 Test piece fixturing

Gripping considerations − The electric potential difference method of crack size determination relies on a current of constant magnitude passing through the test piece when the potential voltage is measured. During such potential measurements it is essential that no portion of the applied current be shunted in a parallel circuit through the test machine. For most commercially available test machines and grip assemblies the resistance through the test frame is considerably greater than that of the test piece. However, in some situations an alternative path for the applied current may exist through the test frame and/or thermocouple.

The test piece must be electrically isolated from the load machine so that the measuring current passes principally through the test piece.

The test piece resistance should be determined for the range of crack sizes encountered during the test.

The ratio of the electrical resistance of the load train, measured at the grips with the test piece removed, to the resistance of the test piece itself at the same location should be ~ 10^4:1.

Isolation of the test piece from the load frame is particularly important when using power supplies with non-isolated (ground referenced) outputs. Use of this type of power supply may require isolating both ends of the test piece from the test frame to avoid ground-loop problems.

A.5 Current source

The relative stability of the power supply should be equal to the effective resolution of the voltage measurement system; that is, if the voltage measurement system can effectively resolve one part in 10^4 of the output voltage from the test piece (including electrical noise, inherent inaccuracies such as nonlinearity, and so forth) then the power supply should be stable to one part in 10^4. Constant or pulsed DC current may be used.

A potential change of 0,005 mV should be measurable with relatively low DC signal - to - AC RMS noise ratios. Due to the contribution of the current to test piece heating, stabilisation of the test piece temperature should be performed with the current on if constant DC current is used.

A.6 Current input location

The optimal current input location generates a uniform potential field at the crack plane. A distributed current input can be created by attaching current leads to the test piece grip assemblies.

A.7 Lead wire placement

Voltage wire placements are usually a compromise between good sensitivity to crack size changes and freedom from errors caused by minor variations in lead location among test pieces. Near-crack-plane lead locations yield better sensitivity to changes in crack size.

Voltage sensing wires should be located above and below the starting notch, as close to the corners of the notch as possible as shown in Figure C.10.

Errors in crack depth measurements may arise if the notch depth is used as the reference crack size, since the ratio of crack surface area for a notch to the surface area of a crack of the same depth is $4:\pi$.

The number of connections and lead wire length should be kept to a minimum, and all connections outside the furnace should be isolated from temperature fluctuations. Embedding the connections within a block of aluminium 50 mm on a side should be sufficient to eliminate temperature variations at the two connection points. Lead wires should be twisted to further reduce noise, and shielded (coaxial) leads should be used where possible. Holding them rigid also helps reduce the stray voltages which could be generated by moving the wires through any static magnetic fields that may exist near the test frame. In addition, routing the voltage measurement leads away from motors, transformers, the test piece current leads or other devices which produce strong magnetic fields is recommended.

The voltage sensing wires must be resistance spot-welded to the test piece to ensure a reliable, consistent joint.

For materials with a lower conductivity (i.e. titanium, nickel), a direct current in the range of 5 A to 50 A and voltage resolution of about $\pm$ 0,2 μV or $\pm$ 0,01 % of V, will yield a resolution in crack size of better than 0,01 % of the test piece width. The final potential ($a/W = 0{,}5$) will be ~ 20 times the initial potential ($a/W = 0{,}025$).

A.8 Thermoelectric effect

The DC method is susceptible to thermoelectric effects which produce DC potentials in addition to those due to the test piece electrical field. For DC systems, thermal emf measurement and correction is critically important. A minimum number of connections should be used and maintained at a constant temperature to minimise thermoelectric effects. These thermoelectric voltages can be a substantial fraction of the total measured voltage, even when the lead wire material is similar to the test piece. Since the thermoelectric effect is present even without the input current, it is possible to account for it by subtracting voltage measurements taken with the current off from the measurements made with the current on. Allow a sufficient stabilisation period, after turning the DC electric potential current either on or off, before making a voltage measurement.

The thermoelectric effect may be accounted for by either:

1) Switching off the current and considering the difference

$$V_{\text{actual}} = V_{\text{i > o}} - V_{\text{i = o}} \qquad (20)$$

2) Reversing the current and using the mean potential

$$V_{\text{actual}} = (V_{i > \text{o}} - V_{i < \text{o}})/2,$$

or (21)

3) Using a square wave, with:

$$V_{\text{actual}} = V_{\text{max.}} - V_{\text{min}} \qquad (22)$$

where

$V_{\text{max.}}$ is the voltage measured at stabilized maximum current;

$V_{\text{min.}}$ is the voltage measured at zero current.

Some voltmeters for DC systems have built-in automatic correction for internal thermoelectric effects. These units may be of benefit in cases where it is not possible to control the laboratory environment.

A.9 Electrical grounding

Proper grounding of all devices (current source, voltmeters, and so forth) should be made, avoiding ground loops. All of the electrical equipment should have a common electrical ground.

Annex B
(normative)

Stress-intensity function for corner-crack test pieces 2)

The stress intensity factor range ΔK is given by:

$$\Delta K = y_n \Delta\sigma \sqrt{\pi a} \tag{23}$$

where

y_n is the compliance function;

$\Delta\sigma$ is the stress range and a is the crack length.

The compliance function is calculated via:

$$y_n = M_G \times M_B \times M_S \times \frac{2}{\pi} \tag{24}$$

where

M_G is the general correction factor;

M_B is the back face correction factor;

M_S is the side face correction factor.

These correction factors vary with a/W and position, such that:

If $a/W \leq 0{,}2$ then

$$M_G = 1{,}143 \tag{25}$$

$$M_B = 1 + 0{,}06\ \frac{a}{w} \tag{26}$$

$$M_{\mathrm{S}} = 1 + 0{,}07\ \frac{a}{w} \tag{27}$$

If $0{,}2 < a/W \leq 0{,}75$ then

$$M_G = 0{,}1\left(\frac{a}{w}\right)^2 + 0{,}29\left(\frac{a}{w}\right) + 1{,}081 \tag{28}$$

$$M_B = 0{,}75\left(\frac{a}{w}\right)^2 - 0{,}185\left(\frac{a}{w}\right) + 1{,}019 \tag{29}$$

---

2) A.C. Pickard, (1980), Stress intensity factors for cracks with circular and elliptical crack fronts determined by 3D finite element methods, *Numerical Methods in Fracture Mechanics,* (Edited by D.R.J. Owens and A.R. Luxmore), Pineridge Press, Swansea, UK, pp. 599-614.

$$M_S = 0{,}9\left(\frac{a}{w}\right)^2 - 0{,}21\left(\frac{a}{w}\right) + 1{,}02 \tag{30}$$

The compliance function applies to surface cracks. At the 45° position, the compliance function y_{n45} is:

$$y_{n45} = y_n \times \left[0{,}933\,5 - 0{,}004\,5\,\frac{a}{w} + 0{,}129\,5\left(\frac{a}{w}\right)^2 - 0{,}484\,5\left(\frac{a}{w}\right)^3\right] \tag{31}$$

The mean compliance function is the simply the mean of y_n and y_{n45} . This relation is equivalent to that shown in.

Annex C
(normative)

Guidelines on test piece handling and degreasing

C.1 General

Unless otherwise specified by the customer or where special surface treatments have been applied, the following guidelines should be adhered to.

C.2 Steels

Degrease by full submersion in an acetone bath immediately prior to testing. The use of an ultrasonic bath is recommended. Test pieces that are degreased and then not tested for some reason should be retreated with an anti-corrosion fluid.

No special handling requirements are necessary subsequently.

Thread lubricants should not be necessary at the test temperatures encountered.

C.3 Nickel and cobalt base alloys

Degrease the test section with acetone and wipe dry with a clean soft cloth.

No special handling requirements are necessary subsequently.

For tests at temperatures greater than 650 °C, a thread lubricant should be used sparingly. Any excess still evident once the test piece has been inserted should be removed.

C.4 Titanium based alloys

Degrease the test section with acetone and wipe dry with a clean soft cloth.

Once degreased, the test section must not be touched other than with clean cotton gloves. In addition, everything which touches the test section (extensometer probes, string used to tie on thermocouples, etc.) should be clean and should be handled with gloves (to prevent any transfer of salt from the skin to the test piece).

Thread lubricants must not be used.

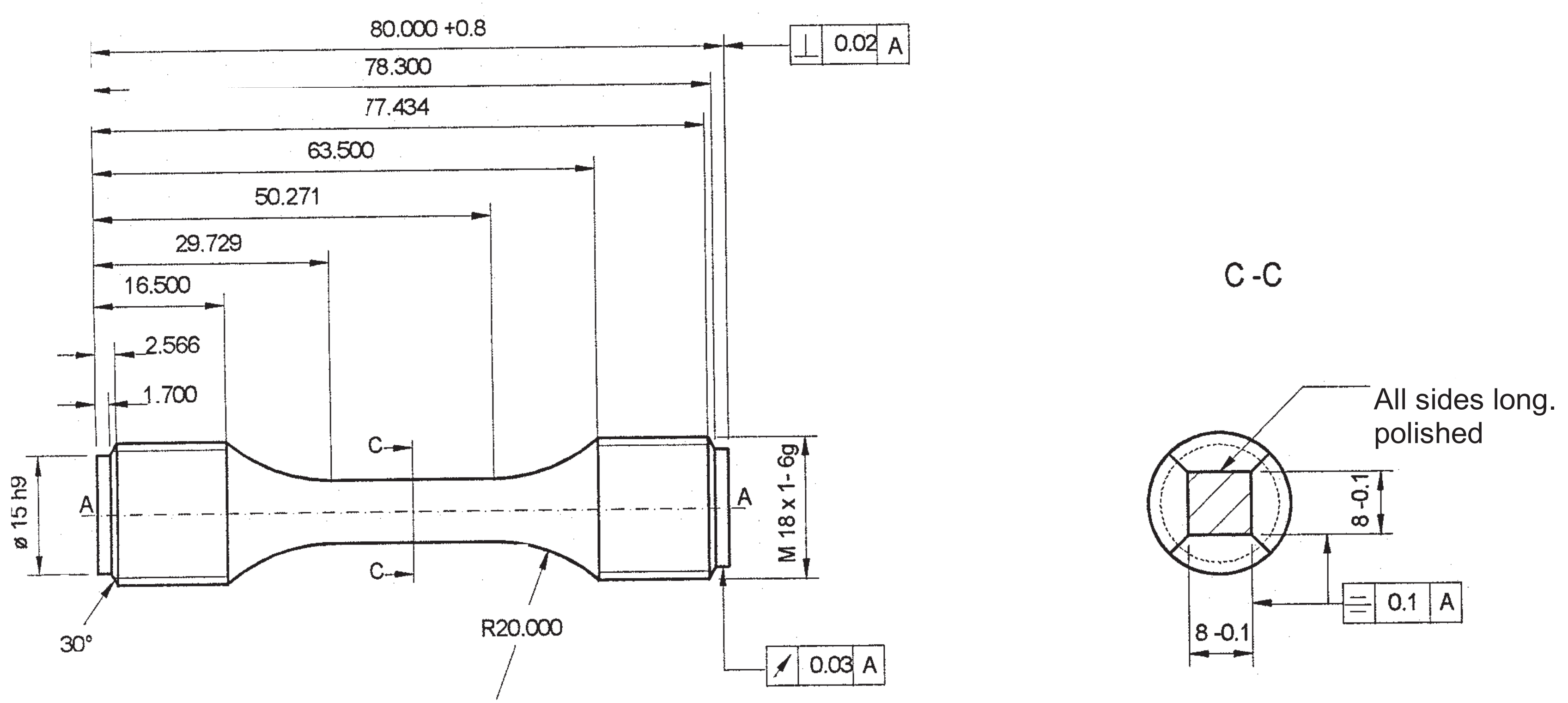
C.5 Aluminium and magnesium alloys

Degrease the test section with acetone and wipe dry with a clean soft cloth.

No special handling requirements are necessary subsequently.

Thread lubricants should not be necessary at the test temperatures encountered.

Dimensions in millimetres



Key

1 All sides long polished

Figure C.1 — Standard corner-crack (CC) test piece for fatigue crack growth rate testing (here, an (8 × 8) mm cross section is used; this can vary according to available material dimensions)

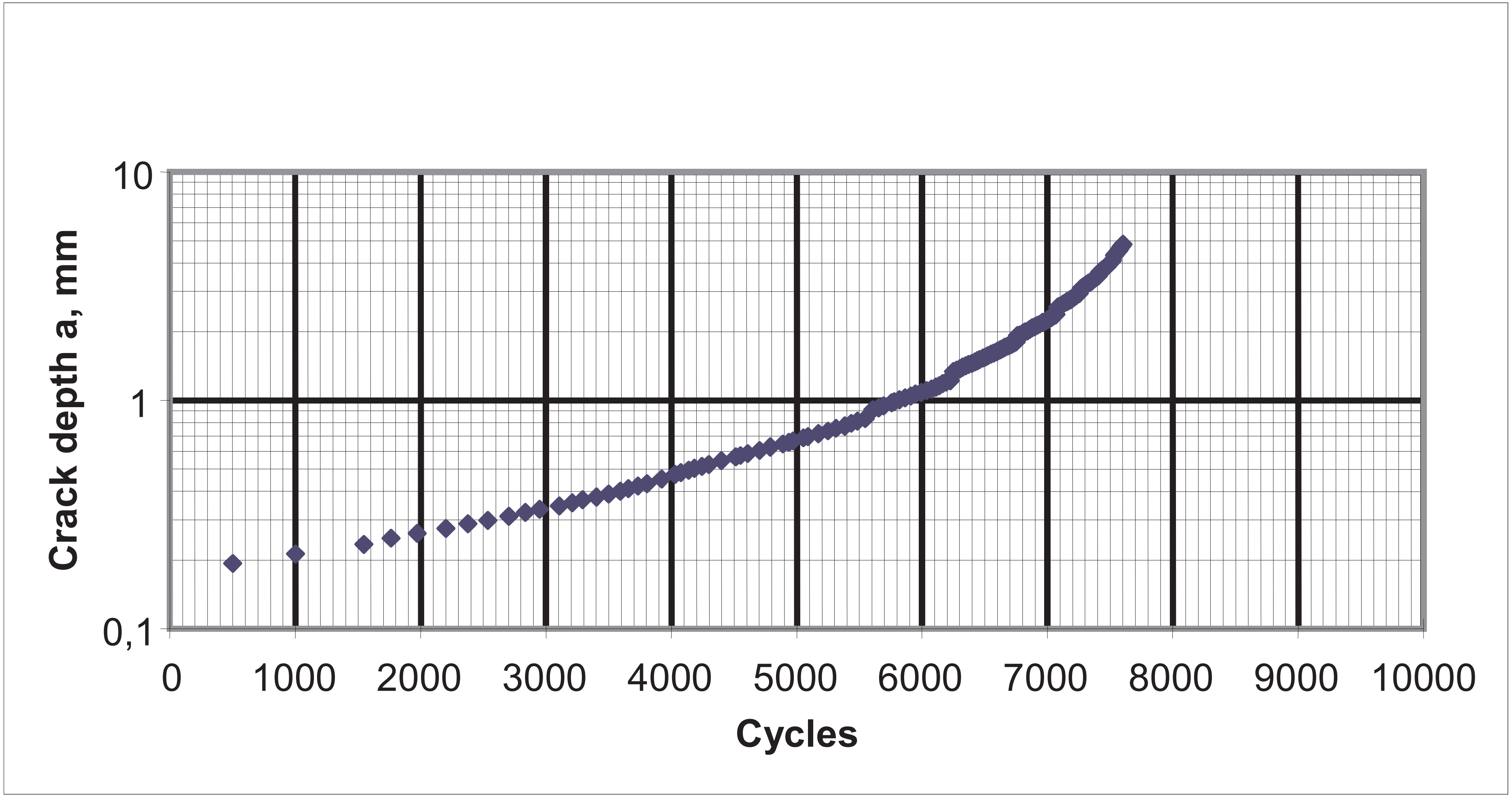


Figure C.2 — Example plot of crack growth curve

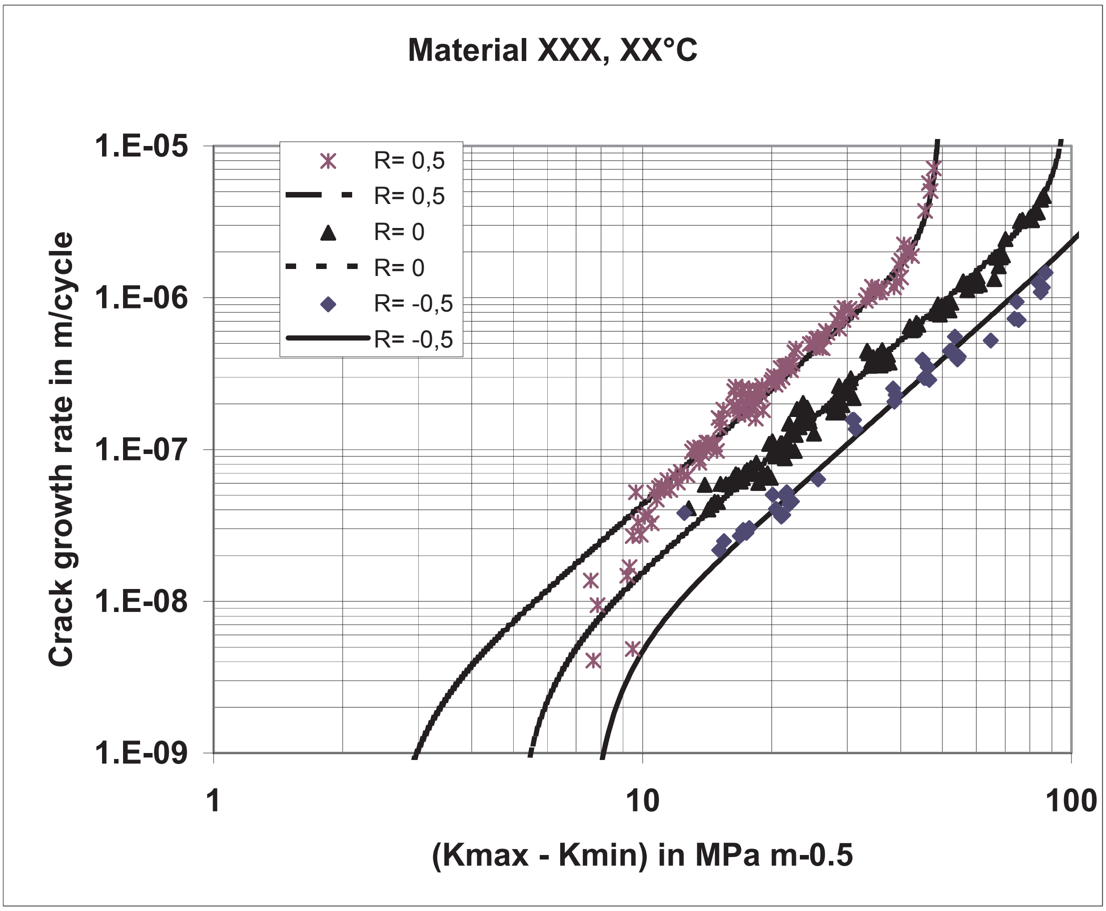
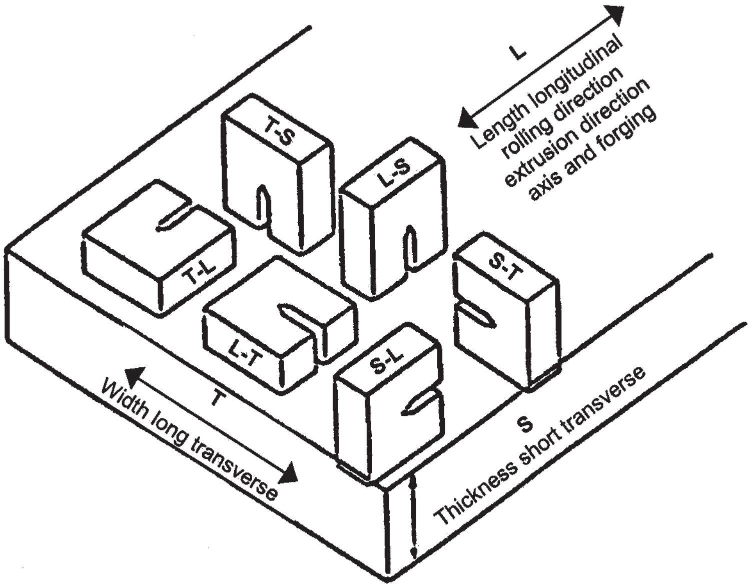
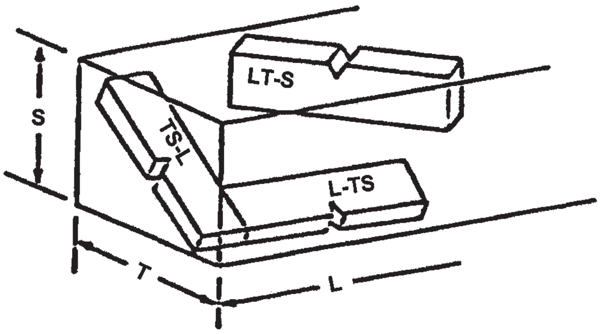


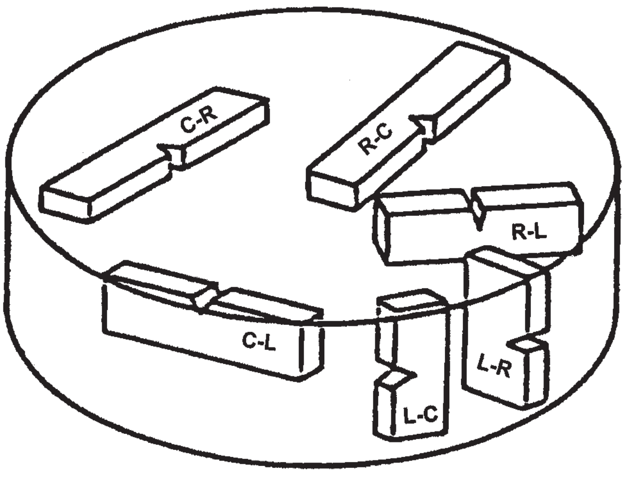
Figure C.3 — Example plot of da/dN versus ΔK



a) Crack plane orientation code for rectangular sections



b) Crack plane orientation code for rectangular sections where specimens are tired with respect to the reference directions



c) Crack plane orientation code for bar and hollow cylinder

Figure C.4 — Fracture plane orientation identification

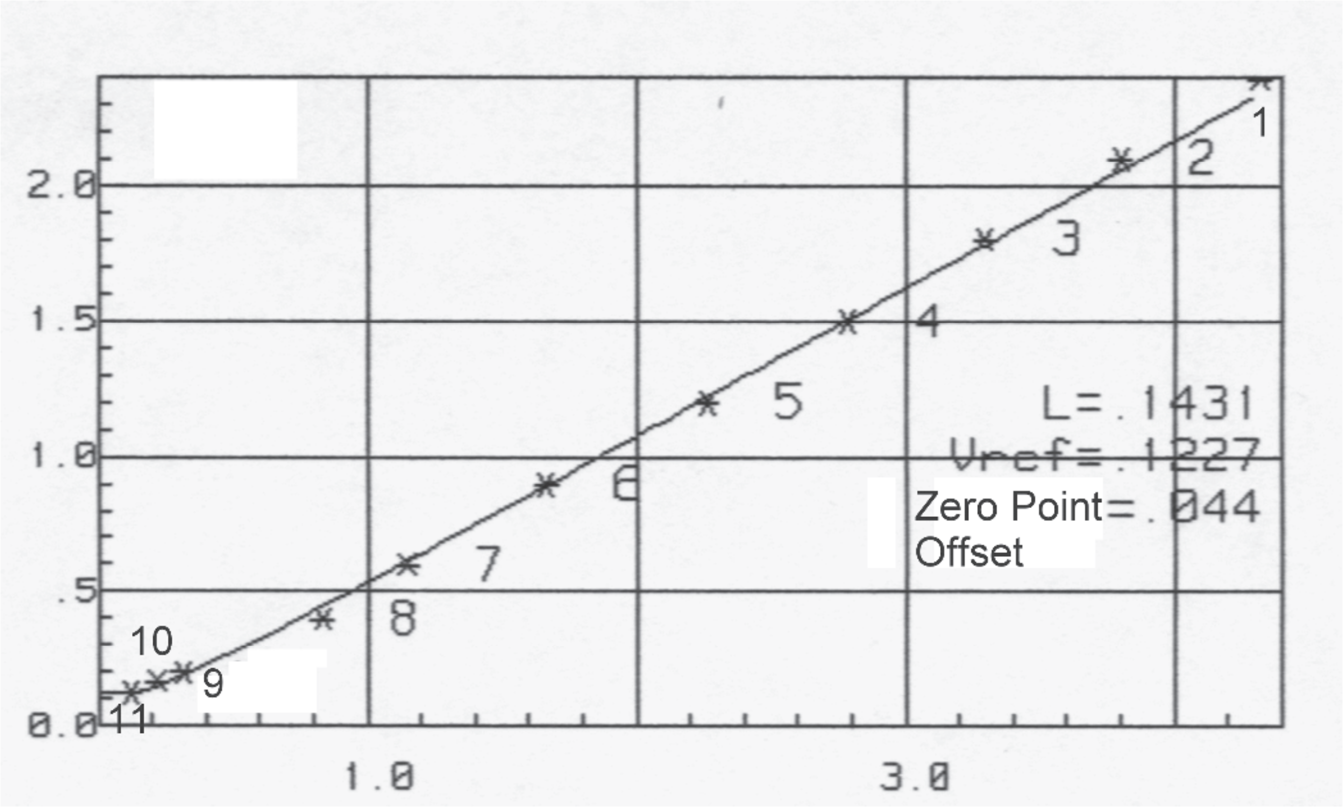


Figure C.5 — Calibration curve of normalised potential versus crack depth *a*

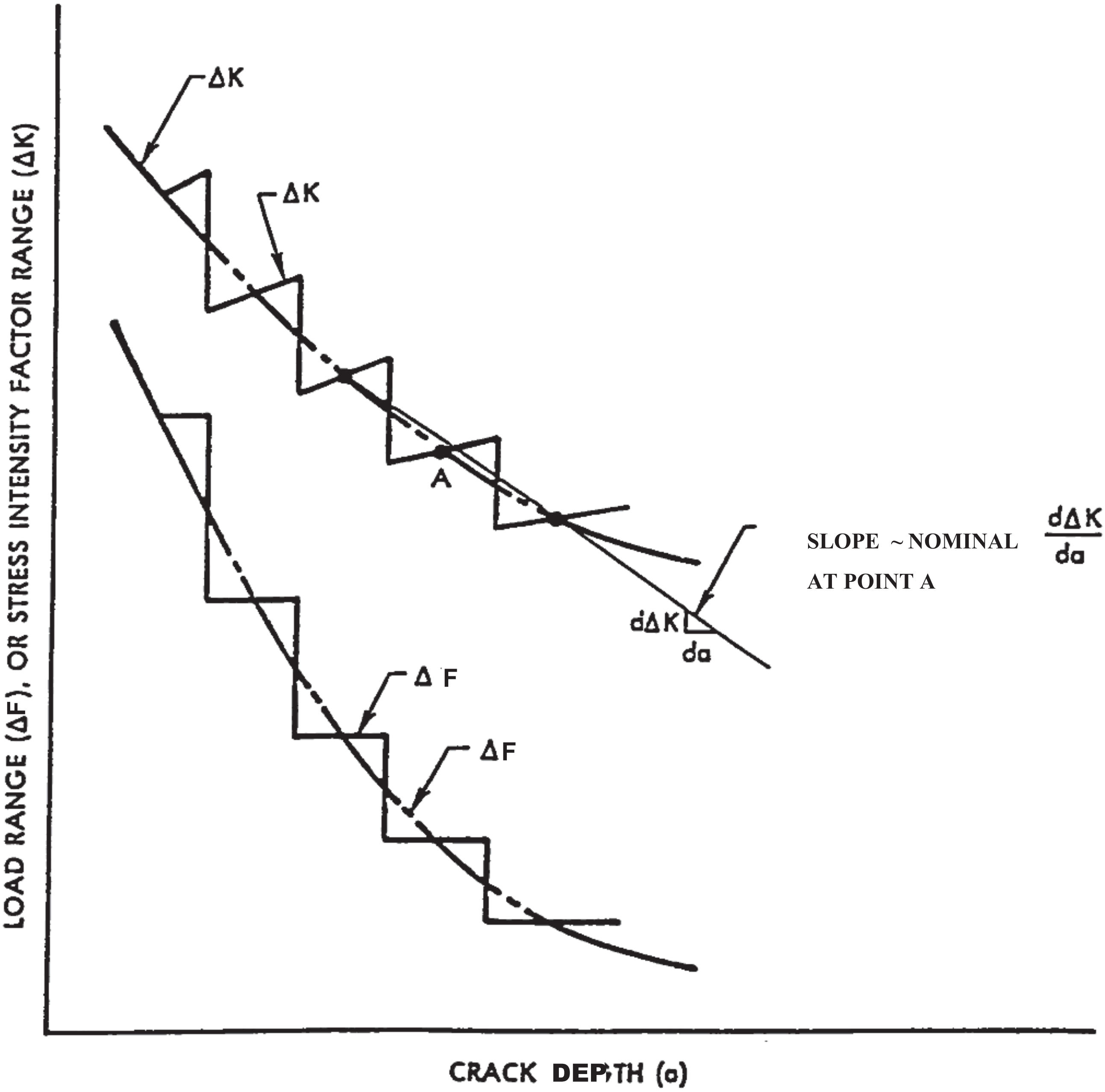


Figure C.6 — Typical *K*-decreasing test by stepped load-reduction method

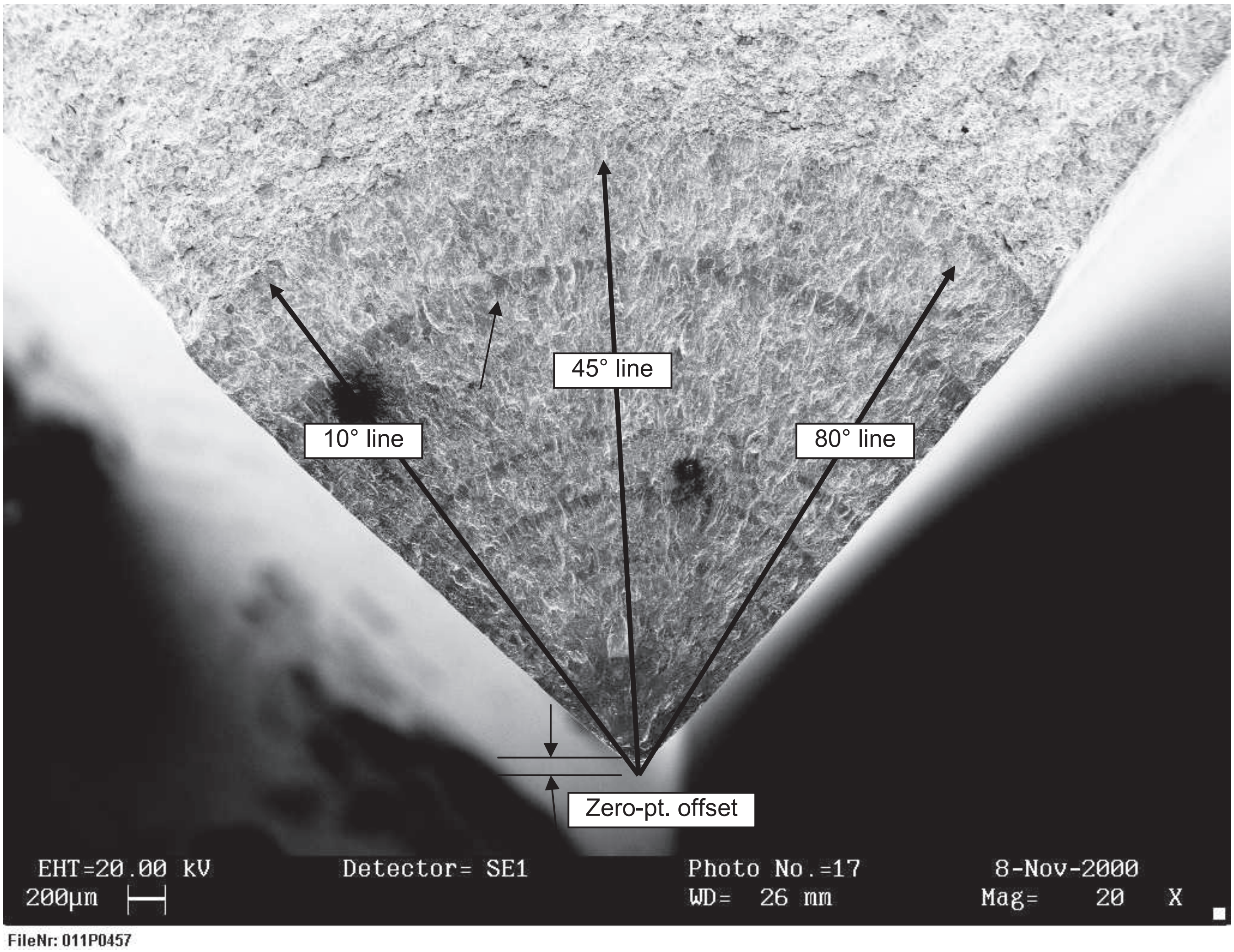


Figure C.7 — Post-test crack-front measurement location on fracture surface. Measurement positions are indicated by 10°, 45° and 80° lines. Small arrow indicates marker band caused by cycling at increased R-ratio at predetermined intervals.

da/dN Test record

Test date: Test piece type: corner crack

Labor. number: Width: $W =$ ....

Thickness: $B =$ ....

Material code:

$R_{p0.2}$ - RT - MPa

Test temp - MPa at test temp: .... °C

Material form:

Component:

Crack orientation:

Crack measurement: Potential drop

Measurement spacing: lead.. mm Test current: .... A

Initial potential, mV:

	RT	At test temperature	For a mm
At notch	....	....	....
At precrack	....	....	....

Precracking: sinus/Waveform Freg..

	ΔK	$F_{max.}$ kN	$F_{min.}$ kN	R	a	Frequency
Beginning conditions:	....	....	....	....	....	....
End conditions:	....	....	....	....	....	....

Normalized load-shedding rate: $C =$ .... mm^{-1}

Test conditions: R: .... Waveform: .... Frequency: .... Hz

ΔK at start: $F_{max.} =$.................................. $F_{min.} =$..................................... $a =$...

ΔK at end:

First valid ΔK:

Final valid ΔK:

Tabulated results: (must be available as computer file)

Format: N cycles, $a_{(mm)}$, da/dN$_{(m/cycle)}$, ΔK (MPa$\sqrt{}$m), $K_{max.}$ tested

Analysis method: modified polynomial, or secant, or polynomial

Test deviations:

Figure C.8 — Example report form

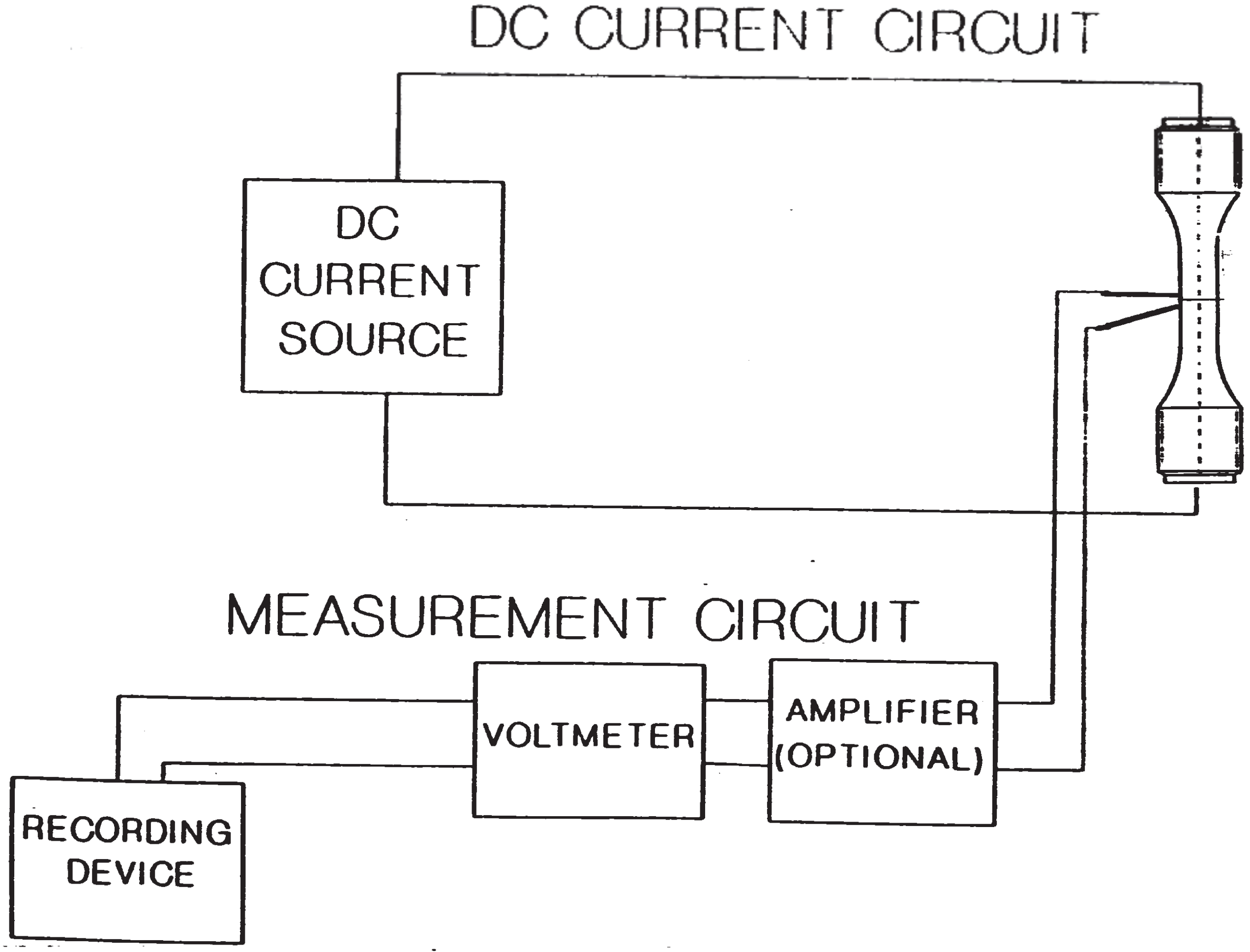


Figure C.9 — Schematic diagram of the DC potential system

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