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Corrosion of metals and alloys — Corrosion fatigue testing —

Part 2:
Crack propagation testing using precracked specimens

Corrosion des métaux et alliages — Essais de fatigue-corrosion —

Partie 2: Essais d'amorce de rupture sur des éprouvettes préfissurées

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Foreword

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

Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

International Standard ISO 11782-2 was prepared by Technical Committee ISO/TC 158, *Corrosion of metals and alloys*.

ISO 11782 consists of the following parts, under the general title *Corrosion of metals and alloys — Corrosion fatigue testing*:

— *Part 1: Cycles to failure testing*

— *Part 2: Crack-propagation testing using precracked specimens*

Annex A of this part of ISO 11782 is for information only.

Introduction

Crack propagation testing employs precracked specimens to provide information on the threshold conditions and on rates of corrosion fatigue crack growth. These data can be used in the design and evaluation of engineering structures where corrosion fatigue crack growth can dominate component life.

Because of the need to maintain elastically constrained conditions at the crack tip, the precracked specimens used for crack propagation tests are not suitable for the evaluation of thin products such as sheet or wire and are generally used for thicker products including plate, bar and forgings. They can also be used for parts joined by welding.

The results of corrosion fatigue testing are suitable for direct application only when the service conditions exactly parallel the test conditions especially with regard to material, environmental and stressing considerations.

Corrosion of metals and alloys — Corrosion fatigue testing —

Part 2:
Crack propagation testing using precracked specimens

1 Scope

1.1 This part of ISO 11782 describes the fracture mechanics method of determining the crack growth rates of pre-existing cracks under cyclic loading in a controlled environment and the measurement of the threshold stress intensity factor range for crack growth below which the rate of crack advance falls below some defined limit agreed between parties.

1.2 This part of ISO 11782 provides guidance and instruction on corrosion fatigue testing of metals and alloys in aqueous or gaseous environments.

2 Normative reference

The following standard contains provisions which, through reference in this text, constitute provisions of this part of ISO 11782. At the time of publication, the edition indicated was valid. All standards are subject to revision, and parties to agreements based on this part of ISO 11782 are encouraged to investigate the possibility of applying the most recent edition of the standard indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

ISO 7539-1:1987, *Corrosion of metals and alloys — Stress corrosion testing — Part 1: General guidance on testing procedures.*

3 Definitions

For the purposes of this part of ISO 11782, the following definitions apply.

3.1 corrosion fatigue: Process involving conjoint corrosion and alternating straining of the metal, often leading to cracking.

NOTE — Corrosion fatigue may occur when a metal is subjected to cyclic straining in a corrosive environment.

3.2 force, P: Force applied to the specimen considered positive when its direction is such as to cause the crack faces to move apart.

3.3 maximum force, P_{max}: Algebraic maximum value of force during a loading cycle.

3.4 minimum force, P_{min}: Algebraic minimum value of force during a loading cycle.

3.5 force range, ΔP: Difference between the algebraic maximum and minimum values of the force.

3.6 stress intensity factor, K_I: Function of applied load, crack length and specimen geometry having dimensions of stress (length)$^{1/2}$ which uniquely defines the elastic stress field intensification at the tip of a crack subjected to opening mode displacements (mode I).

NOTE — It has been found that stress intensity factors, calculated assuming that specimens respond purely elastically, correlate the behaviour of real cracked bodies provided that the size of the zone of plasticity at the crack tip is small compared to the crack length and the length of the uncracked ligament. In this standard, mode I is assumed and the subscript I is implied everywhere.

3.7 maximum stress intensity factor, K_{max}, in fatigue: Highest algebraic value of the stress intensity factor in a cycle corresponding to the maximum load.

3.8 minimum stress intensity factor, K_{min}, in fatigue: Lowest algebraic value of the stress intensity factor in a cycle.

NOTE — This value corresponds to the minimum load when the stress ratio, R, is greater than zero and is set equal to zero when R is less than or equal to zero.

3.9 range of stress intensity factor, ΔK, in fatigue: Algebraic difference between the maximum and minimum stress intensity factors in a cycle:

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

3.10 threshold stress intensity factor range, ΔK_{th}, in fatigue: Value of the stress intensity factor range below which the rate of crack advance becomes insignificant for the application.

3.11 stress ratio, R, in fatigue loading: Algebraic ratio of the minimum and maximum force in a cycle

$$R = \frac{P_{min}}{P_{max}} = \frac{K_{min}}{K_{max}}$$

3.12 cycle: Smallest segment of the load- or stress-time function which is repeated periodically. The terms fatigue cycle, load cycle and stress cycle are also commonly used.

3.13 fatigue crack growth rate, da/dN: Rate of crack extension caused by fatigue loading and expressed in terms of crack extension per cycle.

3.14 stress intensity factor coefficient, Y: Factor derived from the stress analysis for a particular specimen geometry which relates the stress intensity factor for a given crack length to the load and specimen dimensions.

3.15 plane strain fracture toughness, K_{Ic}: The critical value of K at which the first significant environmentally independent extension of the crack occurs under the influence of rising stress intensity under conditions of high constraint to plastic deformation.

3.16 specimen orientation: The fracture plane of the specimen identified in terms of firstly the direction of stressing and secondly the direction of crack growth expressed with respect to three reference axes. These are identified by the letters X, Y and Z.

where

Z is coincident with the main working force employed during manufacture of the material (short-transverse axis);

X is coincident with the direction of grain flow (longitudinal axis);

Y is normal to the X and Z axes (see figure 1).

3.17 crack length, a: Effective crack length measured from the crack tip to either the mouth of the notch or the loading point axis depending on the specimen geometry.

3.18 specimen width, W: Effective width of the specimen measured from the back face to either the face containing the notch or the loading plane depending on the specimen geometry.

3.19 waveform: Shape of the peak-to-peak variation of load as a function of time.

3.20 cyclic frequency: Number of cycles per unit time, usually expressed in terms of cycles per second (Hz).

4 Test

4.1 Principle of corrosion fatigue crack propagation testing

A fatigue pre-crack is induced in a notched specimen by cyclic loading. As the crack grows the loading conditions are adjusted until the values of ΔK and R are appropriate for the subsequent determination of ΔK_{th} or crack growth rates and the crack is of sufficient length for the influence of the notch to be negligible.

Corrosion fatigue crack propagation tests are then conducted using cyclic loading under environmental and stressing conditions relevant to the particular application. During the test, crack length is monitored as a function of elapsed cycles. These data are subjected to numerical analysis so that the rate of crack growth, da/dN, can be expressed as a function of the stress intensity factor range, ΔK.

Crack growth rates presented in terms of ΔK are generally independent of the geometry of the specimen used. The principle of similitude allows the comparison of data obtained from a variety of specimen types and allows da/dN versus ΔK data to be used in the design and evaluation of engineering structures provided that appropriate mechanical, chemical and electrochemical test conditions are employed. An important deviation from the principle of similitude can occur in relation to short cracks because of crack-tip chemistry differences, microstructurally sensitive growth and crack tip shielding considerations.

The threshold stress intensity factor range for corrosion fatigue, ΔK_{th} may be higher or lower than the threshold in air depending on the particular metal/environment conditions. It may be determined by a controlled reduction in load range (see 6.3) until the rate of growth becomes insignificant for the specific application. Practically, from a measurement perspective it is necessary to assign a value to this (see 8.5).

NOTE — Both crack growth rate measurements and threshold stress intensity factor range determinations can be markedly affected by residual stresses. Thermal stress relief should, therefore, be considered prior to testing, but if this is not acceptable, the possibility of an effect should be recognized in the interpretation of the results. In particular, the presence of residual stresses can lead to an apparent dependence of ΔK_{th} on specimen thickness. Thickness effects can also arise in principle in relation to hydrogen charging and also where through-thickness transport of fluid occurs in flowing aqueous solutions. In the latter case it should be recognized that solution transport via the crack sides in the through-thickness direction is an artifact of the fracture mechanics specimen and may not be representative of cracking in service.

Results of corrosion fatigue crack growth rate tests for many metals have shown that the relationship between da/dN and ΔK can differ significantly from the three-stage relationship usually observed for tests in air, as shown in figure 2. The shape of the curve depends on the material/environment system and for some cases time-dependent (as distinct from cycle-dependent) cracking modes can ensue which can enhance crack growth producing frequency-dependent growth rate plateaux as shown in figure 2.

4.2 Specimens for corrosion fatigue crack propagation testing

4.2.1 General

A wide range of standard specimen geometries of the type used in fracture toughness testing may be used. The particular type of specimen selected will be dependent upon the form of the material to be tested and the conditions of test.

Pin-loaded specimens such as compact tension (CT) specimens are not suitable for tests with R values of zero or less than zero because of backlash effects. For such purposes four-point single edge notch bend (SENB4) or centre cracked tension (CCT) specimens loaded by friction grips are suitable.

A basic requirement is that the dimensions of the specimens be sufficient to maintain predominantly triaxial (plane strain) conditions in which plastic deformation is limited in the vicinity of the crack tip. Experience with fracture toughness testing has shown that for a valid K_{Ic} measurement a, B and $(W\text{-}a)$ should not be less than

$$2{,}5\left[\frac{K_{Ic}}{\sigma_y}\right]^2$$

where σ_y is the yield strength.

It is recommended that a similar criterion be used to ensure adequate constraint during corrosion fatigue crack growth testing where K_{max} is substituted for K_{Ic} in the above expression.

4.2.2 Specimen design

Specimen geometries which are frequently used for corrosion fatigue crack growth rate testing include the following:

a) three-point single edge notch bend (SENB3);

b) four-point single edge notch bend (SENB4);

c) compact tension (CT);

d) centre-cracked tension (CCT).

Details of standard specimen designs for each of these types of specimen are given in figures 3 to 6 and permitted notch geometries are given in figure 7. Suitable machining tolerances are given in table 1.

4.2.3 Stress intensity factor considerations

It can be shown, using elastic theory, that the stress intensity factor acting at the tip of a crack in specimens or structures of various geometries can be expressed by relationships of the form:

$$K_I = Q\sigma\sqrt{a}$$

where

Q is the geometrical constant;

σ is the applied stress;

a is the crack length.

Stress intensity factors can be calculated by means of a dimensionless stress intensity coefficient, Y, related to crack length expressed in terms of a/W (where W is the width of the specimen) through a stress intensity factor function of the form:

$$K_{\mathrm{I}} = \frac{YP}{BW^{1/2}}$$

NOTE — Where $P \leqslant 0$, $K = 0$. Nevertheless, it should not be assumed that negative loading will have no influence on the rate of crack growth.

The values of Y appropriate to the four specimen geometries discussed above are given in tables 2 to 5.

4.2.4 Specimen preparation

Specimens of the required orientation (see figure 1) shall, where possible, be machined in the fully heat-treated condition, i.e. in the material condition of interest. For specimens in material that cannot easily be completely machined in the fully heat-treated condition, the final heat-treatment may be given prior to the notching and finishing operations provided that at least 0,5 mm per face is removed from the thickness at the finish machining stage. However, heat treatments may be carried out on fully machined specimens in cases where heat treatment will not result in detrimental surface conditions, residual stresses, quench cracking or distortion.

After machining, the specimens shall be fully degreased in order to ensure that no contamination of the crack tip occurs during subsequent fatigue precracking or corrosion fatigue crack propagation testing. In cases where it is necessary to attach electrodes to the specimens by soldering or brazing for crack length monitoring purposes, the specimens should be degreased following this operation prior to precracking in order to remove traces of remnant flux.

4.2.5 Specimen identification

Specimen identification marks may be stamped or scribed on either the face of the specimen bearing the notch or the end faces parallel to the notch.

5 Apparatus

5.1 Environmental chamber

The environmental chamber shall completely enclose the test section of the specimen. Wherever possible, the gripped portions shall be excluded from contact with the solution environment to prevent galvanic effects and crevice corrosion. If this is not possible, appropriate measures shall be taken through, for example, the use of similar metals, electrical insulation or coatings. An adequate volume of solution to metal area ratio is required (dependent on reaction rates and exposure time) and a circulation system is usually necessary. For conditions of applied potential or applied current a separate compartment for the counter electrode may be necessary to limit any effects caused by reaction products from this electrode. Non-metallic materials are recommended for the environmental chamber and circulation system where this is practicable. These materials shall be inert. Note that glass and certain plastics are not inert at elevated temperatures. Where metallic chambers are necessary these shall be electrically insulated from the specimen to prevent galvanic interaction.

For tests in gaseous environment an all-metal-chamber is preferred.

5.2 Crack length measurement

The most commonly used techniques for the measurement of crack length are described in annex A. Optical methods of measurement are often precluded by the environment and test chamber and, in any case, provide guidance only to the surface length of a crack. Enhancement of crack visibility by removal of corrosion products may perturb the local electrochemistry and is not recommended. Methods that measure the average crack length across the thickness of the specimen are generally preferred. These include electrical resistance methods. AC and DC potential drop measurements are suitable but should be checked to ensure that they exert no detectable influence on the rate of corrosion fatigue crack propagation and appropriate methods should be used to eliminate galvanic effects. Compliance methods based on measurement of displacement across the notch or of strain in the back face of the specimen opposite the notch can also be used.

6 Fatigue precracking

6.1 General

The machine used for fatigue cracking should have a method of loading such that the stress distribution is symmetrical about the notch and the applied force should be known to an accuracy within ± 2,5 %.

In corrosion fatigue studies in the laboratory an artificial precracking procedure is introduced to provide a sharpened fatigue crack of adequate size and straightness. In principle, this procedure can affect subsequent crack growth depending on the frequency used, the manner in which the loading parameters are adjusted and whether precracking is conducted in air or in the test environment.

In some materials, the introduction of the corrosion fatigue test environment during the precracking operation will promote a change from the normal ductile transgranular mode of fatigue cracking to a less ductile corrosion fatigue mode. This may facilitate the subsequent initiation of cracking during corrosion fatigue testing. However, unless corrosion fatigue testing is conducted immediately following the precracking operation, corrodent remaining at the crack tip may promote blunting due to corrosive attack. For this reason, it is recommended that, unless agreed otherwise between the parties, fatigue precracking should be conducted in the normal laboratory air environment. In this case, precracking can be expedited by the use of high cyclic frequency.

6.2 Precracking procedure

Conduct fatigue precracking with the specimen fully heat-treated to the condition in which it is to be tested until the crack extends beyond the notch at the side surfaces by at least 0,025W or 1,25 mm, whichever is greater.

The final K_{max} during precracking shall not exceed the initial K_{max} for which test data are to be obtained. Ideally, precracking should be conducted without reduction in the value of K_{max}. This is feasible for da/d$N > 10^{-8}$ m/cycle but impractical for lower growth rates (see 6.3).

NOTE — The ΔK values to give growth rates of about 10^{-8} m/cycle are:

— steels, nickel, titanium and copper alloys: ΔK = 13 MPa·m$^{1/2}$

— aluminium alloys: ΔK = 6 MPa·m$^{1/2}$

The K_{max} value can be evaluated from the R value of interest. The value of K_{max} shall not exceed 0,7K_{Ic}.

The K_{min} value can be as important as K_{max} during precracking; K_{min} will dictate crack wake effects. For example, high R versus low R crack wake effects can dramatically affect corrosion fatigue testing results. Transient da/dN (crack closure influenced) behaviour can result.

At the end of precracking check that the surface crack lengths do not differ by more than 0,1a. If the fatigue crack departs more than ± 5° from the plane of symmetry the specimen is not suitable for further testing.

The precracked specimen may be stored in a dessicated vessel until required. Long storage periods should be avoided because of possible crack tip blunting or contamination effects.

6.3 Precracking for low crack growth rates or ΔK_{th} determination

For da/d$N < 10^{-8}$ m/cycle and for determination of the threshold ΔK (see 8.5) the precracking procedure described in 6.2 should be followed initially. A load-shedding procedure is then adopted until the lowest ΔK or crack growth rate of interest is achieved.

Cyclically load the specimen, smoothly varying K_{max} with crack length according to:

$$K_{max} = K_s \exp\left[C_k\left(a - a_s\right)\right]$$

where

a_s is the crack length after the preliminary precracking stage (see 6.2);

K_s is the corresponding value of K_{max};

C_k is a load shedding factor; ($C_k = -100\ m^{-1}$ is generally satisfactory when a and a_s are expressed in metres).

Continue load shedding, varying P_{min} so that the stress ratio R remains constant and equal to R_s, the value after the preliminary precracking.

NOTE — Continuous load shedding by computer control is recommended. If step shedding of load is employed the reduction in P shall not exceed 10 % of the previous value, and adjustments should not be made until the crack has grown by at least the prior plane strain plastic zone size $\left(R_p = 0{,}1\left[K_{max}/\sigma_y\right]^2, m\right)$.

An alternative method of precracking for low crack growth rates or threshold ΔK determination can be used for high R values simply by increasing K_{min} while maintaining K_{max} constant until the relevant ΔK value is obtained.

Assuming the notch to behave as a crack of the equivalent length, cyclically load the specimen such that K_{max} equals the value of interest and K_{min} is derived from the target value of R.

When a reaches a_s, cyclically load the specimen, smoothly varying K_{min} with crack length according to

$$K_{min} = K_s\left[1 - \left(1 - R_s\right)\exp\left\{C_k\left(a - a_s\right)\right\}\right]$$

where C_k is a load shedding factor ($C_k = -280\ m^{-1}$ is generally satisfactory when a and a_s are expressed in metres).

Vary P_{max} so that K_{max} remains constant and equal to K_s. Continue until the appropriate ΔK value is obtained.

NOTE — K_s (1 – R_s) which equals ΔK at the beginning of the determination can conceivably be less than ΔK_{th} at this value of $R = R_s$ and this test method would clearly be inappropriate.

7 Test conditions

7.1 Environmental considerations

Because of the specificity of metal-environment interactions, it is essential that corrosion fatigue crack propagation tests are conducted under environmental conditions which are closely controlled (see paragraphs 3 and 4 below).

The environmental testing conditions depend upon the intent of the test but, ideally, should be the same as those prevailing for the intended use of the alloy or comparable to the anticipated service condition.

Environmental factors of importance are electrode potential, temperature, solution composition, pH, concentration of dissolved gases, flowrate and pressure. ISO 7539-1 provides useful background information. In relation to gaseous environments a critical factor is purity of the gas.

Tests may be conducted under open circuit conditions in which the electrode potential of the metal is dependent on the specific environmental conditions of the test, of which the degree of aeration is an important factor. Alternatively, the electrode potential may be displaced from the open circuit value by potentiostatic or galvanostatic methods.

Auxiliary electrodes to apply external current should be designed to produce uniform current distribution on the specimen, i.e the electrode potential should be constant.

7.2 Stressing considerations

7.2.1 Cyclic frequency

As in cycles to failure testing, cyclic frequency is usually the most important variable that influences corrosion fatigue crack propagation.

The rate of corrosion fatigue crack propagation generally increases with decreasing frequency because of the time dependence of the corrosion and diffusion processes that contribute to the corrosion fatigue process. At higher cyclic frequencies (generally greater than 10 Hz), the rate of corrosion fatigue crack propagation may be no greater than that of fatigue crack growth in air because insufficient time is available during each loading cycle for significant effects to occur. In some cases, the rate of corrosion fatigue crack propagation may also fall at very low cyclic frequencies because repassivation may outpace the rate of rupture of protective surface films at the crack tip.

Since too high or too low a cyclic frequency can lead to non-conservative data, it is important that corrosion fatigue crack propagation tests be conducted at a cyclic frequency that is relevant to the application under consideration. It is desirable to run tests at several frequencies both at greater and less than the application under consideration to assess the effects of changing frequencies.

7.2.2 Stress ratio

The rates of corrosion fatigue crack propagation are usually increased by higher stress ratios for several reasons depending on the system and including effects of stress ratio on crack tip straining, stress distribution ahead of the crack tip, crack tip shielding and crack chemistry. For this reason, the stress ratio used shall be representative of that encountered.

7.2.3 Waveform

For a given cyclic frequency, the waveform of the loading cycle governs the rate of film rupture at the crack tip and may, therefore, influence the rate of corrosion fatigue crack propagation. Hold periods at minimum, intermediate or maximum load in the cycle can either increase or decrease the rate of corrosion fatigue crack propagation, depending on the mechanism of the cracking process. For example, where K_{max} exceeds the K value for time dependent modes, a hold time at maximum load may be expected to increase the rate of crack propagation. However, in materials which are resistant to cracking under static load, a hold time at maximum load may reduce the rate of crack propagation because of time dependent crack blunting due to corrosion or plasticity. Such effects necessitate the use of an appropriate waveform and hold times during corrosion fatigue crack propagation testing.

Some practical applications involve exposure to random loading cycles or to well-defined periodic changes in the cyclic loading conditions. While some insight into the influence of these fluctuations may be gained by the summation of the effects observed during a series of tests under different loading conditions, it is preferable to simulate the service conditions by computer control using block or random loading programs.

7.2.4 Crack tip shielding (closure) effects

Rough intergranular corrosion fatigue fracture surfaces, oxides or calcareous deposits on the fracture surfaces can cause premature crack surface contact at a stress intensity factor $K = K_{closure}$ during unloading. This reduces the effective crack tip driving force below the applied ΔK and can greatly reduce fatigue crack propagation rates. Under these circumstances an effective ΔK is appropriate, as follows:

$$\Delta K_{eff} = K_{max} - K_{closure}$$

This reinforces the need for environmental and loading conditions to be carefully controlled during crack progagation measurements so that beneficial crack closure effects relevant to service can be identified.

8 Test procedure

8.1 General

Before testing, the thickness, B, and width, W, should be measured to within 0,001W on a line not further than 0,1W from the crack plane. The average length of the fatigue precrack on both sides of the specimen should also be determined and this value should be used in assessing the loads required to produce the initial stress intensity factor range, ΔK.

8.2 Starting procedure

The starting procedure invariably has some effect on the initial crack growth rates because of time-dependent changes in the local environment in the crack and the electrode potential, changes in crack-tip shape, charging of the metal with hydrogen, development of oxides or other deposits. For this reason considerable caution shall be exercised in interpreting initial data and this becomes of most significance in attempts to quantify threshold ΔK.

The precracked specimen and environmental chamber shall be mounted and the environment introduced to the cell. Cyclic loading shall then commence on immersion of the crack.

8.3 Environmental control and monitoring

The environment shall be monitored and controlled during the test as required. In unbuffered systems the pH can be maintained constant using an automatic pH control system; otherwise the effect of any variations in pH on crack growth shall be assessed.

In systems open to the atmosphere, aeration can be maintained by bubbling air through the solution. In closed systems, monitoring is required. The flowrates used in testing should simulate the range of conditions in service because flow can affect the electrode potential, e.g. by influencing the flux of oxygen, and mass transfer between the crack enclave and the bulk solution. The orientation of flow with respect to the crack can be important in the latter case. Sealing of the crack sides to limit artificial through-thickness transport should be considered but may introduce local crevice problems.

It is strongly recommended that the electrode potential be measured with a reference electrode appropriate for the application. Care shall be taken to limit IR drop in the measurement of potential. The temperature of the solution should be controlled to ± 2 °C.

8.4 Determination of corrosion fatigue crack propagation rates

8.4.1 Length of crack

Crack length must be recorded as a function of elapsed cycles either continuously or at intervals of crack extension of 0,01W. Crack lengths shall be measured to within 0,01W; changes in crack length shall be measured to within 0,002W.

Any test interruptions and time off-load shall be recorded together with the crack length associated with them.

It is desirable to terminate the test before a/W exceeds 0,65 and the specimen shall be removed from the test environment so that the crack front position can be marked before fracturing the specimen.

NOTE — The object of marking the crack front position is to enable a check to be made for crack front curvature. Possible methods are heat tinting followed by static fracture or continued cycling to failure in air using a substantially different stress range.

The length of the corrosion fatigue crack shall be measured on the fracture surface at both edges and at points 0,25B, 0,5B and 0,75B from one edge. Similar measurements shall be made at other locations on the fracture surface where the corrosion fatigue crack front is well defined. It should be confirmed that at all locations the maximum and minimum values of crack length do not differ by more than 0,1a.

It shall be confirmed that the measured length of the corrosion fatigue crack conforms with the value indicated by the crack monitoring method used during the test to within 0,01W.

8.4.2 Growth rate of crack

Crack growth rates can be calculated from the crack length versus elapsed cycles data using either the secant method or an incremental polynomial method.

8.4.2.1 Secant method

The secant (or point-to-point technique) for computing the crack growth rate simply involves calculating the slope of the straight line connecting two adjacent points on the a versus N curve. It is more formally expressed as follows:

$$\frac{\mathrm{d}a}{\mathrm{d}N}(\mathrm{m/cycle}) = \frac{a_{i+1} - a_i}{N_{i+1} - N_i} \times 10^{-3}$$

where

a_{i+1} is the crack length, in millimetres, of the next record;

a_i is the crack length, in millimetres, of the current record;

N_{i+1} is the count of individual cycles for the next record;

N_i is the count of individual cycles for the current record.

Since the computed da/dN is an average rate over the $(a_{i+1} - a_i)$, increment, the average length, $\bar{a} = \frac{1}{2}\left(a_{i+1} + a_i\right)$, is normally used to calculate ΔK.

8.4.2.2 Incremental polynomial method

This method for computing da/dN involves fitting a second-order polynomial (parabola) to sets of $(2n + 1)$ successive data points where n is usually 2 or 3 for five-point and seven-point fits, respectively. The form of the equation for the local fit is as follows:

$$\hat{a}_i = b_0 + b_1\left[\frac{N_i - C_1}{C_2}\right] + b_2\left[\frac{N_i - C_1}{C_2}\right]^2$$

where

$$-1 \leqslant \left[\frac{N_i - C_1}{C_2}\right] \leqslant +1$$

b_0, b_1 and b_2 are the regression parameters that are determined by the least squares regression method over the range $a_{i-n} \leqslant a \leqslant a_{i+n}$;

$\hat{a}_i$ is the fitted value of crack length at N_i.

The parameters: $C_1 = \frac{1}{2}\left(N_{i-n} + N_{i+n}\right)$ and $C_2 = \frac{1}{2}\left(N_{i+n} - N_{i-n}\right)$ are used to scale the input data, thus avoiding difficulties in determining the regression parameters.

The rate of crack growth at N_i is obtained from the derivative of the above parabola, which is given by the following expression:

$$\left[\frac{\mathrm{d}a}{\mathrm{d}N}\right]_{a_i} = \frac{b_1}{C_2} + \frac{2b_2\left(N_i - C_1\right)}{C_2^2}$$

The value of ΔK associated with this da/dN value is computed using the fitted crack length, $\hat{a}_i$, corresponding to N_i.

8.5 Determination of corrosion fatigue threshold stress intensity factor range

The procedure for precracking was described in clause 6 and for introduction of the environment in 8.2. The conventional definition of threshold ΔK in air involves the observation of no evidence of crack extension over a period of 5×10^6 cycles, or $q/10^{-8}$ (where q is the resolution of the crack length measurement system in mm). Clearly, this is unrealistic at test frequencies of 0,1 Hz or less. At low frequencies the relevant threshold ΔK_{th} may not be measurable because of the time scale involved. The minimum da/dN measured (corresponding to the "threshold") is influenced by the measurement resolution and long term reliability, patience and economics of measurement. For this reason, establishing a working definition of the threshold criterion in terms of an acceptably low da/dN for an arbitrary metal/environment system is not possible. The relevant criterion shall be agreed by the relevant parties.

NOTES

1 The starting procedure in relation to thresholds has, potentially, a significant influence. Precracking in air and subsequent immersion may give unrealistic transients. Precracking in solution at frequencies higher than those of relevance may give unrealistic crack-tip chemistry.

2 The degree of crack closure, which is directly affected by oxide or corrosion product thickness, fracture surface roughness plastic zone size, loading ratio, and deviation from Mode I loading, will also affect ΔK_{th}.

9 Test report

The report should include the following information:

a) specimen type and dimensions B and W (in millimetres) and notch depth;

b) description of the test machine and equipment used to measure crack length and the precision with which crack length measurement were made;

c) test material characterization in terms of, for example, chemical composition, melting and fabrication process, heat treatment, microstructure, grain size, non-metallic inclusion content and mechanical properties; product size and form shall also be reported as shall the method of stress relief, if applicable;

d) specimen orientation and its location with respect to the parent product from which it was removed;

e) terminal values of ΔK, R and crack length from fatigue precracking;

f) test loading variables, including ΔP, R, cyclic frequency and waveform;

g) descriptions of the environmental chamber and all equipment used for environmental monitoring or control;

h) initial solution composition, pH, degree of aeration (or concentration of other relevant gases), flow conditions, temperature and electrode potential; specification of flowrate shall be in terms of approximate linear rate past specimen if determined by the recirculation rate; reference electrode used, the potential shall be reported and referred to an appropriate standard electrode (example: standard hydrogen electrode or saturated calomel electrode at 25 °C); variations in these parameters during testing shall be recorded;

i) starting procedure for the test;

j) transients in the environment, or in the loading (including test interruptions) during testing noting the nature and duration and the associated crack lengths;

k) analysis methods applied to the data, including the technique used to convert a versus N to $\mathrm{d}a/\mathrm{d}N$;

l) specimen K-calibration and size criterion used to ensure predominantly elastic behaviour (for specimens not described in this part of ISO 11782);

m) extent of crack curvature (measurements at five locations across the specimen are recommended);

n) for corrosion fatigue crack propagation tests $\mathrm{d}a/\mathrm{d}N$ shall be plotted as a function of ΔK (it is recommended that ΔK be plotted on the abscissa and $\mathrm{d}a/\mathrm{d}N$ on the ordinate — log-log coordinates are commonly used); all data that violate the size requirements of 4.2.1 shall be identified.

o) for corrosion fatigue threshold stress intensity factor range determinations the value of ΔK_{th}, the associated crack length, the associated value of ΔP and the number of cycles without evidence of crack extension.

Annex A
(informative)

Information on methods for measuring crack lengths

A.1 Visual methods

A microscope or telescope is used having, typically, a magnification of × 20. Commonly, crack length is estimated from the travel of this but rigid mounting is essential if the necessary accuracy is to be obtained.

Alternatively a measured grid may be printed on the specimen faces and crack length estimated by comparison with this. The mounting of the optics is less critical in this case, but more specimen preparation is required.

Though the equipment costs for these methods are low, the methods themselves are very laborious. The methods are not amenable to automation so that unless 24 h supervision is available, test interruptions are likely to lead to a loss of data.

Necessarily, only surface crack length measurements are made.

A.2 Electrical resistance measurement methods

A.2.1 DC potential drop method

The specimen is electrically isolated and a constant current passed through it, across the crack plane. Typically the current density used on a ferritic steel specimen will be of the order of 10^4 A/m^2 to 10^5 A/m^2 on the net section, but higher current densities may be required on metals of lower resistivity. The potential drop between two points on either side of the crack plane is monitored and a calibration, derived either experimentally, analytically or numerically, used to relate this to crack length. In the latter cases experimental verification is desirable.

The method is well established and proprietary equipment with the necessary stability and reliability is readily available. It is not well suited to large specimens or to those of low resistivity because of the very high currents that may be required. A derivative of the method exists however, which can be used in these circumstances. This involves monitoring the length of the crack in a brittle metal foil attached to the specimen, the length of crack in the foil being taken to be equal to the surface length of the crack in the underlying specimen.

Potential sources of error with the general method are as follows:

a) thermal resistivity changes;

b) thermal emfs;

c) cyclic fluctuations usually attributed to crack closure.

A comparator technique may be used to overcome a). The potential drop across the crack is divided by the potential drop either measured between points on a second specimen similar to the first, electrically in series with it and physically close to it, but not cyclically loaded, or between a second pair of probes on the specimen under test. The latter, though experimentally easier, requires care in calibration as both the measured potentials may vary with crack length.

Thermal emfs can be eliminated by using voltage probes of similar material to the specimen. When junctions between two dissimilar metals are inevitable they should be embedded within a relatively large thermal mass. A split, hollowed-out cube of aluminium of 50 mm side is suitable.

Cyclic fluctuations are usually attributed to crack closure but an additional influence is the voltage induced by the movement of the specimen. This is at a maximum when the specimen's velocity is at its greatest but falls to zero at the points of maximum and minimum force. Ideally therefore, measurements should be taken at the point of maximum force in the cycle to eliminate both closure and induced voltage effects. A simple peak-reading circuit could mislead by picking out the induced voltage peak. Pulsed DC synchronized with force maxima, may be used to eliminate both thermal emf and crack closure effects.

The method provides a measure of the average crack length across the specimen and is well suited to automatic data collection and machine control.

A.2.2 AC potential drop methods

Potential drop methods fall into two categories: low- and high-frequency systems.

The low-frequency systems (typically operating in the range 10 Hz to 100 Hz) are essentially developments of the DC methods. The use of phase-sensitive detection systems enables a high signal-to-noise ratio to be obtained and thus the sensitivity is enhanced. Thermal emfs also cease to be a problem. However, calibrations are required as with the DC method. Cyclic fluctuations due to crack closure can also affect the AC method (see A.2.1).

High-frequency systems (5 kHz to 8 kHz) make use of the localization of current flow to the "skin" of the specimen that occurs at these frequencies. This minimizes the current requirements and leads to a linear relationship between voltage and crack length which is independent of specimen size. The method is thus particularly suitable for measuring cracks in large specimens.

The electronics of AC systems are relatively complex and there may be difficulty in achieving the required long-term stability. Depending on the particular characteristics of the system, great care may be necessary to avoid spurious signals due to pick-up. Thus, the physical loop formed between the probe wires and the specimen surface should be kept as small as possible and the probe wires should be twisted together or miniature screened/shielded cable used. Wires should be screened to prevent their movement and the probe and field current wires well separated.

Incorporating the higher-frequency methods into automatic monitoring systems is particularly convenient due to the linear voltage to crack length relationship obtained.

A.3 Compliance methods

The two most popular methods are as follows:

a) measurement of the displacement per unit force across the notch;

b) measurement of the "back face strain" per unit force.

In a) a suitable transducer, eg clip-on extensometer, LVDT (Linear Variable Displacement Transducer) or ring dynamometer is mounted across the notch mouth (in the case of SENB3, SENB4 and CT specimens) or notch centre (in the case of CCT specimens). The displacement per unit force is determined and related by calibration to the crack length. If a second specimen is used, it should be placed under identical environmental conditions as the test specimen. This will ensure similar transient thermal, etc. behaviour. Thermal effects can also be minimized by using a reversing polarity technique.

The "back face strain" (BFS) method is similar in principle. In this instance the transducer is a strain gauge bridge located on the "back face" of the specimen, i.e. that opposite the notch. This method has been particularly successful with CT specimens and similar sensitivity would be expected with SENB4. It is not suitable for SENB3 due to the location of a loading point opposite the notch, not for CCT as BFS in this geometry is not very sensitive to crack length. BFS may be preferred to other compliance methods at high frequencies due to the practical absence of inertial effects. Displacement transducers and strain gauges should be kept out of contact with the solution to preserve their integrity and to avoid galvanic effects.

With both approaches non-linear force displacement relationships may be encountered due to crack closure. When this occurs, the compliance is best determined from the force-displacement relationship evident during the high force part of the cycle.

The methods provide a measure of the average crack length and are well suited to automated data collection and machine control.

Table 1 — Toleranced dimensions of specimens

Dimension	Tolerances	Surface finish, squareness and parallelism
L *G* *H* F_1	± 0,01*W*	Surfaces shall be perpendicular and parallel as applicable to within 0,002*W* (Total indicator reading) Surface finish of faces perpendicular to the line of the notch root to be *Ra* 0,8 µm
F	± 0,004*W*	Notch to be equidistant about centreline to within 0,01*W*
D	+ 0,004*W* 0	Holes to be square to faces within ± 0,007 5*W* and parallel within ± 0,000 5*W* Surface finish *Ra* 0,4 µm

Table 2 — Stress intensity factor function values for SENB3 specimens

Tabulated values = $(KB/P) \times \sqrt{W/1\,000}$

Span = $4W$

a/W	0,000	0,001	0,002	0,003	0,004	0,005	0,006	0,007	0,008	0,009
0,10	3,39	3,40	3,42	3,43	3,45	3,46	3,48	3,49	3,50	3,52
0,11	3,53	3,55	3,56	3,58	3,59	3,60	3,62	3,63	3,64	3,66
0,12	3,67	3,69	3,70	3,71	3,73	3,74	3,75	3,77	3,78	3,79
0,13	3,81	3,82	3,83	3,85	3,86	3,87	3,89	3,90	3,91	3,93
0,14	3,94	3,95	3,96	3,98	3,99	4,00	4,02	4,03	4,04	4,05
0,15	4,07	4,08	4,09	4,11	4,12	4,13	4,14	4,16	4,17	4,18
0,16	4,19	4,21	4,22	4,23	4,25	4,26	4,27	4,28	4,30	4,31
0,17	4,32	4,33	4,35	4,36	4,37	4,38	4,40	4,41	4,42	4,43
0,18	4,45	4,46	4,47	4,48	4,50	4,51	4,52	4,54	4,55	4,56
0,19	4,57	4,59	4,60	4,61	4,62	4,64	4,65	4,66	4,67	4,69
0,20	4,70	4,71	4,72	4,74	4,75	4,76	4,78	4,79	4,80	4,81
0,21	4,83	4,84	4,85	4,87	4,88	4,89	4,90	4,92	4,93	4,94
0,22	4,96	4,97	4,98	5,00	5,01	5,02	5,03	5,05	5,06	5,07
0,23	5,09	5,10	5,11	5,13	5,14	5,15	5,17	5,18	5,19	5,21
0,24	5,22	5,23	5,25	5,26	5,27	5,29	5,30	5,32	5,33	5,34
0,25	5,36	5,37	5,38	5,40	5,41	5,43	5,44	5,45	5,47	5,48
0,26	5,49	5,51	5,52	5,54	5,55	5,57	5,58	5,59	5,61	5,62
0,27	5,64	5,65	5,67	5,68	5,69	5,71	5,72	5,74	5,75	5,77
0,28	5,78	5,80	5,81	5,83	5,84	5,86	5,87	5,89	5,90	5,92
0,29	5,93	5,95	5,96	5,98	5,99	6,01	6,02	6,04	6,05	6,07
0,30	6,08	6,10	6,12	6,13	6,15	6,16	6,18	6,20	6,21	6,23
0,31	6,24	6,26	6,28	6,29	6,31	6,32	6,34	6,36	6,37	6,39
0,32	6,41	6,42	6,44	6,46	6,47	6,49	6,51	6,52	6,54	6,56
0,33	6,57	6,59	6,61	6,63	6,64	6,66	6,68	6,69	6,71	6,73
0,34	6,75	6,77	6,78	6,80	6,82	6,84	6,85	6,87	6,89	6,91
0,35	6,93	6,95	6,96	6,98	7,00	7,02	7,04	7,06	7,08	7,09
0,36	7,11	7,13	7,15	7,17	7,19	7,21	7,23	7,25	7,27	7,29
0,37	7,31	7,33	7,34	7,36	7,38	7,40	7,42	7,44	7,46	7,48
0,38	7,51	7,53	7,55	7,57	7,59	7,61	7,63	7,65	7,67	7,69
0,39	7,71	7,73	7,75	7,78	7,80	7,82	7,84	7,86	7,88	7,91
0,40	7,93	7,95	7,97	7,99	8,02	8,04	8,06	8,08	8,11	8,13
0,41	8,15	8,17	8,20	8,22	8,24	8,27	8,29	8,31	8,34	8,36
0,42	8,38	8,41	8,43	8,46	8,48	8,50	8,53	8,55	8,58	8,60
0,43	8,63	8,65	8,68	8,70	8,73	8,75	8,78	8,80	8,83	8,85
0,44	8,88	8,90	8,93	8,96	8,98	9,01	9,04	9,06	9,09	9,12
0,45	9,14	9,17	9,20	9,22	9,25	9,28	9,31	9,33	9,36	9,39
0,46	9,42	9,45	9,47	9,50	9,53	9,56	9,59	9,62	9,65	9,68
0,47	9,70	9,73	9,76	9,79	9,82	9,85	9,88	9,91	9,94	9,97
0,48	10,01	10,04	10,07	10,10	10,13	10,16	10,19	10,22	10,26	10,29
0,49	10,32	10,35	10,38	10,42	10,45	10,48	10,52	10,55	10,58	10,62

Table 2 — Stress intensity factor function values for SENB3 specimens (*concluded*)

a/W	0,000	0,001	0,002	0,003	0,004	0,005	0,006	0,007	0,008	0,009
0,50	10,65	10,68	10,72	10,75	10,79	10,82	10,86	10,89	10,93	10,96
0,51	11,00	11,03	11,07	11,10	11,14	11,18	11,21	11,25	11,29	11,32
0,52	11,36	11,40	11,43	11,47	11,51	11,55	11,59	11,63	11,68	11,70
0,53	11,74	11,78	11,82	11,86	11,90	11,94	11,98	12,02	12,06	12,10
0,54	12,15	12,19	12,23	12,27	12,31	12,35	12,40	12,44	12,48	12,53
0,55	12,57	12,61	12,66	12,70	12,75	12,79	12,84	12,88	12,92	12,97
0,56	13,02	13,06	13,11	13,16	13,20	13,25	13,30	13,35	13,39	13,44
0,57	13,49	13,54	13,59	13,64	13,69	13,74	13,79	13,84	13,89	13,98
0,58	13,99	14,04	14,10	14,15	14,20	14,25	14,31	14,36	14,41	14,47
0,59	14,52	14,58	14,63	14,69	14,74	14,80	14,86	14,91	14,97	15,03
0,60	15,09	15,14	15,20	15,26	15,32	15,38	15,44	15,50	15,56	15,62
0,61	15,69	15,75	15,81	15,87	15,94	16,00	16,06	16,13	16,19	16,26
0,62	16,32	16,39	16,46	16,52	16,59	16,66	16,73	16,80	16,86	16,93
0,63	17,00	17,08	17,15	17,22	17,29	17,36	17,44	17,51	17,58	17,60
0,64	17,73	17,81	17,88	17,96	18,04	18,12	18,19	18,27	18,25	18,43
0,65	18,51	18,59	18,67	18,76	18,84	18,92	19,01	19,09	19,18	19,26
0,66	19,35	19,44	19,52	19,61	19,70	19,79	19,85	19,97	20,06	20,15
0,67	20,25	20,34	20,44	20,53	20,63	20,72	20,82	20,92	21,02	21,12
0,68	21,22	21,32	21,42	21,52	21,63	21,73	21,84	21,94	22,05	22,16
0,69	22,27	22,38	22,49	22,60	22,71	22,82	22,94	23,05	23,17	23,28
0,70	23,40	23,52	23,64	23,76	23,88	24,01	24,13	24,25	24,38	24,51
0,71	24,64	24,76	24,90	25,03	25,16	25,29	25,43	25,56	25,70	25,84
0,72	25,98	26,12	26,26	26,41	26,55	26,70	26,85	27,00	27,15	27,30
0,73	27,45	27,61	27,76	27,92	28,08	28,24	28,40	28,56	28,73	28,90
0,74	29,06	29,23	29,41	29,53	29,75	29,93	30,11	30,29	30,47	30,65
0,75	30,84	31,03	31,22	31,41	31,60	31,80	31,99	32,19	32,39	32,60
0,76	32,80	33,01	33,22	33,43	33,65	33,86	34,08	34,31	34,53	34,76
0,77	34,98	35,22	35,45	35,69	35,92	36,17	36,41	36,66	36,91	37,16
0,78	37,42	37,67	37,94	38,20	38,47	38,74	39,01	39,29	39,57	39,85
0,79	40,14	40,43	40,73	41,02	41,32	41,63	41,94	42,25	42,57	42,89
0,80	43,21	43,54	43,87	44,21	44,55	44,90	45,25	45,60	45,96	46,33
0,81	46,70	47,07	47,45	47,83	48,22	48,62	49,02	49,42	49,83	50,25
0,82	50,67	51,10	51,54	51,98	52,43	52,88	53,34	53,81	54,28	54,76
0,83	55,25	55,74	56,25	56,76	57,27	57,80	58,33	58,88	59,43	59,98
0,84	60,55	61,13	61,72	62,31	62,92	65,53	64,16	64,79	65,44	66,09
0,85	66,76	67,44	68,13	68,83	69,55	70,27	71,01	71,77	72,53	73,31
0,86	74,11	74,91	75,74	76,57	77,43	78,30	79,18	80,09	81,01	81,94
0,87	82,90	83,87	84,87	85,88	86,91	87,97	89,04	90,14	91,26	92,40
0,88	93,57	94,76	95,98	97,23	98,50	99,80	—	—	—	—
0,89	—	—	—	—	—	—	—	—	—	—

Source: SRAWLEY, J.E., *Int. J. Fracture*, 1976, 12, 475, 1987, Martinus Nijhoff Publishers, Dordrecht, Boston, Lancaster.

Closed form approximation:

$$Y = \frac{6\sqrt{\alpha\left[1{,}99 - \alpha(1-\alpha)\left(2{,}15 - 3{,}93\alpha + 2{,}7\alpha^2\right)\right]}}{(1+2\alpha)(1-\alpha)^{1{,}5}}$$

where

$\alpha = a/W$

Applicability: all values of a/W

Table 3 — Stress intensity factor function values for SENB4 specimens

Tabulated values = $(KB/P) \times \sqrt{W/1\,000}$ for the case where the inner and outer spans differ by $2W$. The value of the compliance function is directly proportional to this difference.

a/W	0,000	0,001	0,002	0,003	0,004	0,005	0,006	0,007	0,008	0,009
0,10	1,75	1,76	1,77	1,77	1,78	1,79	1,80	1,81	1,81	1,82
0,11	1,83	1,84	1,84	1,85	1,86	1,87	1,87	1,88	1,89	1,90
0,12	1,90	1,91	1,92	1,93	1,93	1,94	1,95	1,96	1,96	1,97
0,13	1,98	1,99	1,99	2,00	2,01	2,01	2,02	2,03	2,04	2,04
0,14	2,05	2,06	2,06	2,07	2,08	2,09	2,09	2,10	2,11	2,11
0,15	2,12	2,13	2,13	2,14	2,15	2,15	2,16	2,17	2,18	2,18
0,16	2,19	2,20	2,20	2,21	2,22	2,22	2,23	2,24	2,24	2,25
0,17	2,26	2,26	2,27	2,28	2,29	2,29	2,30	2,31	2,31	2,32
0,18	2,33	2,33	2,34	2,35	2,35	2,36	2,37	2,37	2,38	2,39
0,19	2,39	2,40	2,41	2,41	2,42	2,43	2,44	2,44	2,45	2,46
0,20	2,46	2,47	2,48	2,48	2,49	2,50	2,50	2,51	2,52	2,52
0,21	2,53	2,54	2,54	2,55	2,56	2,57	2,57	2,58	2,59	2,59
0,22	2,60	2,61	2,61	2,62	2,63	2,64	2,64	2,65	2,66	2,66
0,23	2,67	2,68	2,68	2,69	2,70	2,71	2,71	2,72	2,73	2,73
0,24	2,74	2,75	2,76	2,76	2,77	2,78	2,78	2,79	2,80	2,81
0,25	2,81	2,82	2,83	2,84	2,84	2,85	2,86	2,86	2,87	2,88
0,26	2,89	2,89	2,90	2,91	2,92	2,92	2,93	2,94	2,95	2,95
0,27	2,96	2,97	2,98	2,98	2,99	3,00	3,01	3,02	3,02	3,03
0,28	3,04	3,05	3,05	3,06	3,07	3,08	3,09	3,09	3,10	3,11
0,29	3,12	3,12	3,13	3,14	3,15	3,16	3,16	3,17	3,18	3,19
0,30	3,20	3,21	3,21	3,22	3,23	3,24	3,25	3,25	3,26	3,27
0,31	3,28	3,29	3,30	3,31	3,31	3,32	3,33	3,34	3,35	3,36
0,32	3,36	3,37	3,38	3,39	3,40	3,41	3,42	3,43	3,43	3,44
0,33	3,45	3,46	3,47	3,48	3,49	3,50	3,51	3,52	3,52	3,53
0,34	3,54	3,55	3,56	3,57	3,58	3,59	3,60	3,61	3,62	3,63
0,35	3,64	3,65	3,65	3,66	3,67	3,68	3,69	3,70	3,71	3,72
0,36	3,73	3,74	3,75	3,76	3,77	3,78	3,79	3,80	3,81	3,82
0,37	3,83	3,84	3,85	3,86	3,87	3,88	3,89	3,90	3,91	3,92
0,38	3,93	3,94	3,96	3,97	3,98	3,99	4,00	4,01	4,02	4,03
0,39	4,04	4,05	4,06	4,07	4,08	4,10	4,11	4,12	4,13	4,14
0,40	4,15	4,16	4,17	4,19	4,20	4,21	4,22	4,23	4,24	4,25
0,41	4,27	4,28	4,29	4,30	4,31	4,33	4,34	4,35	4,36	4,37
0,42	4,39	4,40	4,41	4,42	4,44	4,45	4,46	4,47	4,49	4,50
0,43	4,51	4,52	4,54	4,55	4,56	4,57	4,59	4,60	4,61	4,63
0,44	4,64	4,65	4,67	4,68	4,69	4,71	4,72	4,73	4,75	4,76
0,45	4,77	4,79	4,80	4,82	4,83	4,84	4,86	4,87	4,89	4,90
0,46	4,92	4,93	4,94	4,96	4,97	4,99	5,00	5,02	5,03	5,05
0,47	5,06	5,08	5,09	5,11	5,12	5,14	5,15	5,17	5,19	5,20
0,48	5,22	5,23	5,25	5,26	5,28	5,30	5,31	5,33	5,35	5,36
0,49	5,38	5,39	5,41	5,43	5,44	5,46	5,48	5,50	5,51	5,53

Table 3 — Stress intensity factor function values for SENB4 specimens (*concluded*)

a/W	0,000	0,001	0,002	0,003	0,004	0,005	0,006	0,007	0,008	0,009
0,50	5,55	5,56	5,58	5,60	5,62	5,63	5,65	5,67	5,69	5,71
0,51	5,72	5,74	5,76	5,78	5,80	5,82	5,83	5,85	5,87	5,89
0,52	5,91	5,93	5,95	5,97	5,99	6,01	6,03	6,05	6,07	6,09
0,53	6,11	6,13	6,15	6,17	6,19	6,21	6,23	6,25	6,27	6,29
0,54	6,31	6,33	6,35	6,38	6,40	6,42	6,44	6,46	6,48	6,51
0,55	6,53	6,55	6,57	6,60	6,62	6,64	6,67	6,69	6,71	6,73
0,56	6,76	6,78	6,81	6,83	6,85	6,88	6,90	6,93	6,95	6,98
0,57	7,00	7,03	7,05	7,08	7,10	7,13	7,15	7,18	7,20	7,23
0,58	7,26	7,28	7,31	7,34	7,36	7,39	7,42	7,45	7,47	7,50
0,59	7,53	7,56	7,59	7,61	7,64	7,67	7,70	7,73	7,78	7,79
0,60	7,82	7,85	7,88	7,91	7,94	7,97	8,00	8,03	8,06	8,09
0,61	8,13	8,16	8,19	8,22	8,25	8,29	8,32	8,35	8,39	8,42
0,62	8,45	8,49	8,52	8,56	8,59	8,62	8,68	8,69	8,73	8,77
0,63	8,80	8,84	8,87	8,91	8,95	8,99	9,02	9,06	9,10	9,14
0,64	9,18	9,21	9,25	9,29	8,33	9,37	9,41	9,45	9,49	9,53
0,65	9,58	9,62	9,66	9,70	9,74	9,79	9,83	9,87	9,92	9,96
0,66	10,00	10,05	10,09	10,14	10,18	10,23	10,28	10,32	10,37	10,42
0,67	10,47	10,51	10,56	10,61	10,66	10,71	10,76	10,81	10,86	10,91
0,68	10,96	11,02	11,07	11,12	11,17	11,23	11,28	11,34	11,39	11,45
0,69	11,50	11,56	11,61	11,67	11,73	11,79	11,85	11,99	11,96	12,02
0,70	12,08	12,15	12,21	12,27	12,33	12,39	12,46	12,52	12,59	12,65
0,71	12,72	12,78	12,85	12,92	12,99	13,06	13,12	13,19	13,26	13,34
0,72	13,41	13,48	13,55	13,65	13,70	13,78	13,85	13,93	14,01	14,08
0,73	14,16	14,24	14,32	14,40	14,48	14,57	14,65	14,73	14,82	14,90
0,74	14,99	15,08	15,16	15,25	15,34	15,43	15,52	15,62	15,71	15,80
0,75	15,90	16,00	16,09	16,19	16,29	16,39	16,49	16,59	16,70	16,80
0,76	16,91	17,01	17,12	17,23	17,34	17,45	17,56	17,67	17,79	17,91
0,77	18,02	18,14	18,26	18,38	18,50	18,63	18,75	18,88	19,01	19,14
0,78	19,27	19,40	19,53	19,67	19,81	19,94	20,08	20,23	20,37	20,51
0,79	20,66	20,81	20,96	21,11	21,27	21,42	21,58	21,74	21,90	22,07
0,80	22,32	22,10	22,57	22,74	22,92	23,09	23,27	23,45	23,64	23,82
0,81	24,01	24,20	24,40	24,59	24,79	24,99	25,20	25,40	25,61	25,83
0,82	26,04	26,26	26,48	26,71	26,93	27,17	27,40	27,64	27,88	28,13
0,83	28,37	28,63	28,88	28,14	29,41	29,67	29,95	30,22	30,50	30,79
0,84	31,08	31,37	31,67	31,97	32,28	32,59	32,91	33,23	33,56	33,90
0,85	34,24	34,58	34,93	35,29	35,65	36,02	36,40	36,78	37,17	37,57
0,86	37,97	38,38	38,80	39,22	39,66	40,10	40,55	41,01	41,47	41,95
0,87	42,44	42,93	43,43	43,95	44,47	45,01	45,55	46,11	46,68	47,26
0,88	47,85	48,45	49,07	49,70	50,35	51,00	51,68	52,36	53,07	53,79
0,89	54,52	55,27	56,04	56,83	57,64	58,46	53,91	60,17	61,06	61,97

Source: TADA, H., Paris, P.C. and IRWIN, G.R. *Stress analysis of cracks handbook*, 2nd ed., 1985, p. 2. 14, Paris Productions Inc. (and Del Research Corporation) St. Louis.

Closed form approximation:

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

where

$\theta = \pi a/2W$

Applicability: all values of a/W

Table 4 — Stress intensity factor function values for CT specimens

Tabulated values = $(KB/P) \times \sqrt{W/1\ 000}$

a/W	0,000	0,001	0,002	0,003	0,004	0,005	0,006	0,007	0,008	0,009
0,20	4,27	4,29	4,30	4,31	4,32	4,34	4,35	4,36	4,38	4,39
0,21	4,40	4,41	4,43	4,44	4,45	4,47	4,48	4,49	4,50	4,52
0,22	4,53	4,54	4,56	4,57	4,58	4,59	4,61	4,62	4,63	4,65
0,23	4,66	4,67	4,69	4,70	4,71	4,73	4,74	4,75	4,77	4,78
0,24	4,79	4,80	4,82	4,83	4,84	4,86	4,87	4,98	4,90	4,91
0,25	4,92	4,94	4,95	4,96	4,98	4,99	5,01	5,02	5,03	5,05
0,26	5,06	5,07	5,09	5,10	5,11	5,13	5,14	5,16	5,17	5,18
0,27	5,20	5,21	5,22	5,24	5,25	5,27	5,28	5,29	5,31	5,32
0,28	5,34	5,35	5,36	5,38	5,39	5,41	5,42	5,43	5,45	5,46
0,29	5,48	5,49	5,51	5,52	5,53	5,55	5,56	5,58	5,59	5,61
0,30	5,62	5,64	5,65	5,66	5,68	5,69	5,71	5,72	5,74	5,75
0,31	5,77	5,78	5,80	5,81	5,83	5,84	5,86	5,87	5,89	5,90
0,32	5,92	5,93	5,95	5,96	5,98	5,99	6,01	6,03	6,04	6,06
0,33	6,07	6,09	6,10	6,12	6,13	6,15	6,17	6,18	6,20	6,21
0,34	6,23	6,25	6,26	6,28	6,29	6,31	6,33	6,34	6,36	6,38
0,35	6,39	6,41	6,42	6,44	6,46	6,47	6,49	6,51	6,52	6,54
0,36	6,56	6,58	6,59	6,61	6,63	6,64	6,66	6,68	6,70	6,71
0,37	6,73	6,75	6,76	6,78	6,80	6,82	6,84	6,85	6,87	6,89
0,38	6,91	6,92	6,94	6,96	6,98	7,00	7,02	7,03	7,05	7,07
0,39	7,09	7,11	7,13	7,15	7,16	7,18	7,20	7,22	7,24	7,26
0,40	7,28	7,30	7,32	7,34	7,36	7,38	7,40	7,42	7,43	7,45
0,41	7,47	7,49	7,51	7,53	7,56	7,58	7,60	7,62	7,64	7,66
0,42	7,68	7,70	7,72	7,74	7,76	7,78	7,80	7,83	7,85	7,87
0,43	7,89	7,91	7,93	7,95	7,98	8,00	8,02	8,04	8,07	8,09
0,44	8,11	8,13	8,16	8,18	8,20	8,22	8,25	8,27	8,29	8,32
0,45	8,34	8,36	8,39	8,41	8,43	8,46	8,48	8,51	8,53	8,55
0,46	8,58	8,60	8,63	8,65	8,68	8,70	8,73	8,75	8,78	8,80
0,47	8,83	8,86	8,88	8,91	8,93	8,96	8,99	9,01	9,04	9,07
0,48	9,09	9,12	9,15	9,17	9,20	9,23	9,26	9,28	9,31	9,34
0,49	9,37	9,40	9,43	9,45	9,48	9,51	9,54	9,57	9,60	9,63
0,50	9,66	9,69	9,72	9,75	9,78	9,81	9,84	9,87	9,90	9,93
0,51	9,96	10,00	10,03	10,06	10,09	10,12	10,16	10,19	10,22	10,23
0,52	10,29	10,32	10,35	10,39	10,42	10,45	10,49	10,52	10,56	10,59
0,53	10,63	10,66	10,70	10,73	10,77	10,80	10,84	10,87	10,91	10,95
0,54	10,98	11,02	11,06	11,10	11,13	11,17	11,21	11,25	11,29	11,33
0,55	11,36	11,40	11,44	11,48	11,52	11,56	11,60	11,64	11,68	11,73
0,56	11,77	11,81	11,85	11,89	11,94	11,98	12,02	12,06	12,11	12,15
0,57	12,20	12,24	12,28	12,33	12,37	12,42	12,47	12,51	12,56	12,60
0,58	12,65	12,70	12,75	12,79	12,84	12,89	12,94	12,99	13,04	13,09
0,59	13,14	13,19	13,24	13,29	13,34	13,39	13,44	13,50	13,55	13,60

Table 4 — Stress intensity factor function values for CT specimens (*concluded*)

a/W	0,000	0,001	0,002	0,003	0,004	0,005	0,006	0,007	0,008	0,009
0,60	13,65	13,71	13,76	13,82	13,87	13,93	13,98	13,04	14,09	14,15
0,61	14,21	14,27	14,32	14,38	14,44	14,50	14,56	14,62	14,68	14,74
0,62	14,80	14,86	14,92	14,99	15,05	15,11	15,18	15,24	15,31	15,37
0,63	15,44	15,50	15,57	15,64	15,70	15,77	15,84	15,91	15,98	16,05
0,64	16,12	16,19	16,26	16,34	16,41	16,48	16,56	16,63	16,71	16,78
0,65	16,86	16,93	17,01	17,09	17,17	17,25	17,33	17,41	17,49	17,57
0,66	17,65	17,73	17,82	17,90	17,99	18,07	18,16	18,25	18,33	18,42
0,67	18,51	18,60	18,69	18,78	18,87	18,97	19,06	19,15	19,25	19,34
0,68	19,44	19,54	19,64	19,74	19,83	19,94	20,04	20,14	20,24	20,35
0,69	20,45	20,56	20,66	20,77	20,88	20,99	21,10	21,21	21,32	21,44
0,70	21,55	21,67	21,78	21,90	22,02	22,14	22,26	22,38	22,50	22,63
0,71	22,75	22,80	23,01	23,13	23,26	23,40	23,53	23,66	23,79	23,93
0,72	24,07	24,21	24,35	24,49	24,63	24,77	24,92	25,06	25,21	25,36
0,73	25,51	25,66	25,82	25,97	26,13	26,29	26,45	26,61	26,77	26,93
0,74	27,10	27,27	27,44	27,61	27,78	27,96	28,13	28,31	28,49	28,67
0,75	28,86	29,04	29,23	29,42	29,61	29,80	30,00	30,20	30,40	30,60
0,76	30,80	31,01	31,22	31,43	31,64	31,86	32,08	32,30	32,52	32,74
0,77	32,97	33,20	33,43	33,67	33,91	34,16	34,39	34,64	34,89	35,14
0,78	35,40	35,66	35,92	36,18	36,45	36,72	36,99	37,27	37,55	37,83
0,79	38,12	38,41	38,71	39,01	39,31	39,61	39,92	40,24	40,55	40,87
0,80	41,20	41,53	41,86	42,20	42,54	42,89	43,24	43,60	43,96	44,33
0,81	44,70	45,07	45,45	45,84	46,23	46,63	47,03	47,44	47,85	48,27
0,82	48,69	49,13	49,56	50,01	50,46	50,91	51,38	51,85	52,32	52,81
0,83	53,30	53,80	54,30	54,82	55,34	55,87	56,41	56,95	57,51	58,07
0,84	58,64	59,22	59,82	60,42	61,03	61,65	62,28	62,92	63,57	64,23
0,85	64,90	65,59	66,28	66,99	67,71	68,45	69,19	69,95	70,72	71,51
0,86	72,31	73,13	73,96	74,80	75,66	76,54	77,43	78,34	79,27	80,22
0,87	81,18	82,16	83,27	84,19	85,23	86,29	87,38	88,49	89,62	90,77
0,88	91,95	93,15	94,38	95,63	96,92	98,23	99,57	—	—	—
0,89	—	—	—	—	—	—	—	—	—	—

Source: Srawley, J.E., *Int. J. Fracture*, 1976, 12, 475, 1987, Martinus Nijhoff Publishers, Dordrecht, Boston, Lancaster.

$$Y = \frac{(2+\alpha)\left(0{,}886 + 4{,}64\alpha - 13{,}32\alpha^2 + 14{,}72\alpha^3 - 5{,}6\alpha^4\right)}{(1-\alpha)^{1{,}5}}$$

where

$\alpha = a/W$

Applicability: a/W greater than 0,2

Table 5 — Stress intensity function values for CCT specimens

Tabulated values = $(KB/P) \times \sqrt{W/1\ 000}$

a/*W*	0,000	0,001	0,002	0,003	0,004	0,005	0,006	0,007	0,008	0,009
0,10	0,282	0,283	0,285	0,286	0,288	0,289	0,290	0,292	0,293	0,295
0,11	0,296	0,297	0,299	0,300	0,302	0,303	0,304	0,306	0,307	0,308
0,12	0,310	0,311	0,312	0,314	0,315	0,316	0,318	0,319	0,320	0,321
0,13	0,323	0,324	0,325	0,327	0,328	0,329	0,330	0,332	0,333	0,334
0,14	0,335	0,337	0,338	0,339	0,340	0,342	0,343	0,344	0,345	0,347
0,15	0,348	0,349	0,350	0,351	0,353	0,354	0,355	0,356	0,358	0,359
0,16	0,360	0,361	0,362	0,363	0,365	0,366	0,367	0,368	0,369	0,371
0,17	0,372	0,373	0,374	0,375	0,376	0,378	0,379	0,380	0,381	0,382
0,18	0,383	0,384	0,386	0,387	0,388	0,389	0,390	0,381	0,392	0,394
0,19	0,395	0,396	0,397	0,398	0,399	0,400	0,402	0,403	0,404	0,405
0,20	0,406	0,407	0,408	0,409	0,410	0,412	0,413	0,414	0,415	0,416
0,21	0,417	0,418	0,419	0,420	0,421	0,423	0,424	0,425	0,426	0,427
0,22	0,428	0,429	0,430	0,431	0,432	0,433	0,435	0,436	0,437	0,438
0,23	0,439	0,440	0,441	0,442	0,443	0,444	0,445	0,446	0,447	0,449
0,24	0,450	0,451	0,452	0,453	0,454	0,455	0,456	0,457	0,458	0,459
0,25	0,460	0,461	0,462	0,464	0,465	0,466	0,467	0,468	0,469	0,470
0,26	0,471	0,472	0,473	0,474	0,475	0,476	0,477	0,478	0,479	0,481
0,27	0,482	0,483	0,484	0,485	0,486	0,487	0,488	0,489	0,490	0,491
0,28	0,492	0,493	0,494	0,495	0,496	0,497	0,498	0,500	0,501	0,502
0,29	0,503	0,504	0,505	0,506	0,507	0,508	0,509	0,510	0,511	0,512
0,30	0,513	0,514	0,515	0,516	0,517	0,519	0,520	0,521	0,522	0,523
0,31	0,524	0,525	0,526	0,527	0,528	0,529	0,530	0,531	0,532	0,533
0,32	0,534	0,535	0,537	0,538	0,539	0,540	0,541	0,542	0,543	0,544
0,33	0,545	0,546	0,547	0,548	0,549	0,550	0,551	0,553	0,554	0,555
0,34	0,556	0,557	0,558	0,559	0,560	0,561	0,562	0,563	0,564	0,565
0,35	0,566	0,568	0,569	0,570	0,571	0,572	0,573	0,574	0,575	0,576
0,36	0,577	0,578	0,579	0,581	0,582	0,583	0,584	0,585	0,586	0,587
0,37	0,588	0,589	0,590	0,591	0,593	0,594	0,595	0,596	0,597	0,598
0,38	0,599	0,600	0,601	0,603	0,604	0,605	0,606	0,607	0,608	0,609
0,39	0,610	0,611	0,613	0,614	0,615	0,616	0,617	0,618	0,619	0,620
0,40	0,622	0,623	0,624	0,625	0,626	0,627	0,628	0,629	0,631	0,632
0,41	0,633	0,634	0,635	0,636	0,637	0,639	0,640	0,641	0,642	0,643
0,42	0,644	0,646	0,647	0,648	0,649	0,650	0,651	0,653	0,654	0,655
0,43	0,656	0,657	0,658	0,660	0,661	0,662	0,663	0,664	0,665	0,667
0,44	0,668	0,669	0,670	0,671	0,673	0,674	0,675	0,676	0,677	0,679
0,45	0,680	0,681	0,682	0,684	0,685	0,686	0,687	0,688	0,690	0,691
0,46	0,692	0,693	0,695	0,696	0,697	0,698	0,700	0,701	0,702	0,703
0,47	0,705	0,706	0,707	0,708	0,710	0,711	0,712	0,713	0,715	0,716
0,48	0,717	0,718	0,720	0,721	0,722	0,724	0,725	0,726	0,727	0,729
0,49	0,730	0,731	0,733	0,734	0,735	0,737	0,738	0,739	0,741	0,742

Table 5 — Stress intensity function values for CCT specimens (*concluded*)

a/W	0,000	0,001	0,002	0,003	0,004	0,005	0,006	0,007	0,008	0,009
0,50	0,743	0,745	0,746	0,747	0,749	0,750	0,751	0,753	0,754	0,755
0,51	0,757	0,758	0,759	0,761	0,762	0,764	0,765	0,766	0,768	0,769
0,52	0,770	0,772	0,773	0,775	0,776	0,777	0,779	0,780	0,782	0,783
0,53	0,785	0,786	0,787	0,789	0,790	0,792	0,793	0,795	0,796	0,798
0,54	0,799	0,800	0,802	0,803	0,805	0,806	0,808	0,809	0,811	0,812
0,55	0,814	0,815	0,817	0,818	0,820	0,821	0,823	0,824	0,826	0,827
0,56	0,829	0,830	0,832	0,834	0,835	0,837	0,838	0,840	0,841	0,843
0,57	0,845	0,846	0,848	0,849	0,851	0,853	0,854	0,856	0,857	0,859
0,58	0,861	0,862	0,864	0,865	0,867	0,869	0,870	0,872	0,874	0,875
0,59	0,877	0,879	0,880	0,882	0,884	0,886	0,887	0,889	0,891	0,892
0,60	0,894	0,896	0,898	0,899	0,901	0,903	0,905	0,906	0,908	0,910
0,61	0,912	0,914	0,915	0,917	0,919	0,921	0,923	0,924	0,926	0,928
0,62	0,930	0,932	0,934	0,936	0,937	0,939	0,941	0,943	0,945	0,947
0,63	0,949	0,951	0,953	0,955	0,956	0,958	0,960	0,962	0,964	0,966
0,64	0,968	0,970	0,972	0,974	0,976	0,978	0,980	0,982	0,984	0,986
0,65	0,988	0,991	0,993	0,995	0,997	0,999	1,00	1,00	1,01	1,01
0,66	1,01	1,01	1,01	1,02	1,02	1,02	1,02	1,02	1,03	1,03
0,67	1,03	1,03	1,03	1,04	1,04	1,04	1,05	1,05	1,05	1,05
0,68	1,05	1,06	1,06	1,06	1,06	1,07	1,07	1,07	1,07	1,08
0,69	1,08	1,08	1,08	1,09	1,09	1,09	1,10	1,10	1,10	1,10
0,70	1,10	1,11	1,11	1,11	1,11	1,12	1,12	1,12	1,12	1,13
0,71	1,13	1,13	1,13	1,14	1,14	1,14	1,15	1,15	1,15	1,15
0,72	1,16	1,16	1,16	1,16	1,17	1,17	1,18	1,18	1,18	1,18
0,73	1,18	1,19	1,19	1,19	1,20	1,20	1,20	1,21	1,21	1,21
0,74	1,21	1,22	1,22	1,22	1,23	1,23	1,23	1,24	1,24	1,24
0,75	1,25	1,25	1,25	1,26	1,26	1,27	1,27	1,27	1,27	1,28
0,76	1,28	1,28	1,29	1,29	1,29	1,30	1,30	1,31	1,31	1,31
0,77	1,32	1,32	1,32	1,33	1,33	1,33	1,34	1,34	1,35	1,35
0,78	1,35	1,36	1,36	1,37	1,37	1,37	1,38	1,38	1,39	1,39
0,79	1,39	1,40	1,40	1,41	1,41	1,42	1,42	1,42	1,43	1,43
0,80	1,44	1,44	1,45	1,45	1,46	1,46	1,47	1,47	1,47	1,48
0,81	1,48	1,49	1,49	1,50	1,50	1,51	1,51	1,52	1,52	1,53
0,82	1,53	1,54	1,55	1,55	1,56	1,56	1,57	1,57	1,58	1,58
0,83	1,59	1,59	1,60	1,61	1,61	1,62	1,62	1,63	1,64	1,64
0,84	1,65	1,65	1,66	1,67	1,67	1,68	1,69	1,69	1,70	1,71
0,85	1,71	1,72	1,73	1,73	1,74	1,75	1,76	1,76	1,77	1,78
0,86	1,78	1,79	1,80	1,81	1,82	1,82	1,83	1,84	1,85	1,86
0,87	1,86	1,87	1,88	1,89	1,90	1,91	1,92	1,92	1,92	1,94
0,88	1,95	1,96	1,97	1,98	1,99	2,00	2,01	2,02	2,03	2,04
0,89	2,05	2,06	2,07	2,08	2,10	2,11	2,12	2,13	2,14	2,15

Source: TADA, H., Paris, P.C. and IRWIN, G.R. *Stress analysis of cracks handbook*, 2nd ed., 1985, p. .2.2. Paris Productions Inc. (and Del Research Corporation) St. Louis.

Closed form approximation:

$$Y = \sqrt{\theta \sec\theta}\left(0{,}707 - 0{,}007\theta^2 + 0{,}007\theta^4\right)$$

where

$\theta = \pi a / 2W$

Applicability: all values of a/W