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Plastics — Determination of tension-tension fatigue crack propagation — Linear elastic fracture mechanics (LEFM) approach

Plastiques — Détermination de la propagation de fissure par fatigue en traction — Approche de la mécanique linéaire élastique de la rupture (LEFM)

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Foreword

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

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Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT) see the following URL: Foreword - Supplementary information.

The committee responsible for this document is ISO/TC 61, *Plastics*, Subcommittee SC 2, *Mechanical properties*.

This second edition cancels and replaces the first edition (ISO 15850:2002) of which it constitutes a minor revision.

Plastics — Determination of tension-tension fatigue crack propagation — Linear elastic fracture mechanics (LEFM) approach

1 Scope

This International Standard specifies a method for measuring the propagation of a crack in a notched specimen subjected to a cyclic tensile load varying between a constant positive minimum and a constant positive maximum value. The test results include the crack length as a function of the number of load cycles and the crack length increase rate as a function of the stress intensity factor and energy release rate at the crack tip. The possible occurrence of discontinuities in crack propagation is detected and reported.

The test can be also used for the purpose of determining the resistance to crack propagation failure. In this case, the results can be presented in the form of number of cycles to failure or total time taken to cause crack propagation failure versus the stress intensity factor (see Annex A).

The method is suitable for use with the following range of materials:

- rigid and semi-rigid thermoplastic moulding and extrusion materials (including filled and short-fibre-reinforced compounds) plus rigid and semi-rigid thermoplastic sheets;
- rigid and semi-rigid thermosetting materials (including filled and short-fibre-reinforced compounds) plus rigid and semi-rigid thermosetting sheets.

2 Normative references

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

ISO 291, *Plastics — Standard atmospheres for conditioning and testing*

ISO 527 (all parts), *Plastics — Determination of tensile properties*

ISO 2818, *Plastics — Preparation of test specimens by machining*

3 Terms and definitions

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

3.1
cycle
smallest segment of a load-time or stress-time function which is repeated periodically

Note 1 to entry: The terms fatigue cycle, load cycle, and stress cycle are also commonly used.

3.2
number of cycles completed
N
number of load cycles since the beginning of a test

3.3

waveform

shape of the load-time curve within a single cycle

3.4

maximum load

P_{max}

highest value of the load during a cycle

Note 1 to entry: It is expressed in newtons.

Note 2 to entry: Only positive, i.e. tensile, loads are used in this test method.

3.5

minimum load

P_{min}

lowest value of the load during a cycle

Note 1 to entry: It is expressed in newtons.

Note 2 to entry: Only positive, i.e. tensile, loads are used in this test method.

3.6

load range

ΔP

difference between the maximum and the minimum loads in one cycle, given by:

$$\Delta P = P_{\text{max}} - P_{\text{min}}$$

3.7

load ratio

stress ratio

R

ratio of the minimum to the maximum load in one cycle, i.e.:

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

3.8

stress intensity factor

K

limiting value of the product of the stress σ (r) perpendicular to the crack area at a distance r from the crack tip and of the square root of $2\pi r$, as r tends to zero:

$$K = \lim_{r \to 0} \sigma(r)\sqrt{2\pi r}$$

[SOURCE: ISO 13586:2000, 3.3]

Note 1 to entry: It is expressed in pascal root metres ($\text{Pa}\cdot\text{m}^{1/2}$).

Note 2 to entry: The term factor is used here because it is in common usage, even though the quantity has dimensions.

3.9

maximum stress intensity factor

K_{max}

highest value of the stress intensity factor in one cycle

3.10
minimum stress intensity factor

K_{min}

lowest value of the stress intensity factor in one cycle

3.11
stress intensity factor range

ΔK

difference between the maximum and minimum stress intensity factors in one cycle, given by:

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

3.12
energy release rate

G

difference between the external work δU_{ext} done on a body to enlarge a cracked area by an amount δA and the corresponding change in strain energy δU_S:

$$G = \frac{\delta U_{ext}}{\delta A} - \frac{\delta U_S}{\delta A}$$

Note 1 to entry: It is expressed in joules per square metre.

Note 2 to entry: Assuming linear elastic behaviour, the following relationship between the stress intensity factor K and the energy release rate G holds:

$$G = \frac{K^2}{E'}$$

where

$E' = E$ for plane stress;

$E' = \frac{E}{1 - \nu^2}$ for plane strain conditions;

E and ν are the tensile modulus and Poisson’s ratio, respectively.

3.13
maximum energy release rate

G_{max}

highest value of the energy release rate in one cycle

3.14
minimum energy release rate

G_{min}

lowest value of the energy release rate in one cycle

3.15
energy release rate range

ΔG

difference between the maximum and minimum energy release rates in one cycle, given by:

$$\Delta G = G_{max} - G_{min}$$

3.16

notch

sharp indentation made in the specimen, generally using a razor blade or a similar sharp tool, before a test and intended as the starting point of a fatigue-induced crack

3.17

initial crack length

a_0

length of the notch (3.16)

Note 1 to entry: It is expressed in metres.

Note 2 to entry: For compact tensile (CT) specimens, it is measured from the line joining the load-application points (i.e. the line through the centres of the loading-pin holes) to the notch tip (see Figure 2). For single-edge-notched tensile (SENT) specimens, it is measured from the edge of the specimen to the notch tip. Details of the measurement procedure are given in 7.3.

3.18

crack length

a

total crack length at any time during a test, given by the initial crack length a_0 plus the crack length increment due to fatigue loading

Note 1 to entry: It is expressed in metres.

3.19

fatigue crack growth rate

$\mathrm{d}a/\mathrm{d}N$

rate of crack extension caused by fatigue loading and expressed in terms of average crack extension per cycle

Note 1 to entry: It is expressed in metres per cycle.

3.20

stress intensity calibration

mathematical expression, based on empirical or analytical results, that relates the stress intensity factor to load and crack length for a specific specimen geometry

3.21

gauge length

L_0

<single-edge-notched tensile (SENT) specimen> free distance between the upper and lower grips after the specimen has been mounted in the test machine

Note 1 to entry: It is expressed in metres.

3.22

number of cycles to failure

N_f

total number of load cycles from the beginning of the test to fatigue crack propagation to sample failure

3.23

t_f

time to failure

total number of load cycles from the beginning of the test to fatigue crack propagation to sample failure, expressed in time

Note 1 to entry: It is expressed in hours.

4 Principle

A constant-amplitude cyclic tensile load is imposed on a specimen under suitable test conditions (specimen shape and size, notching, maximum and minimum loads, load cycle frequency, etc.), causing a crack to start from the notch and propagate.

The crack length a is monitored during the test and recorded as a function of the number N of load cycles completed.

Numerical differentiation of the experimental function $a(N)$ provides the fatigue crack growth rate $\mathrm{d}a/\mathrm{d}N$ which is reported as a function of stress intensity factor and energy release rate at the crack tip.

For the case where total number of cycles to failure or time to failure is to be determined, the crack length need not be monitored.

5 Significance and use

Fatigue crack propagation, particularly when expressed as the fatigue crack growth rate $\mathrm{d}a/\mathrm{d}N$ as a function of crack-tip stress intensity factor range ΔK or energy release rate range ΔG, characterizes a material’s resistance to stable crack extension under cyclic loading. Background information on the fatigue behaviour of plastics and on the fracture mechanics approach to fatigue for these materials is given in References [1] and [2].

Expressing $\mathrm{d}a/\mathrm{d}N$ as a function of ΔK or ΔG provides results that are independent of specimen geometry, thus enabling exchange and comparison of data obtained with a variety of specimen configurations and loading conditions. Moreover, this feature enables $\mathrm{d}a/\mathrm{d}N$ versus ΔK or ΔG data to be utilized in the design and evaluation of engineering structures. The concept of similitude is assumed, which implies that cracks of differing lengths subjected to the same nominal ΔK or ΔG will advance by equal increments of crack extension per cycle.

Fatigue crack propagation data are not geometry independent in the strict sense since thickness effects generally occur. The potential effects of specimen thickness have to be considered when generating data for research or design.

Anisotropy in the molecular orientation or in the structure of the material, and the presence of residual stresses, can have an influence on fatigue crack propagation behaviour. The effect can be significant when test specimens are removed from semi-finished products (e.g. extruded sheets) or finished products. Irregular crack propagation, namely excessive crack front curvature or out-of-plane crack growth, generally indicates that anisotropy or residual stresses are affecting the test results.

This test method can serve the following purposes:

a) to establish the influence of fatigue crack propagation on the lifetime of components subjected to cyclic loading, provided data are generated under representative conditions and combined with appropriate fracture toughness data (see ISO 13586) and stress analysis information;

b) to establish material-selection criteria and inspection requirements for damage-tolerant applications;

c) to establish, in quantitative terms, the individual and combined effects of the material’s structure, the processing conditions, and the loading variables on fatigue crack propagation;

d) used as an accelerated test for the evaluation of service life performance of components subjected to static fatigue loading conditions (this would also include ranking between materials — see Annex A).

6 Test specimens

6.1 Shape and size

6.1.1 Standard specimens

Two different types of specimen can be used: single-edge-notched tensile (SENT) and compact tensile (CT). Figures 1 and 2 describe their geometrical characteristics.

For the case where the test is to be carried out to sample failure for the purpose of determining the total number of cycles to failure or time failure, and where crack propagation need not be monitored, a full notch tensile (FNT) specimen of ISO 16770 and a cracked round bar (CRB) specimen[6] may be also utilized.

6.1.2 Thickness and width

When the specimen thickness h is too small compared to the width w, it is difficult to avoid lateral deflections or out-of-plane bending of the specimen. Conversely, with very thick specimens, through-thickness crack curvature corrections are often necessary and difficulties can be encountered in meeting the through-thickness straightness requirement of 8.1.

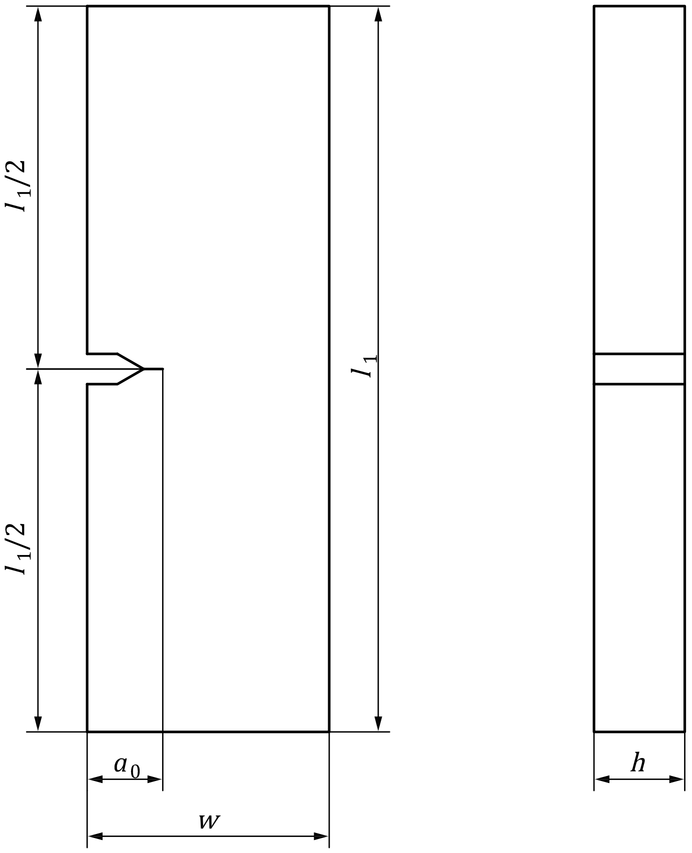
On the basis of these considerations, the following limits are recommended for h and w:

a) for CT specimens, $w/10 \le h \le w/2$;

b) for SENT specimens, $w/20 \le h \le w/4$.

It should be noted that the test results are in general thickness dependent: specimens obtained from the same material but having different thicknesses are likely to give different responses.

It is usually convenient to make the thickness h of specimens equal to the thickness of the sheet sample from which the specimens are cut.



Key

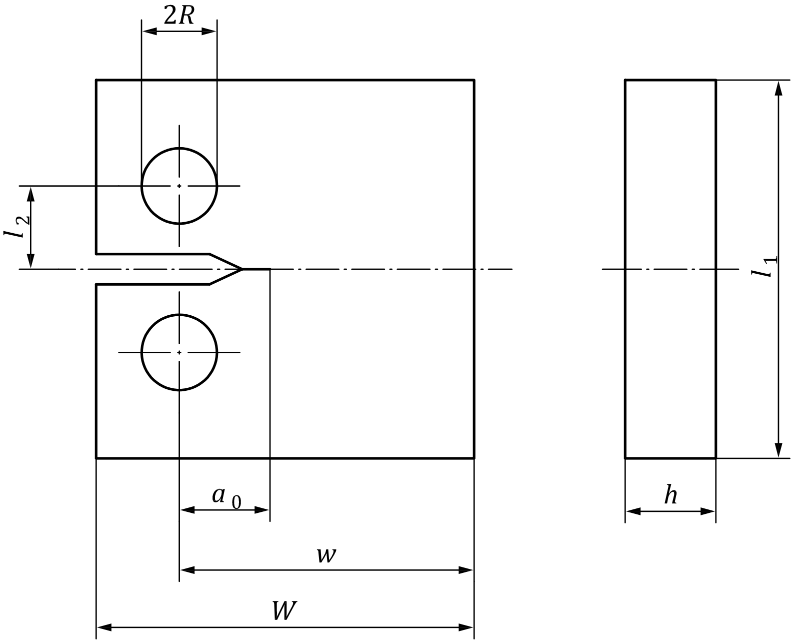
w	width
l_1	length
h	thickness
a_0	initial crack length

$w/20 \le h \le w/4$ (recommended)

$l_1 > 2{,}5w$

The notch shall be within ±0,01w of the specimen centreline.

Figure 1 — Standard single-edge-notched tensile (SENT) specimen for fatigue crack propagation testing



Key

w	effective width	$w/10 \leq h \leq w/2$ (recommended)
W	overall width	$W = 1{,}25w \pm 0{,}01w$
l_1	length	$l_1 = 1{,}2w \pm 0{,}01w$
l_2	distance between centres of loading-pin holes located symmetrically to the crack plane to within ± 0,005w	$l_2 = 0{,}55w \pm 0{,}005w$
R	radius of loading-pin hole	$R = 0{,}125w \pm 0{,}005w$
h	thickness	
a_0	initial crack length	$a_0 \geq 0{,}2w$

The notch shall be within ±0,01w of the specimen centreline.

Figure 2 — Standard compact tensile (CT) specimen for fatigue crack propagation testing

6.1.3 Size requirements

In order for the results obtained by this test method to be valid, it is required that the material behaviour be predominantly linear elastic at all values of applied load and crack length. Deviations may arise from either viscoelastic behaviour of the material or large-scale plasticity ahead of the crack tip. The former may result in significant nonlinearity of the mechanical behaviour, possibly aggravated by a progressive rise of the specimen temperature during the test. The test procedure outlined in this International Standard is therefore recommended only for materials exhibiting very limited viscoelasticity under the loading frequency used and for the expected test duration. Large-scale plasticity of the ligament can be avoided by ensuring that the plastic zone around the crack tip is small compared with the size of the uncracked ligament ($w - a$). On the basis of previous experience with metallic materials[3], it is required that the following size limits be satisfied in order for the test results to be valid:

$$(w-a) \geq (4/\pi)\left(K_{\max}/\sigma_{y}\right)^{2} \tag{1}$$

where

$w - a$ is the uncracked-specimen ligament width;

σ_y is the tensile-yield stress measured in accordance with the relevant part of ISO 527.

The same size limits are expressed in graphical form in Figure 3, where the dimensionless quantities $K_{\max}/\left(\sigma_y\sqrt{w}\right)$ and a/w are plotted against each other. All combinations of specimen size, crack length, material yield stress, and stress intensity factor which lie below the curve in Figure 3 satisfy the specimen size requirements of this test method.

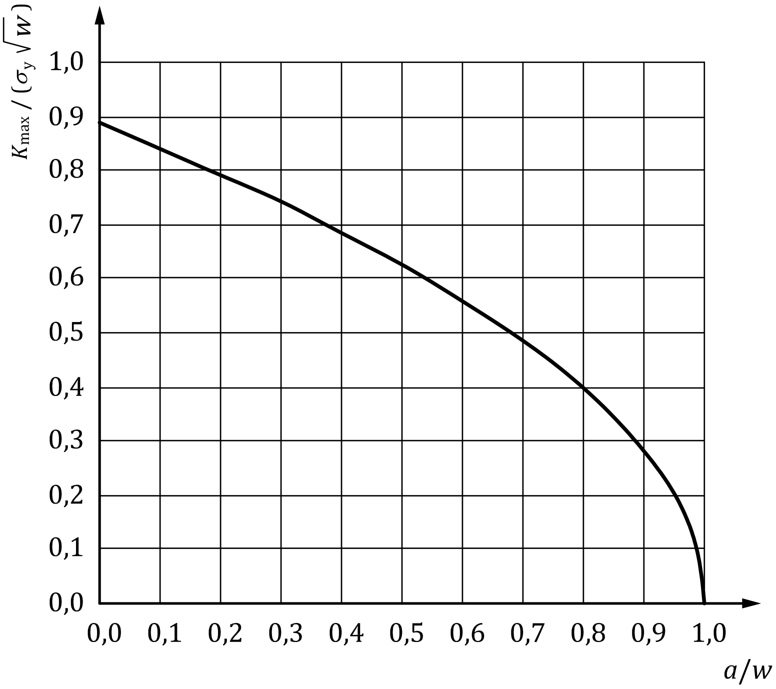


Figure 3 — Size requirements for standard fatigue crack propagation specimens (Values which lie below the curve satisfy the specimen size requirements of this method)

6.2 Preparation

Prepare specimens in accordance with the relevant materials specification and in accordance with ISO 2818. In the case of anisotropic materials, take care to indicate the reference direction on each specimen.

6.3 Notching

Produce a sharp notch or, when feasible, a natural crack, intended as the starting point of the fatigue-induced crack, in the specimen at the locations depicted in Figures 1 and 2, either in a single step or by sharpening the tip of a blunt slot or notch made by machining.

It is required that the initial crack length a_0 in the CT specimen be at least 0,2w so that K-calibration is not influenced by small variations in the location and dimensions of the loading-pin holes. The notch length in CT specimens shall be chosen accordingly (see 7.3 for details of measurement of initial crack length a_0).

The notch in both the CT and SENT specimens shall be within ±0,01w of the specimen centreline.

When sharpening a blunt notch produced by machining, the length of the sharp notch shall be more than four times the blunt notch tip radius. Methods a), b), c), or d) can be used to create a natural crack or a sharp notch:

a) Machine a sharp notch in the specimen and then generate a natural crack by tapping on a new razor blade placed in the notch (it is essential to practice this since, in brittle specimens, a natural crack can be generated by this process but some skill is required in avoiding too long a crack or local damage).

b) If control is difficult or repeatability problems are experienced with method a), it is possible with some brittle specimens to generate a sharp notch by simply pressing the razor blade against the specimen at a temperature close to, but lower than, the glass-transition temperature of the material. With this notching procedure, proper handling of the specimen and correct choice of temperature are essential to avoid deformation of, or damage to, the specimen. Use a new razor blade for each specimen.

c) If a natural crack cannot be generated, as in tough specimens, then sharpen the notch by sliding a razor blade across the notch. Use a new razor blade for each specimen.

d) With tough materials, cooling the specimen and then tapping with a razor blade is sometimes successful.

It may be useful to check the effectiveness of the notching procedure by performing preliminary tests at a constant displacement or constant loading rate on specimens notched using different methods. The best notching method is the one which gives the lowest K-value at crack initiation.

6.4 Side grooves

Specimens may need side grooves to avoid the crack path deviating from the plane of symmetry (see 8.4) and to promote straighter crack fronts. Side grooves may also, in some cases, improve the visibility of the crack tip when using visual methods for crack length measurement.

The side grooves shall be equal in depth, have an included angle of 45° ± 5° and have a root radius of 0,25 mm ± 0,05 mm.

The total reduction in specimen thickness due to side grooving shall not exceed $0{,}2h$.

When using side grooves, the specimen thickness h shall be taken as the distance between the roots of the side grooves.

6.5 Conditioning

After notching, condition specimens as specified in the International Standard for the material tested. In the absence of this information, select the most appropriate conditions from ISO 291, unless otherwise agreed upon by the interested parties.

7 Apparatus

7.1 Test machine

7.1.1 General

The test machine shall be capable of imposing a prescribed load on the specimen (i.e. of operating in the “load control” mode) and of varying the load with time in accordance with a specified waveform. The load distribution shall be symmetrical to the specimen notch. Hydraulically driven test machines with electronic control are generally suitable for this purpose. Mechanically driven machines can also be used but are less versatile as regards the cycle types and frequency range available.

For the case where the load cycle frequency is lower than or equal to 0,1 Hz with load amplitude not greater than 1 000 N, pneumatically driven test machines with electronic load-pressure feedback control could be also suitable.

7.1.2 Load-cycle waveform

The most commonly employed waveform is a sine wave, but other types, e.g. triangular or square waves, may be used when simulating service conditions or investigating the effects of the waveform itself. Two important test variables, namely maximum load $P_{\max}$ and load ratio R, characterize the load-cycle waveform and significantly affect the test results. Load as a function of time shall be controlled with an accuracy of ±1 %, and the maximum and minimum load values shall be constant, during the entire test, to within 1 %.

7.1.3 Load-cycle frequency

The frequency of the load cycle is a test parameter that may be adjusted according to different criteria, such as the simulation of service conditions or the investigation of the effects of the frequency on the test results. High-frequency values (>5 Hz) are likely to induce significant heating: this shall be taken into account when evaluating the test results. The frequency of the load cycle shall be determined, before the test, with an accuracy of 1 %.

7.1.4 Cycle counter

The test machine shall be equipped with a cycle counter displaying the number of load cycles completed at any given time during the test.

In case cycles to crack propagation to failure needs to be determined, a suitable failure-detection system shall be installed to stop the cycle counter on specimen failure.

7.2 Grips

Conventional grips for tensile testing (see ISO 527) are suitable for use with SENT specimens, provided they can accommodate these specimens, which are usually larger than standard tensile specimens.

Compact tensile (CT) specimens are loaded by two loading pins which pass through holes in the specimen (see Figure 2). The pin diameter shall be $0{,}250w \pm 0{,}005w$, where w is the effective specimen width. The pins shall be free to rotate in their holes during the test.

Careful alignment of the gripping fixtures and of the whole loading train shall be ensured to avoid out-of-plane displacements of the specimen.

7.3 Crack length measurement

7.3.1 General

Determination of the length of a razor-sharpened notch may be difficult on the unloaded specimens before testing. The initial crack length a_0 shall therefore be measured after completion of the test, on the newly created fracture surfaces. Different surface textures usually allow a clear distinction to be made between the razor-sharpened notch and the fatigue crack initiated from the notch. Any visual technique may be used for this measurement, provided a resolution of at least 0,1 mm or $0{,}002w$ (whichever represents the better resolution) is obtained.

Use the a_0 value thus obtained to correct the initial fatigue crack length reading recorded at the beginning of the test (see below).

If measurement of the razor-sharpened notch length is not possible on the fracture surfaces, take the first fatigue crack length reading recorded after the beginning of the test, but before any measurable increase in crack length, as the initial crack length a_0.

All fatigue crack length measurements made during the test shall be made with a resolution of at least 0,1 mm or $0{,}002w$, whichever represents the better resolution. Take crack length readings at fixed crack length increments Δa. The minimum increment $\Delta a_{\min}$ shall be greater than 0,5 mm or five times the crack length measurement resolution, whichever is greater. Make at least 20 crack length measurements between the initial crack length a_0 and the final crack length at the end of the test a_f so that the maximum increment value $\Delta a_{\max}$ will be $\leq (a_f - a_0)/20$. If the above requirements cannot be satisfied (i.e. if $\Delta a_{\max} < \Delta a_{\min}$), the specimen dimensions are not suitable for this test and larger specimens will have to be employed.

At each crack length increment, also record the number of cycles *N* completed since the beginning of test.

Make all crack length measurements without interrupting the test, using one or more of the techniques specified in 7.3.2 to 7.3.5.

7.3.2 Travelling microscope

A low-power (approximately ×15 to ×30) travelling microscope can be used for crack length measurements. Record each crack length and the corresponding reading of the number of cycles completed in accordance with 7.3.1.

It is recommended that, prior to testing, reference marks be made on the specimen surface at precisely determined locations in the direction of cracking. Using such reference marks eliminates potential errors due to accidental movement of the travelling microscope.

If the specimen surface is marked, along the expected crack path, with a grid or scale complying with the resolution requirements given in 7.3.1, the crack length can then be determined directly with any magnifying device of suitable power.

Marks made on the specimen surface shall not affect crack initiation or propagation.

7.3.3 Video recording

The crack length can be monitored automatically during the test by means of a video camera equipped with a low-magnification (approximately × 15 to × 30) lens and connected to a video recorder.

The video recorder shall be synchronized with the cycle counter of the test machine (7.1.4) in order that the number of completed load cycles corresponding to each recorded image can be determined.

When using the video recording technique, accurate calibration of the scale used to read the crack length off the recorded video images shall be carried out before the test in order to ensure that the resolution requirements of 7.3.1 are fulfilled.

Alternatively, the specimen surface may be marked, along the expected crack path, with a grid or scale complying with the resolution requirements given in 7.3.1, allowing the crack length to be read directly from the recorded video images.

Marks made on the specimen surface shall not affect crack initiation or propagation.

7.3.4 Specimen compliance

When using the CT specimen, crack length can be measured by monitoring the specimen compliance.

Specimen compliance is defined as the slope of the linear plot of displacement *V* versus the load *P* applied during a load cycle. This can be determined simply by monitoring the peak value of the displacement, on account of the fact that the peak load is constant during the test. Such a procedure may, however, lead to an incorrect value of the specimen compliance due to nonlinearities in the load-displacement curve. A more accurate value is obtained by recording the load and displacement signals within a single loading cycle in sufficient detail to recognize possible nonlinear portions of the curve and to exclude them from a linear fit. If this procedure is used, it is recommended that either the loading or the unloading portion of the load cycle be consistently used for calculations throughout the test.

After measuring V and P, the normalized compliance C_N is obtained from with Formula (2):

$$C_N = \frac{h \times E \times V}{P} \tag{2}$$

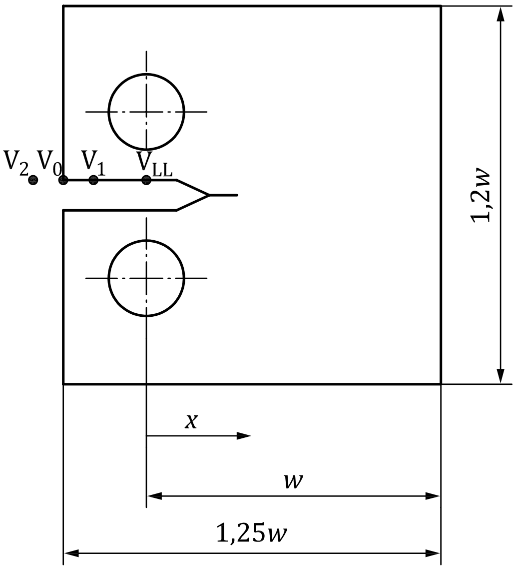
where

h is the specimen thickness;

E is the modulus of elasticity measured in accordance with the relevant part of ISO 527.

The modulus of elasticity of plastic specimens can be affected by processing-induced anisotropy. It is therefore recommended that tensile specimens for modulus determination be as similar as possible, with respect to the processing conditions and specimen orientation, to the fatigue specimens. Usually, fatigue specimens are machined out of sheets or flat moulded parts: tensile specimens can then be machined from the same piece, taking care that the orientation is the same (the longitudinal axis of the tensile specimen has to be parallel to the line joining the two loading-pin holes in the CT specimen).

Four different locations shall be used to measure the displacement in the CT specimen. These are defined in Figure 4.



Key

x	distance from load line (measured away from front face of specimen)	
V_{LL}	load-line compliance	$x/w = 0$
V_1	compliance at location 1	$x/w = -0{,}157\,6$
V_0	compliance at front face of specimen	$x/w = -0{,}25$
V_2	compliance at location 2	$x/w = -0{,}345$

Figure 4 — Locations for measurement of compliance of CT specimens

Selection of displacement-measurement gauges, attachment points, and methods of attachment are dependent on the test conditions and on the material to be tested. The gauges used shall have a linear response over the range of displacements to be measured and shall have adequate resolution and a sufficiently short response time. It shall be possible for the attachment points to be accurately and repeatedly placed on the specimen, and they shall not be liable to wear during the fatigue cycling.

A polynomial expression describing the normalized crack length a/w as a function of the normalized compliance of the CT specimen, measured at the locations defined in Figure 4, has been established for metallic materials and has been proved to be valid for polymeric materials as well:

$$a/w = C_0 + C_1 U_x + C_2 (U_x)^2 + C_3 (U_x)^3 + C_4 (U_x)^4 + C_5 (U_x)^5 \tag{3}$$

where

$$U_x = \frac{1}{\left(\frac{h \times E \times V_x}{P}\right)^{1/2} + 1} \tag{4}$$

the coefficients C_0, C_1, ..., C_5 take the values given in Table 1 at the four measurement locations.

Table 1

Measurement location	C_0	C_1	C_2	C_3	C_4	C_5
V_2	1,001 2	−4,916 5	23,057	−323,91	1 798,3	−3 513,2
V_0	1,001 0	−4,669 5	18,460	−236,82	1 214,9	−2 143,6
V_1	1,000 8	−4,447 3	15,400	−180,55	870,92	−1 411,3
V_{LL}	1,000 2	−4,063 2	11,242	−106,04	464,33	−650,68

The number of compliance measurements performed during the test and their spacing in time shall ensure that the crack length measurement requirements given in 7.3.1 are satisfied. The compliance method of crack length measurement lends itself to automatic data acquisition, and a large number of readings is commonly obtained.

At least two visual crack length readings shall be taken, at crack-tip positions at least 0,2*w* apart, during the test. Correct these visual readings for curvature, using the procedure outlined in 9.2, to obtain the actual crack lengths. Use any difference between the actual and compliance crack lengths to adjust all the compliance crack lengths. This is accomplished by calculating an effective modulus of elasticity E^* and using this in Formula (4) to correct all the crack length calculations. If the effective modulus E^* differs from the modulus of elasticity E by more than 20 %, then the test equipment is improperly set up and data generated by this method are invalid.

At present, the specimen compliance method is not recommended for use with SENT specimens.

7.3.5 Crack gauges

Crack gauges for crack growth measurement are commercially available and commonly used in fatigue testing. They generally consist of thin, electrically conductive foils which are bonded to the specimen surface over the expected crack path and which are progressively split into two parts as the crack propagates. The electrical resistivity measured across the crack path changes from a minimum value corresponding to the uncracked foil to increasingly greater values as the crack grows. The electrical resistance can thus be used as an indirect measure of the crack length.

The adhesive used to bond the crack gauge to the specimen surface shall ensure that the length of the crack in the crack gauge is exactly equal to the length of the crack in the specimen surface. The adhesive shall not affect the fatigue response of the specimen.

Calibration of crack gauges shall be performed by taking at least two visual crack length readings at crack-tip positions at least 0,2*w* apart.

7.4 Test atmosphere

Conduct the test in the same atmosphere as used for conditioning, unless otherwise agreed upon by the interested parties, e.g. for testing at elevated or low temperatures. As the test duration may be long, particular attention shall be given to the constancy of the various parameters characterizing the test atmosphere (temperature, humidity, etc.).

8 Test procedure

8.1 Measurement of specimen dimensions

Before the test, measure the specimen thickness h and width w to the nearest 0,05 mm. The specimen dimensions shall be within the tolerances given in Figures 1 and 2. If the notch edges deviate from the plane of symmetry of the notch by more than the limits given in 8.4 for crack propagation, the specimen is not suitable for testing.

8.2 Specimen mounting

In the case of CT specimens, insert loading pins into the holes in the specimen, checking that the load line is parallel to the longitudinal edges of the specimen (the vertical edges in Figure 2) and that the pins are free to rotate in the holes.

Mount SENT specimens so that the distances between the plane of symmetry of the notch and the upper and lower grips are equal to within $\pm 0{,}02w$. The gauge length L_0 (i.e. the free distance between the grips) shall be greater than $2w$.

8.3 Loading

Loading the specimen has to be performed in a relatively short time (i.e. short with respect to the duration of the test) to avoid creep effects before cyclic loading. A loading time shorter than 1 min is usually feasible and adequate. During this stage, keep the applied load lower than the maximum load to be used during the test to avoid retardation effects on crack propagation.

8.4 Out-of-plane crack propagation

If at any point in the test the crack deviates by more than ±20° from the plane of symmetry over a distance of $0{,}1w$ or greater, data generated by this method are invalid.

8.5 Discontinuous crack propagation

When irregularities in crack propagation are observed, take crack length readings so as to describe the irregularities as accurately as possible. Polymeric materials subjected to fatigue frequently exhibit discontinuous crack propagation: the crack is observed occasionally to stop and then propagation resumes, sometimes with a sudden acceleration, after several cycles. In that case, take readings as close as possible to crack arrest and re-start, in order that the discontinuity will be clearly apparent in a plot of crack length a versus number of cycles N.

8.6 Number of tests

It is good practice to conduct replicate tests. Multiple tests can be planned such that regions of overlapping $\mathrm{d}a/\mathrm{d}N$ versus ΔK or ΔG are obtained.

9 Calculation and interpretation of results

9.1 Crack length versus number of cycles

Add the recorded crack length increments to the initial crack length a_0 to provide the crack length values and plot them against the corresponding values of the number of cycles N. In the case of discontinuous crack propagation, take crack length readings in accordance with 8.5.

9.2 Crack curvature correction

Through-thickness curvature of the crack front may occur during crack propagation. Crack measurements carried out by the methods described in 7.3.2, 7.3.3, and 7.3.5 are taken on the specimen surface, and a correction may be needed to account for crack curvature. When using the specimen compliance method for crack length measurement (see 7.3.4), correction for crack curvature is incorporated in the calibration technique (the visual readings used for calibration, however, are taken on the specimen surface and may need to be corrected for crack curvature).

On completion of testing, examine the fracture surfaces, preferably at two locations, to determine the extent of through-thickness crack curvature. If a crack contour is visible, calculate the average through-thickness crack length as the average of the measurements obtained at the surfaces and at the centre of the specimen. Then calculate the difference δ between the average through-thickness crack length and the corresponding crack length measured during the test. Crack curvature correction is performed by adding δ to the crack length values measured during the test.

If the crack curvature correction results in a greater than 5 % difference in the calculated stress intensity factor at any crack length, then employ this correction when analysing the recorded test data. If the magnitude of the crack curvature correction either increases or decreases with crack length, use a linear interpolation to correct intermediate data points.

9.3 Crack growth rate da/dN

The rate of fatigue crack growth is determined from the data for crack length versus number of cycles completed (see 9.1) by numerical differentiation. A simple secant procedure, based on the calculation of the slope of the straight line connecting two adjacent data points, is generally adequate. According to this procedure, the crack growth rate at any average crack length $\bar{a}$, where $\bar{a} = (a_i + a_{i+1})/2$, is given by

$$\left(\frac{\mathrm{d}a}{\mathrm{d}N}\right)_{\bar{a}} = \frac{(a_{i+1} - a_i)}{(N_{i+1} - N_i)} \tag{5}$$

The value of $\bar{a}$, which is the average crack length within the $a_{i+1} - a_i$ increment, is used to calculate ΔK by means of Formula (6) or (7) (see 9.4).

If discontinuous crack propagation is observed, the crack growth rate shall only be calculated within the continuous regions of the $a(N)$ curve.

9.4 Stress intensity factor range ΔK

Use the average crack length values $\bar{a}$ obtained in 9.3 to calculate the corresponding stress intensity factor range values as follows:

For the CT specimen, ΔK is given by

$$\Delta K = \frac{\Delta P}{h\sqrt{w}} \times \frac{(2+\alpha)}{(1-\alpha)^{3/2}} \times (0{,}886 + 4{,}64\alpha - 13{,}32\alpha^2 + 14{,}72\alpha^3 - 5{,}6\alpha^4) \tag{6}$$

where $\alpha = a/w$.

The expression is valid for $a/w \geq 0{,}2$.

For the SENT specimen, ΔK is given by

$$\Delta K = \frac{\Delta P}{h\sqrt{w}} \times \frac{5\sqrt{\pi\alpha}}{(20-13\alpha-7\alpha^2)^{1/2}} \tag{7}$$

where $\alpha = a/w$.

9.5 Energy release rate range ΔG

The energy release rate range ΔG is calculated from the stress intensity factor range ΔK by means of the following formula:

$$\Delta G = \frac{(\Delta K)^2}{E} \times \frac{1+R}{1-R} \tag{8}$$

where E is the tensile modulus of elasticity measured in accordance with ISO 527. On account of the experimental uncertainities involved in the determination of ΔK, R, and E, the difference between plane stress and plane strain conditions given in definition 3.12 is neglected for the purposes of this particular calculation.

10 Test report

10.1 General

The test report shall include the following information.

10.2 For fatigue crack propagation test

a) a reference to this International Standard, i.e. ISO 15850;

b) the specimen type and dimensions, including thickness h and width w and, for SENT specimens, the gauge length L_0;

c) the yield stress value used to determine specimen size in 6.1.3;

d) the method used to create the notch, and the value of the initial crack length a_0;

e) a description of the test machine and of the grips and fixtures used;

f) a description of the method used to measure the crack length, including the measurement accuracy;

g) the specimen-loading variables, including ΔP, R, frequency of load cycle, and cycle waveform;

h) the maximum and minimum temperature and humidity during the test;

i) whether or not crack curvature occurred and, if it did, the procedure used to correct for it and the magnitude of the correction;

j) whether discontinuous crack propagation occurred;

k) a plot of a versus N;

l) a plot of $\log(\mathrm{d}a/\mathrm{d}N)$ versus $\log(\Delta K)$;

m) a plot of $\log(\mathrm{d}a/\mathrm{d}N)$ versus $\log(\Delta G)$;

n) a table of the test results, including a, N, ΔK, ΔG, and $\mathrm{d}a/\mathrm{d}N$;

o) the date of the test.

10.3 For fatigue crack propagation to failure test

a) If crack propagation need not be monitored, then f), i), j), k), l), m), and n) are not required.

b) If FNT or CRB specimen is used, provide details of the specimens including the stress intensity factor calculation.

c) A plot of log N_f (or log failure time) versus log(ΔK_0). N_f and ΔK_0 are total cycles to failure and stress intensity factor range corresponding to the initial crack length, respectively.

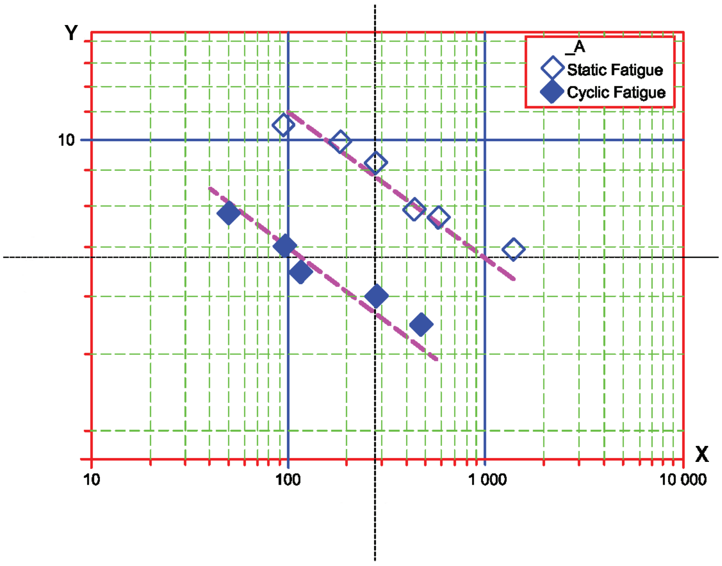
d) A table of the test results, including a_0, N_f, and ΔK_0.

Annex A
(informative)

Abnormality in the use of cyclic fatigue crack propagation test for ranking long-term static fatigue behaviour

In the area of polymer evaluation, the method of dynamic fatigue crack propagation is often used due to the accelerated nature of the test in comparison to crack propagation under static fatigue loading (Figure A.1). This in particular is gaining prominence as new materials having high resistance to crack propagation are being continually developed, where long-term evaluation is essential in designing plastics parts for load-bearing structures. Although the value of dynamic fatigue crack propagation test in greatly shortening the experimental times is generally recognized and being more widely accepted for testing materials, in recent times it was demonstrated that in some cases[7][8], the result between those obtained from dynamic and static fatigue crack propagation tests exhibited completely opposite behaviour in terms of crack propagation resistance (Figures A.2a and A.2b). This in particular is problematic when material lifetime under static loading is being ranked by using dynamic fatigue crack propagation, since prior understanding of such reversal in results is not often available. In addition, the accelerating nature of the dynamic fatigue test in some cases makes ranking difficult as much acceleration can cause materials to appear as if small or no difference exists between crack propagation failure times, although substantial under static fatigue.

The abnormality indicated has been speculated to arise in part from the difference in the response to strain rates, hence the strain rate sensitivity of materials. Figure A.3 illustrates dynamic fatigue crack propagation failure results under different cyclic stress profile, where the square profile is shown to be more effective in causing higher rates of fatigue crack propagation as compared to the sine profile, indicating the strain rate effect. Difference in the materials response to notch sensitivity, as well as load cycling effect, may be also be a factor. Hence, in order to be sure that the predictive results obtained with cyclic fatigue corresponds to the behaviour under static fatigue, one needs to perform additional tests and analysis to understand where their results stand, as appropriate.

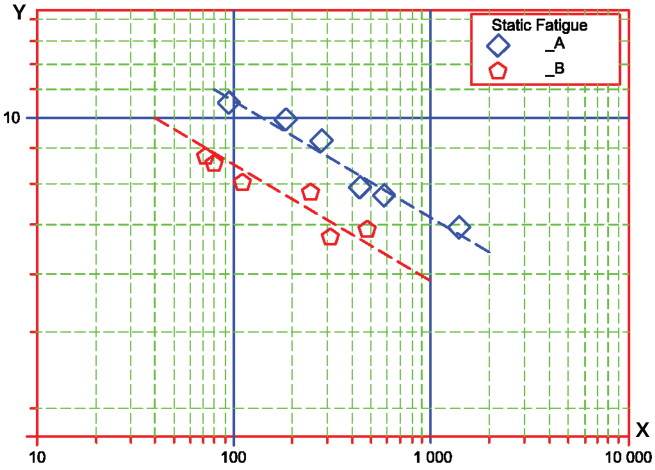


Key

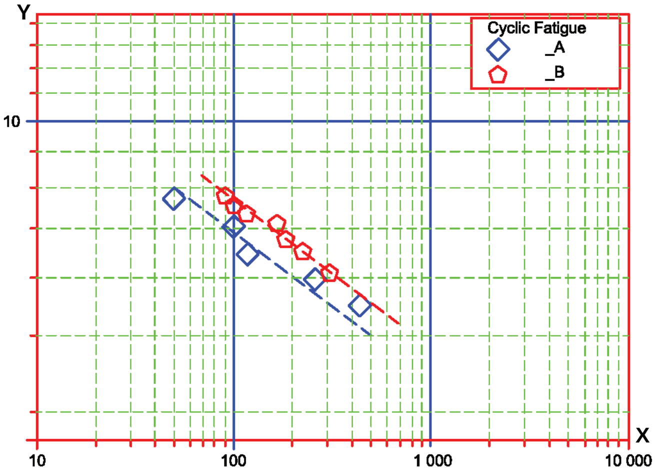
X time to failure (h)

Y stress (MPa)

Figure A.1 — A typical example illustrating the dynamic fatigue versus static fatigue loading in a same material



a) Static fatigue



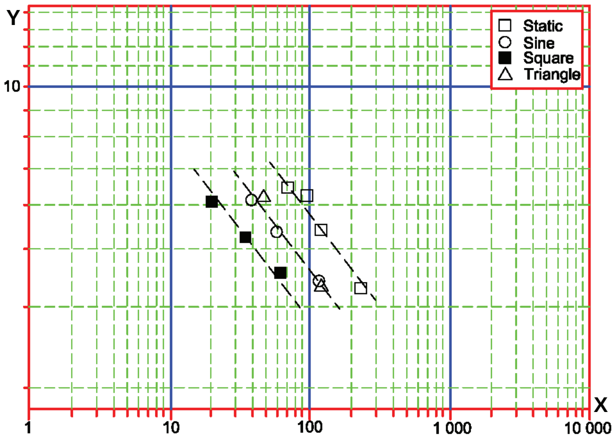
b) Cyclic fatigue

Key

X time to failure (h)

Y stress (MPa)

Figure A.2 — A typical example illustrating the dynamic fatigue versus static fatigue loading in two different materials where reversal in results is apparent



Key

X time to failure (h)

Y stress (MPa)

Figure A.3 — Effect of loading profile on the time to failure of static and cyclic fatigue specimens

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