INTERNATIONAL STANDARD

ISO 13586

First edition
2000-03-01

Plastics — Determination of fracture toughness (G_{IC} and K_{IC}) — Linear elastic fracture mechanics (LEFM) approach

Plastiques — Détermination de la tenacité à la rupture (G_{IC} et K_{IC}) — Application de la mécanique linéaire élastique de la rupture (LEFM)

Reference number
ISO 13586:2000(E)

ISO copyright office
Case postale 56 • CH-1211 Geneva 20
Tel. + 41 22 749 01 11
Fax + 41 22 734 10 79
E-mail copyright@iso.ch
Web www.iso.ch

Printed in Switzerland

Contents

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.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 3.

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.

Attention is drawn to the possibility that some of the elements of this International Standard may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

International Standard ISO 13586 was prepared by Technical Committee ISO/TC 61, *Plastics*, Subcommittee SC 2, *Mechanical properties*.

Annex A forms a normative part of this of ISO 13586.

Plastics — Determination of fracture toughness (G_{IC} et K_{IC}) — Linear elastic fracture mechanics (LEFM) approach

1 Scope

This International Standard specifies the principles for determining the fracture toughness of plastics in the crack-opening mode (mode I) under defined conditions. Two test methods with cracked specimens are defined, namely three-point-bending tests and compact-specimen tensile tests in order to suit different types of equipment available or different types of material.

The methods are suitable for use with the following range of materials:

— rigid and semi-rigid thermoplastic moulding, extrusion and casting materials;

— rigid and semi-rigid thermosetting moulding and casting materials.

Certain restrictions on the linearity of the load-displacement diagram, on the specimen width and on the thickness are imposed to ensure validity (see 6.4) since the scheme used assumes linear elastic behaviour of the cracked material and a state of plane strain at the crack tip. Finally, the crack must be sharp enough so that an even sharper crack will not result in significantly lower values of the measured properties.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this International Standard. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of ISO and IEC maintain registers of currently valid International Standards.

ISO 291:1997, *Plastics — Standard atmospheres for conditioning and testing*.

ISO 527-1:1993, *Plastics — Determination of tensile properties — Part 1: General principles*.

ISO 604:1993, *Plastics — Determination of compressive properties*.

ISO 2818:1994, *Plastics — Preparation of test specimens by machining*.

ISO 5893:1993, *Rubber and plastics test equipment — Tensile, flexural and compression types (constant rate of traverse) — Description*.

3 Terms and definitions

For the purposes of this International Standard, the following terms and definitions apply:

3.1
energy release rate
G
the change in the external work δU_{ext} and strain energy δU_S of a deformed body due to enlargement of the cracked area δA

$$G = \frac{\delta U_{ext}}{\delta A} - \frac{\delta U_S}{\delta A} \quad (1)$$

It is expressed in joules per square metre, J/m^2.

3.2
critical energy release rate
G_{IC}
the value of the energy release rate G in a precracked specimen under plane-strain loading conditions, when the crack starts to grow

It is expressed in joules per square metre, J/m^2.

3.3
stress intensity factor
K
the limiting value of the product of the stress $\sigma(r)$ perpendicular to the crack area at a distance r from the crack tip and of the square root of $2\pi r$, for small values of r

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

It is expressed in Pa·√m.

The term factor is used here because it is common usage, even though the value has dimensions.

3.4
critical stress intensity factor
K_{IC}
the value of the stress intensity factor when the crack under load actually starts to enlarge under a plane-strain loading condition around the crack tip

It is expressed in Pa·√m.

The critical stress intensity factor K_{IC} of a material is related to its critical energy release rate G_{IC} by the equation

$$G_{IC} = K_{IC}^2 / E \quad (3)$$

where E is the modulus of elasticity, determined under similar conditions of loading time (up to crack initiation) and temperature.

In the case of plane-strain conditions:

$$E = \frac{E_t}{1 - \mu^2} \quad (4)$$

where

E_t is the tensile modulus (see ISO 527-1);

μ is Poisson's ratio (see ISO 527-1-).

3.5
displacement
s_a
the displacement of the loading device, corrected as specified in 5.4

It is expressed in metres, m.

3.6
stiffness
S
the initial slope of the force-displacement diagram

$$S = \left(\frac{\mathrm{d}F}{\mathrm{d}s} \right)_{s \to 0}$$

It is expressed in newtons per metre, N/m.

3.7
force
F_Q
the applied load at the initiation of crack growth

It is expressed in newtons, N.

See also subclause 6.1.

3.8
energy
W_B
the input energy when crack growth initiates

It is expressed in joules, J.

W_B is based upon the corrected load-displacement curve.

3.9
crack length
a
the crack length up to the tip of the initial crack prepared as specified in 4.3.

It is expressed in metres, m.

For three-point-bending test specimens, the crack length is measured from the notched face. For compact tensile-test specimens, the crack length is measured from the load line, i.e. from the centres of the holes for the loading pins (see Figures 1 and 3).

The crack length a is normalized by the width w of the test specimen ($\alpha = a/w$).

3.10
energy calibration factor
ϕ

$$\phi(a/w) = -S\left(\frac{\mathrm{d}S}{\mathrm{d}\alpha}\right)^{-1} \quad (5)$$

where

S is the stiffness of the specimen;

$\alpha\,(= a/w)$ is the normalized crack length (see 3.9).

Values of $\phi\,(a/w)$ are given in annex A for both types of specimen.

3.11
geometry calibration factor
f

Values of $f\,(a/w)$ are given in annex A for both types of specimen.

3.12
characteristic length
$\bar{r}$
the size of the plastic deformation zone around the crack tip

It is required for checking fulfilment of the size criteria (see 6.4).

4 Test specimens

4.1 Shape and size

Test specimens for three-point-bending tests (also called single-edge-notch bending, SENB) and for compact tensile (CT) tests shall be prepared in accordance with Figures 1 and 3, respectively. It is usually convenient to make the thickness h of the test specimens equal to the thickness of a sheet sample and to make the test specimen width w equal to $2h$. The crack length a should preferably be in the range given by $0{,}45 \leqslant a/w \leqslant 0{,}55$.

4.2 Preparation

Test specimens shall be prepared in accordance with the relevant material International Standard for the material under test and with ISO 2818. In the case of anisotropic specimens, take care to indicate the reference direction on each test specimen.

4.3 Notching

Method a), b) or c) can be used for notching:

a) Machine a sharp notch into the test 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 test specimens, a natural crack can be generated by this process, but some skill is required in avoiding too long a crack or local damage). The length of the crack thus created shall be more than four times the original notch tip radius.

b) If a natural crack cannot be generated, as in tough test specimens, then sharpen the notch by sliding a razor blade across the notch. Use a new razor blade for each test specimen. The length of the crack thus created shall be more than four times the original notch tip radius.

c) Cooling tough test specimens and then performing razor tapping is sometimes successful.

Pressing the blade into the notch is not recommended because of induced residual stresses.

4.4 Conditioning

Condition test specimens as specified in the International Standard for the material under test. In the absence of this information, select the most appropriate set of conditions from ISO 291, unless otherwise agreed upon by the interested parties.

5 Testing

5.1 Test machine

The machine shall satisfy the requirements of ISO 5893. The load indicator shall show the total load carried by the test specimen. This device shall be essentially free from inertia lag at the test speeds used. It shall indicate the load with an accuracy of at least 1 % of the actual value.

5.2 Displacement transducer

The displacement is recorded during the test. The transducer shall be essentially free from inertia lag at the test speeds used. It shall measure the displacement with an accuracy of 2 % of the relevant length or better. The effects of the transducer on the load measurements shall either be negligible (that is < 1 %) or they shall be corrected.

5.3 Loading rigs

A rig with moving rollers is used for three-point-bending (SENB) tests, as shown in Figure 2. Indentation into the test specimen is minimized by the use of rollers with a large diameter (> w/2). The measurement of the displacement shall be taken at the centre of the span L (see Figure 2).

For the compact tensile test, the test specimen is loaded by means of two pins in holes in the specimen. The displacement of the load points during the test is measured, for example by a clip gauge near the pins (see 5.2).

5.4 Displacement correction

The measured displacement s_a shall be corrected for the indentation of the loading pins, compression of the test specimen and the machine compliance in order to determine properly the stiffness S of the specimen and the work W_B at crack growth initiation. The calibration of the test system shall be performed as follows:

The load-displacement correction curve (see Figure 4) is generated by analogy with the fracture test but by using unnotched test specimens, as indicated in the Figures 5 and 6. The rollers of the three-point-bending rig are moved together to reduce even further the small flexing of the unnotched test specimen under load. The displacement correction shall be performed for each material and at each different temperature and test speed since polymers are generally sensitive to temperature and test speed. The degree of loading-pin penetration and specimen compression can vary with changes in these variables. The indentation tests shall be performed such that the loading times are the same as in the fracture tests. This will involve lower test speeds to reach the same load in the same time, for example about half the speed.

In practice, a linear correction curve is usually obtained up to loads even exceeding the fracture load of cracked test specimens (see Figure 4). Any initial non-linearity due to penetration of the loading pins into the specimen is observed during both the calibration test and the actual fracture test. Therefore, the initial non-linearity is effectively corrected for by the following proposed method:

At corresponding load, the displacement s_j taken from the correction curve is subtracted from the displacement s_a in the actual fracture test with a notched test specimen. In this way, the corrected load-displacement curve is constructed. The stiffness S and the work W_B at crack growth initiation are derived from this curve (see Figure 7). The corrections s_j of the displacements usually amount to less than 20 % of the measured displacement s_a.

5.5 Test atmosphere

Conduct the test in the same atmosphere as used for conditioning, unless otherwise agreed upon by the interested parties, for example for testing at elevated or low temperatures.

5.6 Thickness, width and crack length of test specimens

Measure the thickness h and width w of each test specimen to the nearest 0,02 mm. Record an approximate reading of the crack length a which will be corrected on completion of the test. Usually crack tip lines are visible on the two fracture surfaces. Calculate the mean value of five readings of the crack length taken along the original crack front. These shall be taken at the edges, the centre and half way between. The crack length shall differ by no more than 10 % over the entire crack front. If differences larger than 10 % are found, reject the test. Care shall be taken that it is the original crack tip which is being observed since slow growth can occur.

5.7 Test conditions

It is recommended that 23 °C and a test speed of 10 mm/min be used as the basic test conditions. In all cases, the loading time and the test temperature shall be measured. Speeds greater than 0,1 m/s and loading times less than 10 ms should preferably be avoided since dynamic effects may cause errors.

Carry out at least three tests for each set of conditions. If it is not possible to obtain valid results at 23 °C (see 6.4), it is often possible to do so by decreasing the temperature. Usually, a reduction in the test temperature does not change K_{IC} greatly but increases the yield stress of the polymer, rendering the fractures more brittle. If this procedure is used, both temperature and loading time shall be stated in the test report.

6 Expression of results

6.1 Determination of F_Q

In an ideal material, the load-displacement curve is a linear one with an abrupt drop in the load at the instant of crack growth initiation. In such rather rare cases, F_Q can be identified with the maximum load.

In most cases, there is some non-linearity in the curve and this can be due to plastic deformation at the crack tip, non-linear elasticity, general visco-elasticity or stable crack growth after initiation but prior to instability. The first three effects violate the LEFM assumption and the fourth one means that the true initiation load is not defined by the maximum. In order to circumvent a doubtful definition of initiation, an arbitrary rule is used here. The zero-point tangent is drawn to the curve in Figure 7 to determine the initial stiffness S. This stiffness is reduced by 5 % and a further line is drawn accordingly. If the maximum of the load-displacement curve falls within these two lines, then F_{max} shall be called F_Q (the load at crack growth initiation). If the second line intersects the load curve at F_5 prior to the maximum, then F_5 shall be called F_Q. Referring to Figure 7, the conditions of LEFM are assumed to be met if

$$\frac{F_{max}}{F_5} < 1{,}1$$

If this condition of 10 % non-linearity is violated, the test shall be rejected.

6.2 Provisional result G_Q

Calculate the critical energy release rate from the energy W_B up to the instant of crack growth initiation, where the load is F_Q and the original crack length is a:

$$G_Q = \frac{W_B}{h \times w \times \phi(a/w)} \tag{6}$$

where

W_B is the energy to break;

h is the test specimen thickness;

w is the test specimen width;

$\phi(a/w)$ is the energy calibration factor, depending on the crack length a.

Calculate ϕ as shown in annex A. Tables with values of $\phi(a/w)$ for both types of test specimen are also given in annex A.

6.3 Provisional result K_Q

Calculate the critical stress intensity factor K_Q from the load F_Q at crack growth initiation and the original crack length a:

$$K_Q = f(a/w)\frac{F_Q}{h\sqrt{w}} \tag{7}$$

where

F_Q is the load at crack growth initiation;

h is the test specimen thickness;

w is the test specimen width;

$f(a/w)$ is the geometry calibration factor, depending on the crack length a.

Calculate f as shown in annex A. Tables with values of $f(a/w)$ for both types of test specimen are also given in annex A.

6.4 Size criteria and validation of results

The test is valid only if the dimensions of the test specimen are significantly larger than the plastic zone around the crack tip, characterized by the length $\bar{r}$. Appropriate test specimens for plane-strain fracture tests shall meet the following size criteria:

thickness h $> 2{,}5 \times \bar{r}$

crack length a $> 2{,}5 \times \bar{r}$

ligament width $(w - a)$ $> 2{,}5 \times \bar{r}$

With the specimen dimensions proposed in this International Standard, all the criteria are usually satisfied simultaneously. The criteria cover two limitations in that h must be sufficient to ensure plane strain but $(w - a)$ has to be sufficient to avoid excessive plasticity in the ligament. If $(w - a)$ is too small, the test will usually violate the