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**Plastics — Determination of fracture  
toughness of films and thin sheets  
— Essential work of fracture (EWF)  
method**

*Plastiques — Détermination de la ténacité à la rupture des films et  
feuilles minces — Méthode du travail essentiel de rupture (EWF)*

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# Contents

Page

|                                                                |           |
|----------------------------------------------------------------|-----------|
| Foreword.....                                                  | iv        |
| Introduction.....                                              | v         |
| <b>1 Scope.....</b>                                            | <b>1</b>  |
| <b>2 Normative references.....</b>                             | <b>1</b>  |
| <b>3 Terms, definitions and symbols.....</b>                   | <b>1</b>  |
| 3.1 Terms and definitions.....                                 | 1         |
| 3.2 Symbols.....                                               | 3         |
| <b>4 Principle.....</b>                                        | <b>3</b>  |
| <b>5 Apparatus.....</b>                                        | <b>4</b>  |
| <b>6 Test specimens.....</b>                                   | <b>6</b>  |
| 6.1 Specimen geometry.....                                     | 6         |
| 6.2 Preparation of test specimens.....                         | 6         |
| 6.2.1 General.....                                             | 6         |
| 6.2.2 Width and length.....                                    | 7         |
| 6.2.3 Ligament length.....                                     | 7         |
| 6.2.4 Number of specimens.....                                 | 7         |
| 6.2.5 Specimen notching.....                                   | 7         |
| 6.2.6 Conditioning.....                                        | 8         |
| <b>7 Procedure for the determination of EWF.....</b>           | <b>8</b>  |
| 7.1 Testing speed.....                                         | 8         |
| 7.2 Force-displacement curves.....                             | 8         |
| 7.3 Calculation of the overall fracture energy $W_f$ .....     | 8         |
| 7.4 Stress criterion.....                                      | 9         |
| 7.5 Linear regression.....                                     | 9         |
| 7.6 Outlying data criterion.....                               | 10        |
| 7.7 Results table.....                                         | 11        |
| <b>8 Precision.....</b>                                        | <b>11</b> |
| <b>9 Test report.....</b>                                      | <b>12</b> |
| <b>Annex A (informative) Example.....</b>                      | <b>13</b> |
| <b>Annex B (informative) Interlaboratory test results.....</b> | <b>18</b> |
| <b>Bibliography.....</b>                                       | <b>21</b> |

## 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.

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](http://www.iso.org/directives)).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see [www.iso.org/patents](http://www.iso.org/patents)).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see [www.iso.org/iso/foreword.html](http://www.iso.org/iso/foreword.html).

This document was prepared by Technical Committee ISO/TC 61, *Plastics*, Subcommittee SC 2, *Mechanical behavior*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at [www.iso.org/members.html](http://www.iso.org/members.html).

## Introduction

Fracture occurs under plane stress displaying gross ductility in many practical applications of polymeric materials in which they are used as thin sheets or films (e.g. packaging and coatings). It is inappropriate to adopt thicker test specimens, which are generally used in fracture tests, to measure the fracture toughness in such cases. Thicker test specimens suppress crack tip ductility and bring about a change in stress state which does not occur in practice. The essential work of fracture (EWF) method, described in this document, provides toughness measurement under plane stress. The method which is relatively simple is based on a suggestion by Broberg<sup>[1]</sup>, further developed first by Cotterell, Reddel and Mai for metals<sup>[2],[3]</sup> and then by a series of workers<sup>[4]-[9]</sup> for ductile polymers. More recent reviews on this method are given in References [\[10\]](#), [\[11\]](#), [\[12\]](#).

The method assumes that the overall energy associated with fracture can be partitioned into two components: the essential work necessary to create new surfaces in the so-called fracture process zone, and the non-essential work dissipated for the plastic deformation in the surrounding volume, the process zone.

The essential work of fracture has been shown to be a material property, i.e. independent of the specimen geometry, for a given sheet thickness<sup>[13],[14]</sup>, when the condition of full yielding of the specimen ligament before the onset of crack propagation is fulfilled. In this case, the essential work of fracture is a parameter that gives an intrinsic material property dependent only on thickness and therefore useful in product design. However, the condition of full yielding of the ligament is usually difficult to verify without specific instrumentation, not commonly available in every laboratory.

Even if this condition is not fulfilled, the EWF test method can still be applied to determine the essential work and non-essential work of the fracture energy, which are repeatable and reproducible parameters useful in the development of new materials, in quality control and interlaboratory comparisons.

This document describes the EWF method independently of the verification of the full ligament yielding condition.

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# Plastics — Determination of fracture toughness of films and thin sheets — Essential work of fracture (EWF) method

## 1 Scope

**1.1** This document specifies the principles and the method for determining the fracture toughness of polymeric films and thin sheets in the crack opening mode (mode I) under plane stress conditions. The essential work of fracture (EWF) method is based on the use of double edge notched tensile (DENT) specimens.

**1.2** The method is suitable for use with films or thin sheets, of thickness not greater than 1 mm, made of ductile polymeric materials, in which fracture propagation is stable (crack growth is always driven by the external applied force). If, at any time during the test, brittle fracture occurs, with fast crack propagation driven by the elastic energy stored in the specimen, the sample is not suitable for the application of the present test method.

## 2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

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

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

ISO 4593, *Plastics — Film and sheeting — Determination of thickness by mechanical scanning*

ISO 7500-1, *Metallic materials — Calibration and verification of static uniaxial testing machines — Part 1: Tension/compression testing machines — Calibration and verification of the force-measuring system*

ISO 9513, *Metallic materials — Calibration of extensometer systems used in uniaxial testing*

ISO 16012, *Plastics — Determination of linear dimensions of test specimens*

## 3 Terms, definitions and symbols

### 3.1 Terms and definitions

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

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org/>

### 3.1.1

#### initial distance between the grips

$L_g$

distance between the grips before the beginning of the test

Note 1 to entry: It is expressed in millimetres (mm).

Note 2 to entry: See [Figure 1](#).

### 3.1.2

#### gauge length

$L_0$

initial distance between the grips  $L_g$  ([3.1.1](#)) when the displacement is measured by the change in the distance between the grips during the test

Note 1 to entry: It is expressed in millimetres (mm).

### 3.1.3

#### extensometer gauge length

$L_{0e}$

*gauge length* ([3.1.2](#)), set equal to the ligament length  $b$ , when the displacement is measured by an extensometer

Note 1 to entry: It is expressed in millimetres (mm).

### 3.1.4

#### displacement

$x$

increase in the *gauge length*  $L_0$  ([3.1.2](#)), or in the *extensometer gauge length*  $L_{0e}$  ([3.1.3](#)), occurring from the beginning of the test

Note 1 to entry: It is expressed in millimetres (mm).

### 3.1.5

#### test speed

$v$

rate of separation of the gripping jaws

Note 1 to entry: It is expressed in millimetres per minute (mm/min).

### 3.1.6

#### overall fracture energy

$W_f$

energy measured by the area under the force-displacement curves

Note 1 to entry: It is expressed in millijoules (mJ).

### 3.1.7

#### specific fracture energy

$w_{sf}$

ratio of the *overall fracture energy*,  $W_f$  ([3.1.6](#)) to the minimum cross-section area of the specimen

Note 1 to entry: The minimum cross-section area of the specimen is given by the ligament length,  $b$ , times the thickness,  $h$ .

$$w_{sf} = W_f / hb$$

Note 2 to entry: It is expressed in kilojoules per square metre (kJ/m<sup>2</sup>).

**3.1.8****shape factor** $\beta$ 

dimensionless geometrical factor accounting for the shape of the plastically deformed zone around the fracture zone, the volume of which is proportional to  $hb^2$

**3.1.9****essential work of fracture** $w_e$ 

specific energy to create new surface

Note 1 to entry: It is expressed in kilojoules per square metre (kJ/m<sup>2</sup>).

**3.1.10****non-essential work of fracture** $w_p$ 

energy per unit volume dissipated for plastic deformation in the volume around the fracture zone

Note 1 to entry: It is expressed in megajoules per cubic metre (MJ/m<sup>3</sup>).

**3.1.11****maximum stress** $\sigma_{\max}$ 

maximum force,  $F_{\max}$  divided by the minimum cross-section area of the specimen given by the ligament length,  $b$ , times the thickness,  $h$

$$\sigma_{\max} = F_{\max}/hb$$

Note 1 to entry: It is expressed in megapascals (MPa).

**3.1.12****average maximum stress** $\sigma_m$ 

average of the maximum stress,  $\sigma_{\max}$  (3.1.11) values obtained on the 25 specimens used for the essential work of fracture,  $w_e$  (3.1.9) determination

Note 1 to entry: It is expressed in megapascals (MPa).

**3.2 Symbols**

|                |                                                                                                                 |                                |
|----------------|-----------------------------------------------------------------------------------------------------------------|--------------------------------|
| $h$            | specimen thickness, expressed in millimetres (mm)                                                               | See <a href="#">Figure 1</a> . |
| $B$            | specimen width, expressed in millimetres (mm)                                                                   | See <a href="#">Figure 1</a> . |
| $b$            | un-cracked ligament length, expressed in millimetres (mm)                                                       | See <a href="#">Figure 1</a> . |
| $L$            | specimen length, expressed in millimetres (mm)                                                                  | See <a href="#">Figure 1</a> . |
| $W_s$          | energy necessary to create new surfaces, expressed in millijoules (mJ)                                          |                                |
| $W_{pl}$       | energy dissipated for plastic deformation in the volume around the fracture zone, expressed in millijoules (mJ) |                                |
| $F$            | force                                                                                                           |                                |
| $F_{\max}$     | maximum force, expressed in Newton (N)                                                                          |                                |
| $x_{F_{\max}}$ | displacement at maximum force, expressed in millimetres (mm)                                                    |                                |

**4 Principle**

The principle of the experimental technique is to prepare a series of double edge-notched tensile specimens (see [Figure 1](#)) having the same thickness ( $h$ ), width ( $B$ ) and length ( $L$ ) and varying ligament

length ( $b$ ). Specimens are extended along their major longitudinal axis at constant displacement rate up to fracture. The overall fracture energy  $W_f$  is measured from the relevant force-displacement traces. This energy is supposed to be made of two additive components:  $W_f = W_s + W_{pl}$ . The first component ( $W_s$ ) is the energy necessary to create new surfaces and thus proportional to the fractured area ( $hb$ ). It can therefore be expressed as ( $W_s = w_e hb$ ), where  $w_e$  is the essential work of fracture. The second component ( $W_{pl}$ ) is the energy dissipated for plastic deformation in the volume around the fracture zone. This volume can be expressed as  $\beta hb^2$ ,  $\beta$  being a shape factor. Thus,  $W_{pl}$  can be expressed as ( $W_{pl} = w_p \beta hb^2$ ) where  $w_p$  is the non-essential work of fracture (i.e. the energy per unit volume dissipated for plastic deformation). Accordingly, the specific energy to fracture ( $w_{sf} = W_f/hb$ ) can be written as shown in [Formula \(1\)](#):

$$w_{sf} = w_e + w_p \beta b \quad (1)$$

where the essential work of fracture,  $w_e$ , and the product  $\beta w_p$  shall then be determined from a least squares linear regression to  $w_{sf}$  versus  $b$  experimental data.

To obtain a valid value of  $w_e$ , some limitations shall be taken into consideration:

- plane stress conditions shall prevail: this limits the minimum acceptable ligament length;

In this document, a fixed minimum ligament of 5 mm is specified for all considered specimen thicknesses.

**NOTE** The requirement of plane stress conditions generally limits the minimum acceptable ligament length to at least 5 times the thickness (see Reference [12]). In this document, for the maximum considered thickness of 1 mm (see 1.2), the requirement gives a minimum ligament length of 5 mm. For thinner films smaller ligament lengths can be made, however this gives rise to difficulties in specimen preparation and handling. Therefore, a fixed value of 5 mm for the minimum ligament length  $b_{min}$  is adopted in the present document.

- no edge effects: this condition limits the minimum notch length. This limits in turn the maximum ligament length;
- full yielding of the specimen ligament before crack onset: this last requirement ensures that the fracture mechanism is the same irrespective of ligament length and that  $w_e$  is a material property, i.e. independent of the specimen geometry, for a given sheet thickness. However, as already stated in the Introduction, this document will not consider the verification of this condition. If the condition is not verified,  $w_e$  is not a geometry independent material property but, nevertheless, the method provides a useful, repeatable and reproducible characterization of fracture toughness. This last limitation, therefore, will not be taken into consideration in this document.

## 5 Apparatus

The testing machine shall be in accordance with ISO 7500-1 and ISO 9513, and shall meet the specifications given in [5.1](#) and in [5.2](#).

**5.1 Force measurement system**, in accordance with class 1 as defined in ISO 7500-1 in the relevant range of forces.

**5.2 Extensometer**, in accordance with ISO 9513, class 1. The accuracy of this class shall be attained in the strain range over which measurements are being made.

For the measurement of the displacement, the use of an extensometer is preferred. Non-contact extensometers or low drag-force contact extensometers can be used. If low drag-force contact extensometers are used, ensure that the force applied to the specimen by the extensometer in the test direction does not exceed 2 % of the maximum force  $F_{max}$  measured on the specimen having the smallest ligament length  $b$  (see [5.4](#) and [6.2.3](#)).

When using an extensometer, the gauge length  $L_{0e}$  shall be set equal, for each specimen, to the relevant nominal value of the ligament length  $b$  (see 6.2.3) and shall be perpendicular to the ligament plane; its centre shall correspond with the centre of the specimen.

If suitable extensometers are not available, the displacement shall be measured by the change in the distance between the grips during the test (grip separation). The initial distance between the grips  $L_g$  shall correspond, for all the specimens, to the gauge length  $L_0$  (see 3.1.2 and 3.1.3).

Extension measurements using the crosshead displacement shall be corrected for the compliance of the machine. If the machine is equipped with built in routines for compliance correction, these shall be applied.

When the displacement is measured by the change in distance between the grips, the overall fracture energy  $W_f$  includes both the plastic energy dissipated in the region surrounding the fracture zone and the viscoelastic energy dissipated far from the fracture zone. Instead, when using an extensometer and a gauge length  $L_{0e}$  equal to the ligament length  $b$ , only the plastic energy involved in the fracture process zone is considered in the evaluation of the overall fracture energy,  $W_{f1}$ .

The value of the essential work of fracture,  $w_e$ , is not influenced by the displacement measurement method (extensometer or grip separation), but the value of the product  $Bw_p$ , (the shape factor times the non-essential work of fracture) will be overestimated when the displacement is measured by the change in distance between the grips.

**5.3 Tensile testing machine**, capable of maintaining the test speed,  $v$ , required by the present procedure (see 7.1), i.e. 10 mm/min, with the tolerance of  $\pm 20$  %.

#### 5.4 Vernier caliper and thickness gauge

All dimensions shall be measured in accordance with ISO 16012.

Width and length of the specimens shall be measured with an accuracy of 0,05 mm.

The thickness,  $h$ , shall be measured by a dead weight thickness gauge according to ISO 4593.

The thickness,  $h$ , of each specimen shall be measured (after notching) along the ligament with an accuracy of 1 % of the nominal thickness or 0,001 mm, whichever is greater. Readings every 5 mm of ligament length shall be made and the average value shall be used as the value of the specimen thickness  $h$ .

The ligament length shall be measured by means of a vernier caliper, by placing the tips of the caliper jaws as close as possible to the two notch tips. The ligament length shall be measured with an accuracy of  $\pm 0,05$  mm.

The lengths of the two notches, measured by means of a vernier caliper as the distance between each notch tip and the nearest specimen border, shall be equal within 0,5 mm

The two notch tips shall lie on a plane perpendicular to the longitudinal axis of the specimen. Maximum permissible deviation from perpendicularity, measured as the maximum distance between the two planes, perpendicular to the longitudinal specimen axis, each containing one of the notch tips, shall be 2 % of the ligament length  $b$ .

#### 5.5 Optical microscope

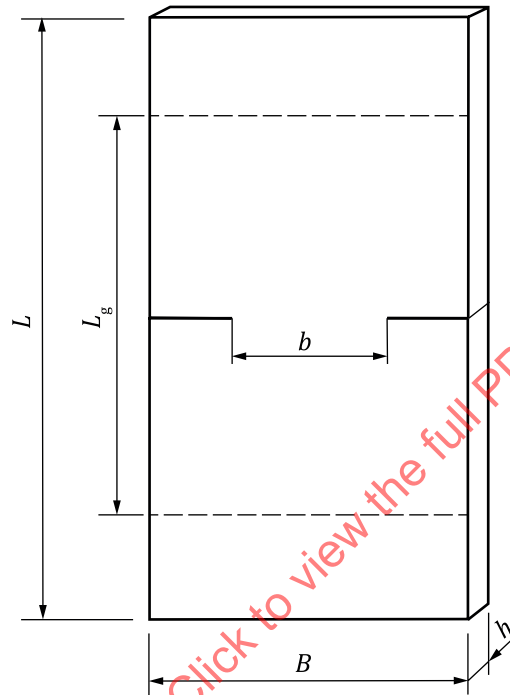
Notch tip radius is required to be smaller than 10  $\mu\text{m}$  (see 6.2.5). This requirement shall be checked by means of an optical microscope using a magnification of 200X or higher. Annex B (see Figure B1) gives some examples on how to perform this verification.

## 6 Test specimens

### 6.1 Specimen geometry

The double edge notched tension specimen (DENT) shall be used for this test method. [Figure 1](#) defines the relevant dimensions and their nomenclature.

The specimen is a rectangular strip with two notches, cut on the centre of the long sides and with the notch plane perpendicular (see [5.4](#)) to the long axis of the specimen. The two notches have equal length, within the tolerance given in [5.4](#). The notches shall have a sharp tip as detailed in [5.5](#) and [6.2.5](#).



#### Key

- $L$  specimen length
- $h$  specimen thickness
- $B$  specimen width
- $b$  ligament length
- $L_g$  initial distance between grips

Figure 1 — DENT specimen and nomenclature

### 6.2 Preparation of test specimens

#### 6.2.1 General

Preparation of the test specimen shall be made in accordance with ISO 2818. In many cases, an appropriate cutting press or a strip cutter can be used.

For a single test run, 25 specimens shall be prepared. All specimens shall have the same width,  $B$ , and length,  $L$  (see [6.2.2](#)), but with different ligament lengths,  $b$  (see [6.2.3](#) and [6.2.4](#)).

The following specifications and guidelines shall be observed.

### 6.2.2 Width and length

The initial step is to cut 25 rectangular specimens of width,  $B$ , and length,  $L$ , from the test material. If films or sheets from which specimens are cut out are anisotropic, all the specimens shall have the same orientation, parallel or perpendicular, with respect to the anisotropy axes of the sample (in a film, for example, they are usually identified as machine direction, MD and transverse direction, TD). This shall be recorded, by specifying the direction in which force is applied during the test.

The specimens shall have the following dimensions:

- thickness,  $h$ : the thickness of the film or thin sheet sample to be tested;
- width,  $B$ : 35 mm  $\pm$  0,2 mm;
- specimen length,  $L$ :  $\geq$  100 mm;
- initial distance between grips,  $L_g$ : 60 mm  $\pm$  0,5 mm;
- gauge length:
  - when the displacement is measured by the change in the distance between the grips during the test (see 5.2), gauge length shall be equal to the initial distance between the grips  $L_g$  (see Figure 1). Gauge length shall be indicated by  $L_0$ ;
  - when the displacement is measured by an extensometer gauge length shall be the extensometer gauge length, set equal to the ligament length,  $b$  as specified in 5.2. Gauge length shall be indicated by  $L_{0e}$ ;
- ligament length,  $b$ : see 6.2.3 and 6.2.4;
- position and dimensions of the notches: see 6.1 and 6.2.4.

### 6.2.3 Ligament length

To satisfy the validity conditions for EWF some limits on ligament length shall be considered.

- plane stress conditions shall prevail: this limits the minimum acceptable ligament length. In this document a fixed minimum ligament of 5 mm is specified for all considered specimen thicknesses (see Clause 4).
- no edge effects: this condition limits the minimum notch length. This limits in turn the maximum ligament length  $b_{\max}$ , which shall be smaller than half the specimen width  $B$ . A maximum ligament length value:  $b_{\max} = 15$  mm shall be adopted.

### 6.2.4 Number of specimens

Twenty five (25) specimens are required, with the ligament length varying between  $b_{\min}$  and  $b_{\max}$  (see 6.2.3). Interlaboratory testing comparisons have shown that the best results are obtained when most specimens are concentrated near the minimum and maximum ligament lengths and some of them (about 20 % of the total number) have ligament length close to the mean value.

Therefore, specimen notching will be performed, according to 6.2.5, aiming to obtain 10 specimens having  $b = 5$  mm; 5 specimens having  $b = 10$  mm; and 10 specimens having  $b = 15$  mm. These are nominal values, and the actual  $b$  value shall be measured for each specimen in accordance with 5.4.

### 6.2.5 Specimen notching

The sharpness of the notches is a critical factor for the repeatability and the reproducibility of the essential work of fracture  $w_e$ . Annex B reports RR results showing the importance of the notch sharpness. Annex B also gives some examples on the verification of notch tip sharpness by means of an optical microscope.

In this document, the value of 10 µm is specified as the maximum limit to the notch tip radius of curvature, to be verified as described in [5.5](#).

The use of common razor blades and a check of the notch tip sharpness by means of an optical microscope make it feasible to satisfy the requirement of a notch tip radius smaller than 10 µm. Any technique can be used to generate a sharp notch. Notches can be introduced by hand-sliding a razor blade with a tip curvature radius below 10 µm; for the thicker specimens, machine razor sliding with a blade having a tip radius below 10 µm can be performed. A template, made of metal or a cut-resistant rigid plastic, can be prepared and used to guide the hand-sliding operation. Also, a pre-notch can be performed and thereafter for the last 2 mm, the razor sliding technique can be used to create a sufficiently sharp notch tip.

Compliance to the notch tip radius requirement shall be checked by optical microscopy as described in [5.5](#). Attention shall be made not to damage the material ahead of the notch: to this purpose, a new blade shall be used for each set of 25 specimens (see [6.2.4](#)).

### 6.2.6 Conditioning

The notched test specimen shall be conditioned as specified in the appropriate standard for the material concerned. In the absence of this information, the most appropriate set of conditions from ISO 291 shall be selected and the conditioning time is at least 16 h, unless otherwise agreed upon by the interested parties, for example, for testing at elevated or low temperatures.

## 7 Procedure for the determination of EWF

### 7.1 Testing speed

Polymers properties are rate dependent and consideration of test speed is important. The speed used shall be fast enough to be practicably viable and yet slow enough to promote full yielding of the largest specimen ligament prior to crack growth.

A test speed of  $v = 10$  mm/min, with the tolerance of  $\pm 20$  % as specified in [5.3](#), shall be adopted.

### 7.2 Force-displacement curves

Each specimen in turn shall be gripped in the tensile testing machine and deformed to failure at the specified constant crosshead speed (see [7.1](#)). The force ( $F$ )-displacement ( $x$ ) traces shall be recorded. Raw output data of the test run will consist of the 25 force-displacement curves obtained. An example is given in [Annex A, Figure A.1](#).

A minimum of 200 data points shall be recorded for each force-displacement curve.

As can be observed in [Figure A.1](#), when specimen preparation, specimen notching and testing procedure are correctly carried out, the  $F$ - $x$  curves will have approximately similar shape, with  $F_{\max}$  and  $x_{\max}$  (see [7.3](#)) increasing with increasing  $b$ . In order to exclude  $F$ - $x$  curves which for any reason may result remarkably different in shape from the others, two rejection criteria shall be applied to the data: the Stress criterion defined in [7.4](#) and the Outlying data criterion defined in [7.6](#).

### 7.3 Calculation of the overall fracture energy $W_f$

The overall fracture energy,  $W_f$ , for each specimen shall be obtained from the area under the force-displacement trace as expressed by [Formula \(2\)](#):

$$W_f = \int_{x=0}^{x_{\max}} F(x) dx \quad (2)$$

where

$F(x)$  is the force measured at displacement,  $x$ ;

$x_{\max}$  is the maximum displacement.

The overall fracture energy  $W_f$  shall be calculated by numerical integration choosing  $x_{\max}$  as the first  $x$  value, greater than  $x_{F_{\max}}$ , where the force  $F(x)$  is lower than 0,005 times the maximum force  $F_{\max}$ .

#### 7.4 Stress criterion

A data rejection criterion based on maximum stress shall be applied to remove force-displacement curves which for any reason may result remarkably different in shape from the others. The following procedure shall be applied: from each force-displacement curve calculate the maximum stress  $\sigma_{\max}$ , then determine an average value for  $\sigma_{\max}$  denoted by  $\sigma_m$  (for the definition of  $\sigma_{\max}$  and  $\sigma_m$ , see 3.1.11 and 3.1.12, respectively). Then apply the criterion that any force-displacement curve, for which  $\sigma_{\max} < 0,9 \sigma_m$  or  $\sigma_{\max} > 1,1 \sigma_m$  shall be rejected, and therefore its data shall be marked as not satisfying the stress criterion in the results table (see 7.7). An example is given in Annex A, Table A.1 and Figure A.2.

#### 7.5 Linear regression

The results table, prepared as described in 7.7, and subjected to the application of the stress criterion defined in 7.4, will provide a series of  $N$  valid pairs  $b_i, w_{sfi}$  ( $N \leq 25$ ). These shall be subjected to a linear regression in terms of the following quantities. See Formulae (3) to (15):

Average ligament length:

$$\bar{b} = \frac{\sum_{i=1}^N b_i}{N} \quad (3)$$

Average specific fracture energy:

$$\overline{w_{sf}} = \frac{\sum_{i=1}^N w_{sfi}}{N} \quad (4)$$

$$S_{11} = \sum_{i=1}^N (w_{sfi} - \overline{w_{sf}})^2 \quad (5)$$

$$S_{22} = \sum_{i=1}^N (b_i - \bar{b})^2 \quad (6)$$

$$S_{12} = \sum_{i=1}^N (b_i - \bar{b})(w_{sfi} - \overline{w_{sf}}) \quad (7)$$

From the above defined quantities, the regression parameters can be calculated as follows:

— Slope of the fitting line:

$$\beta w_p = \frac{S_{12}}{S_{22}} \quad (8)$$

$\beta w_p$  is the product of the shape factor,  $\beta$  times the non-essential work of fracture,  $w_p$

— Intercept of the fitting line with the y-axis:

$$w_e = \overline{w_{sf}} - \beta w_p \cdot \bar{b} \quad (9)$$

where  $w_e$  is the essential work of fracture.

Standard deviation of the  $w_{sf}$  values from the least squares fitted line:

$$S = \sqrt{\frac{1}{(N-2)} \left( S_{11} - \frac{S_{12}^2}{S_{22}} \right)} \quad (10)$$

— standard error on  $\beta w_p$ :

$$SE(\beta w_p) = \frac{S}{\sqrt{S_{22}}} \quad (11)$$

— standard error on  $w_e$ :

$$SE(w_e) = S \sqrt{\frac{1}{N} + \frac{\bar{b}^2}{S_{22}}} \quad (12)$$

— correlation coefficient of the regression:

$$R^2 = \frac{S_{12}^2}{S_{11} \cdot S_{22}} \quad (13)$$

And the 95 % confidence limit on  $w_e$  and  $\beta w_p$  can be calculated as [Formulae \(14\)](#) and [\(15\)](#):

$$CL_{95 \%}(w_e) = t_{0,975;N-2} \cdot SE(w_e) \quad (14)$$

$$CL_{95 \%}(\beta w_p) = t_{0,975;N-2} \cdot SE(\beta w_p) \quad (15)$$

where  $t_{0,975;N-2}$  is the value of the fractiles of Student's t distribution as can be found in ISO 2854:1976, Annex B-Table IIa-Two-sided case, for the confidence level  $t_{0,975}$  and the relevant value of  $v = N-2$ .

A graph shall be drawn by plotting the obtained N pairs  $b_i, w_{sfi}$  with  $b_i$  on the abscissa (x-axis) and  $w_{sfi}$  on the ordinate (y-axis). The x-axis range limits shall be 0 and 20 mm, and the y-axis range limits shall be 0 and  $y_{\max}$  kJ/m<sup>2</sup>, where  $y_{\max}$  shall be an integer value greater than the greatest of the  $w_{sfi}$  values listed in the Results table. On the same graph, the best fitting straight line shall be drawn: this line is defined by its intercept with the y-axis, for  $x = 0$ , which is the Essential work of fracture  $w_e$  and by its slope which is the shape factor times the non-essential work of fracture  $\beta w_p$ . An example is given in [Annex A, Figure A.3](#).

## 7.6 Outlying data criterion

Data for specimens that lie more than  $\pm 2$  times the standard deviation of the  $w_{sf}$  values from the least squares fitted line S (S is defined in [7.5](#)) from the best-fit line shall be eliminated from the analysis. This outlying data rejecting procedure shall be applied only once to the original data fulfilling the stress criterion. Having rejected these points, if the number of valid datapoints is at least 20, a final least squares linear regression is applied to the valid data to give the slope, the intercept and the 95 % confidence limits on the intercept. An example is given in [Annex A, Figure A.3](#) and [Figure A.4](#). If the number of valid datapoints is less than 20, the test shall be rejected, and a new set of specimens shall be prepared.

## 7.7 Results table

The results table shall be prepared (an example is given in [Annex A, Table A.1](#)) listing the specimen numbers, and for each of them the following entries:

- specimen thickness,  $h$ , mm
- ligament length,  $b$ , mm
- maximum force,  $F_{\max}$ , N
- maximum stress,  $\sigma_{\max} = F_{\max}/hb$  (see [3.1.11](#)), MPa
- overall fracture energy,  $W_f$ , mJ
- specific fracture energy,  $w_{sf} = W_f/hb$  (see [3.1.7](#)), kJ/m<sup>2</sup>
- stress criterion (see [7.4](#)): satisfied (Yes or Not).
- outlying data criterion (see [7.6](#)): satisfied (Yes or Not).

## 8 Precision

An interlaboratory test was performed on a PETG film. Five different laboratories participated, with (see [Table 1](#)) and without (see [Table 2](#)) the use of an extensometer to measure displacement, following the test procedure specified in this document (the requirement, which is mandatory in this document, see [5.2](#), of performing the compliance correction when using the grip separation as a measure of displacement, was however not applied for that interlaboratory test).

The essential work of fracture,  $w_e$ , and the product,  $\beta w_p$ , obtained as described in [Clause 7](#) were determined by each laboratory.

Precision of the tests carried out in each single laboratory was expressed on the determination of:

- $w_e$ , as the standard error,  $SE(w_e)$ , the percentage of this value over  $w_e$  and its 95 % confidence limit,  $CL_{95} \%(w_e)$ ,
- the product  $\beta w_p$ , as the standard error,  $SE(\beta w_p)$  and the percentage of this value over  $\beta w_p$ .

Reproducibility was expressed by  $s_R$ , according to ISO 5725-2, on the basis of the between-laboratory variance of the test results  $w_e$  and  $\beta w_p$ . The percentage of these value over the relevant overall mean values is also given.

**Table 1 — Results with displacement measured with an extensometer**

| Group              | $w_e$<br>(kJ/m <sup>2</sup> )      | $SE(w_e)$ | $\frac{SE(w_e)}{w_e}$<br>(%) | $CL_{95} \%(w_e)$ | $\beta w_p$<br>(MJ/m <sup>3</sup> ) | $SE(\beta w_p)$ | $\frac{SE(\beta w_p)}{\beta w_p}$<br>(%) |
|--------------------|------------------------------------|-----------|------------------------------|-------------------|-------------------------------------|-----------------|------------------------------------------|
| lab 1              | 28,8                               | 1,5       | 5                            | 3,1               | 8,7                                 | 0,14            | 2                                        |
| lab 2              | 26,8                               | 0,9       | 3                            | 1,9               | 8,5                                 | 0,08            | 1                                        |
| lab 3              | 31,1                               | 1,1       | 3                            | 2,2               | 8,2                                 | 0,10            | 1                                        |
| lab 4              | 27,3                               | 2,1       | 8                            | 4,4               | 8,1                                 | 0,21            | 3                                        |
| lab 5              | 26,9                               | 1,5       | 5                            | 3,1               | 8,6                                 | 0,14            | 2                                        |
|                    | mean $w_e$<br>(kJ/m <sup>2</sup> ) | $s_R$     | $s_R/w_e$<br>(%)             |                   | $\beta w_p$<br>(MJ/m <sup>3</sup> ) | $s_R$           | $s_R/\beta w_p$<br>(%)                   |
| all 5 laboratories | 28,2                               | 1,8       | 6                            |                   | 8,4                                 | 0,26            | 3                                        |

**Table 2 — Results with displacement measured from cross-head displacement**

| Group              | $w_e$<br>(kJ/m <sup>2</sup> )      | $SE(w_e)$ | $\frac{SE(w_e)}{w_e}$<br>(%) | $CL_{95} \% (w_e)$ | $\beta w_p$<br>(MJ/m <sup>3</sup> ) | $SE(\beta w_p)$ | $\frac{SE(\beta w_p)}{\beta w_p}$<br>(%) |
|--------------------|------------------------------------|-----------|------------------------------|--------------------|-------------------------------------|-----------------|------------------------------------------|
| lab 1              | 27,2                               | 1,9       | 7                            | 4,0                | 9,1                                 | 0,17            | 2                                        |
| lab 2              | 24,0                               |           |                              | 1,7                | 9,3                                 |                 |                                          |
| lab 3              | 30,5                               | 1,2       | 4                            | 2,4                | 8,6                                 | 0,11            | 1                                        |
| lab 4              | 35,1                               | 2,4       | 7                            | 5,0                | 9,8                                 | 0,22            | 2                                        |
| lab 5              | 37,5                               | 1,3       | 4                            | 2,8                | 8,8                                 | 0,12            | 1                                        |
|                    | mean $w_e$<br>(kJ/m <sup>2</sup> ) | $s_R$     | $s_R/w_e$<br>(%)             |                    | $\beta w_p$<br>(MJ/m <sup>3</sup> ) | $s_R$           | $s_R/\beta w_p$<br>(%)                   |
| all 5 laboratories | 30,9                               | 5,6       | 18                           |                    | 9,1                                 | 0,5             | 5                                        |

## 9 Test report

The test report shall contain at least the following:

- a reference to this document, i.e. ISO 23524:2022;
- all data necessary for identification of the material tested, including type, source, manufacturer's code number and history where these are known;
- specimen width  $B$ , thickness  $h$ , testing speed,  $v$ , and test temperature shall be quoted;
- specimen orientation with respect to any preferential direction shall be quoted;
- the method adopted for displacement measurement (see 5.2), i.e. the use of an extensometer, or the measurement of the change in distance between the grips, shall be reported. If the displacement is measured by the change in distance between the grips, the application of the compliance correction (see 5.2) shall be reported;
- maximum and minimum values of  $b$  shall be quoted;
- the tools and technique (e.g. blade type, templates, etc.) used for notching shall be briefly described (see 6.2.5), and verification of the notch tip by optical microscopy (see 5.5), resulting in notch tip radius being smaller than 10  $\mu\text{m}$ , shall be reported;
- the average value of maximum stress,  $\sigma_m$ , shall be quoted;
- the values for  $w_e$  (intercept) and  $\beta w_p$  (slope) shall be quoted from the final least squares regression of  $w_{sf}$  against  $b$  together with the 95 % confidence limits on the determination of  $w_e$ ;
- the graph of  $\sigma_{max}$  against  $b$  shall be provided, together with lines to indicate  $\sigma_m$  and the stress criterion limits 0,9  $\sigma_m$  and 1,1  $\sigma_m$ ;
- the final (after application of the outlying criterion) graph of  $w_{sf}$  against  $b$  shall be included;
- a table of values of specimen thickness, ligament length, maximum force,  $\sigma_{max}$ ,  $W_f$  and  $w_{sf}$  shall be provided. Indication shall be made for those data that have been excluded from the essential work determination and the reason for their exclusion.

## Annex A (informative)

### Example

[Annex A](#) presents an example of determination of the essential work of fracture, following the method described in this document.

Experimental data were obtained on PETG sheets having a nominal thickness of 500  $\mu\text{m}$ . Specimens were cut in the machine direction. 25 specimens were notched and tested.

Please note that, although the material is similar, the data here presented have no relationship with the RR results shown in [Clause 8](#).

[Figure A.1](#) shows the relevant force-displacement curves.

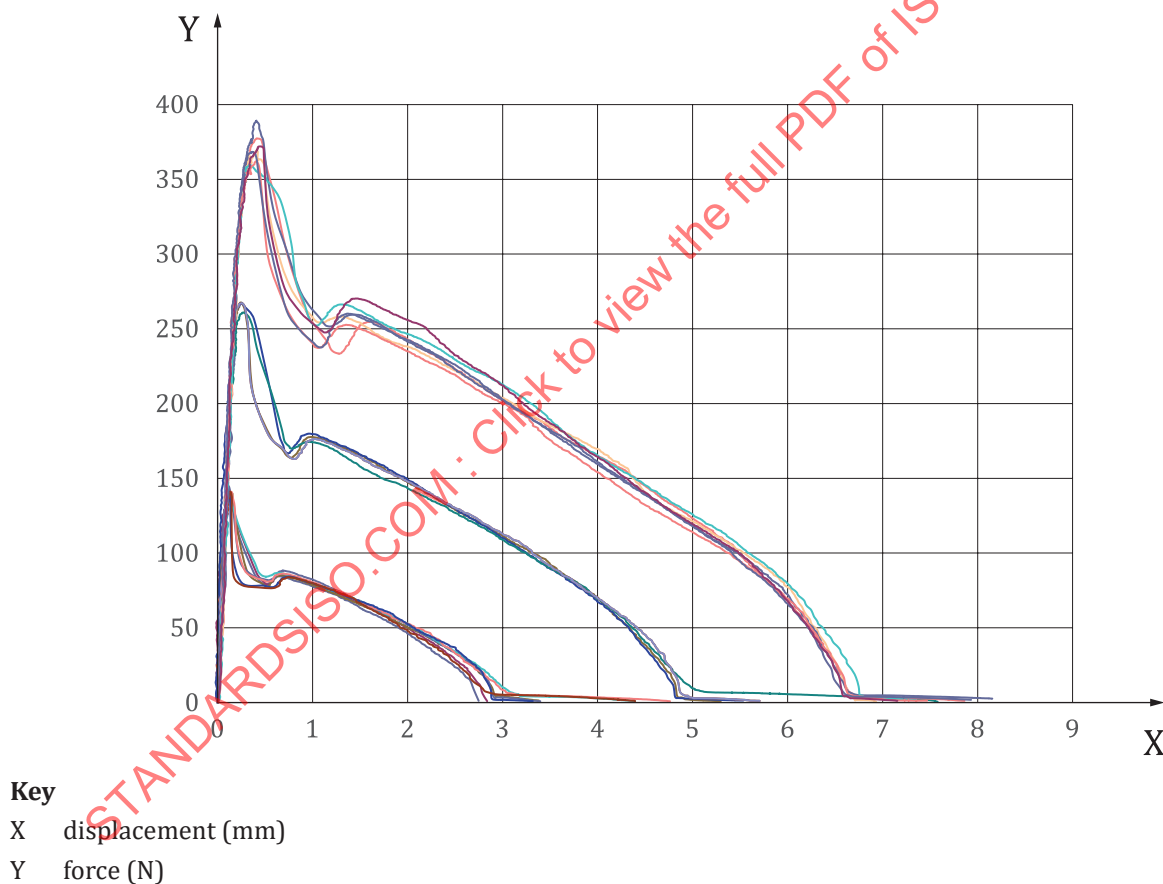


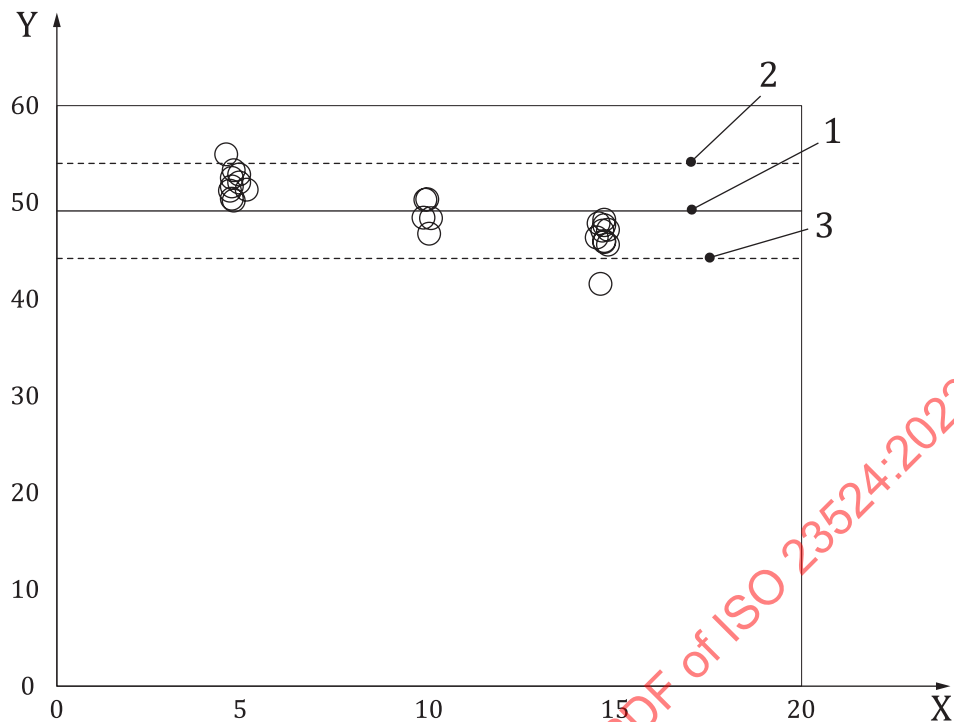
**Figure A.1 — Example of force displacement curves**

[Table A.1](#) is the results table prepared as specified in [7.7](#).

Table A.1 — Results table

| Specimen                                                                                                                                     | Specimen thickness | Ligament length | Maximum force  | Maximum stress        | Overall fracture energy | Specific failure energy       | Stress criterion      | Outlying data criterion |
|----------------------------------------------------------------------------------------------------------------------------------------------|--------------------|-----------------|----------------|-----------------------|-------------------------|-------------------------------|-----------------------|-------------------------|
|                                                                                                                                              | $h$ (mm)           | $b$ (mm)        | $F_{\max}$ (N) | $\sigma_{\max}$ (MPa) | $W_f$ (mJ)              | $w_{sf}$ (kJ/m <sup>2</sup> ) | Satisfied: Yes or Not | Satisfied: Yes or Not   |
| 1                                                                                                                                            | 0,578              | 4,75            | 137,3          | 50,18                 | 175,8                   | 64,3                          | yes                   | yes                     |
| 2                                                                                                                                            | 0,596              | 4,65            | 142            | 51,21                 | 179,2                   | 64,6                          | yes                   | yes                     |
| 3                                                                                                                                            | 0,589              | 4,70            | 140            | 50,37                 | 187,2                   | 67,3                          | yes                   | yes                     |
| 4                                                                                                                                            | 0,57               | 4,75            | 144,8          | 53,31                 | 189,7                   | 69,9                          | yes                   | yes                     |
| 5                                                                                                                                            | 0,538              | 4,90            | 136,8          | 52,04                 | 199,7                   | 76,0                          | yes                   | yes                     |
| 6                                                                                                                                            | 0,539              | 5,10            | 141            | 51,30                 | 196,6                   | 71,5                          | yes                   | yes                     |
| 7                                                                                                                                            | 0,542              | 4,90            | 140,9          | 52,88                 | 188                     | 70,6                          | yes                   | yes                     |
| 8                                                                                                                                            | 0,581              | 4,70            | 141,1          | 51,64                 | 179,4                   | 65,7                          | yes                   | yes                     |
| 9                                                                                                                                            | 0,574              | 4,70            | 141,7          | 52,52                 | 170,8                   | 63,3                          | yes                   | yes                     |
| 10                                                                                                                                           | 0,547              | 4,55            | 136,8          | 54,97                 | 196                     | 78,8                          | not                   |                         |
| 11                                                                                                                                           | 0,537              | 9,90            | 267,6          | 50,27                 | 608                     | 114,2                         | yes                   | yes                     |
| 12                                                                                                                                           | 0,533              | 9,95            | 267,4          | 50,32                 | 624,7                   | 117,5                         | yes                   | yes                     |
| 13                                                                                                                                           | 0,537              | 10,05           | 260,9          | 48,37                 | 616,9                   | 114,4                         | yes                   | yes                     |
| 14                                                                                                                                           | 0,559              | 9,85            | 267,2          | 48,42                 | 614,3                   | 111,3                         | yes                   | yes                     |
| 15                                                                                                                                           | 0,559              | 10,00           | 261,4          | 46,76                 | 625,8                   | 111,9                         | yes                   | yes                     |
| 16                                                                                                                                           | 0,532              | 14,70           | 372,1          | 47,64                 | 1255,2                  | 160,7                         | yes                   | not                     |
| 17                                                                                                                                           | 0,547              | 14,65           | 377,4          | 47,07                 | 1211,8                  | 151,2                         | yes                   | yes                     |
| 18                                                                                                                                           | 0,549              | 14,50           | 369,1          | 46,37                 | 1209,2                  | 151,9                         | yes                   | yes                     |
| 19                                                                                                                                           | 0,55               | 14,70           | 389,3          | 48,20                 | 1214,8                  | 150,4                         | yes                   | yes                     |
| 20                                                                                                                                           | 0,532              | 14,80           | 359,6          | 45,62                 | 1249,5                  | 158,5                         | yes                   | yes                     |
| 21                                                                                                                                           | 0,535              | 14,70           | 362,2          | 46,00                 | 1163,1                  | 147,7                         | yes                   | yes                     |
| 22                                                                                                                                           | 0,528              | 14,80           | 368,3          | 47,17                 | 1189,2                  | 152,3                         | yes                   | yes                     |
| 23                                                                                                                                           | 0,552              | 14,70           | 372            | 45,90                 | 1221                    | 150,7                         | yes                   | yes                     |
| 24                                                                                                                                           | 0,585              | 14,60           | 355,1          | 41,58                 | 1224,8                  | 143,4                         | not                   |                         |
| 25                                                                                                                                           | 0,559              | 14,55           | 389,1          | 47,84                 | 1198,8                  | 147,4                         | yes                   | yes                     |
| Material: PETG<br>test temperature: 23 °C<br>displacement rate (mm/min) = 12<br>specimen width (mm) = 35<br>distance between grips (mm) = 60 |                    |                 |                |                       |                         |                               |                       |                         |

Figure A.2 reports maximum stress as a function of ligament length for the application of the stress criterion (see 7.4).

**Key**

- Y maximum stress (MPa)  
 X  $b$ , mm  
 ○  $\sigma_{\max}$  data points  
 1 average maximum stress,  $\sigma_m$   
 2  $1,1 \sigma_m$   
 3  $0,9 \sigma_m$

**Figure A.2 — Graph of maximum stress  $\sigma_{\max}$  vs. ligament length  $b$**

Application of the stress criterion excludes data points 10 and 24 (see [Table A1](#)). Linear regression of  $w_{sf}$  vs.  $b$  data on the remaining valid data, carried out as described in [7.5](#), provides the following results [see [Formulae \(A.1\) to \(A.6\)](#)]:

$$w_e \text{ (kJ/m}^2\text{)} = 27,54 \quad (\text{A.1})$$

$$S = 3,59 \quad (\text{A.2})$$

$$SE(w_e) = 1,84 \quad (\text{A.3})$$

$$CL_{95 \%}(w_e) = 3,82 \quad (\text{A.4})$$

$$\beta w_p \text{ (mJ/m}^3\text{)} = 8,53 \quad (\text{A.5})$$

$$SE(\beta w_p) = 0,17 \quad (A.6)$$

Therefore, the regression line of  $w_{sf}$  vs.  $b$  is given by [Formula \(A.7\)](#):

$$w_{sf} = 27,54 b + 8,53 \quad (A.7)$$

and the correlation coefficient of the regression  $R^2$  is shown as [Formula \(A.8\)](#):

$$R^2 = 0,9916 \quad (A.8)$$

The linear regression after application of the stress criterion is shown in [Figure A.3](#)

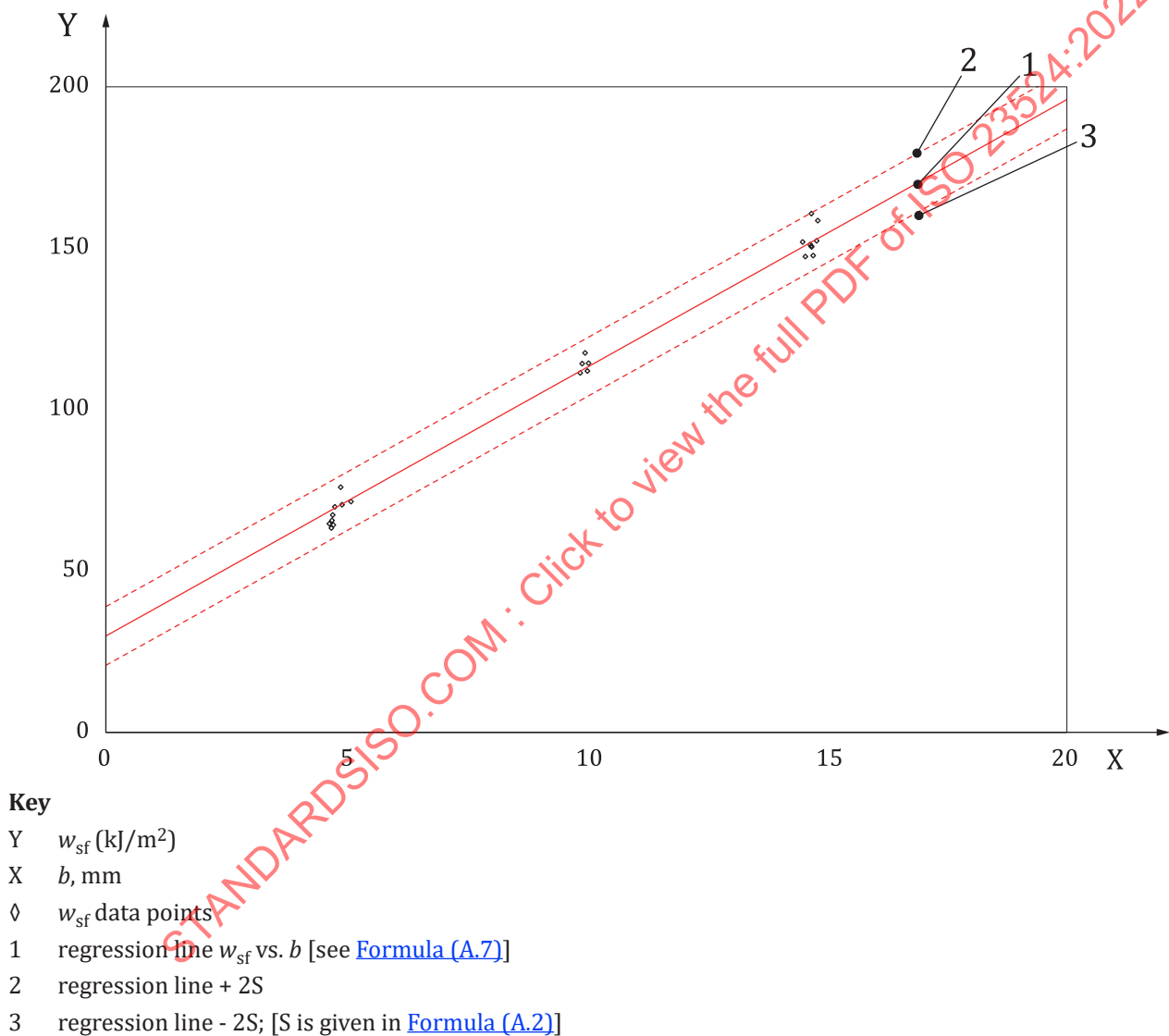


**Figure A.3 — Specific fracture energy  $w_{sf}$ , vs. ligament length  $b$ , all data points (after application of the stress criterion)**

Application of the outlying data criterion (see [7.6](#)) excludes data point 16 (see [Table A.1](#)). A new linear regression on the remaining valid data, carried out as described in [7.5](#), provides the following results [see [Formula \(A.9\)](#) to [\(A.13\)](#)]:

$$w_e \text{ (kJ/m}^2\text{)} = 28,11 \quad (A.9)$$