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BSI Standards Publication

Paper and board — Determination of fracture toughness — Constant rate of elongation method (1,7 mm/s)

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National foreword

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TECHNICAL SPECIFICATION

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Paper and board — Determination of fracture toughness — Constant rate of elongation method (1,7 mm/s)

Papier et carton — Détermination de la résistance à la rupture — Méthode à gradient d'allongement constant (1,7 mm/s)

Reference number
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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. www.iso.org/directives

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The committee responsible for this document is ISO/TC 6, *Paper, board and pulps*, Subcommittee SC 2, *Test methods and quality specifications for paper and board*.

Introduction

The essence of fracture mechanics theory is that the material parameter fracture toughness is determined by controlled laboratory testing before it is used to predict the fracture properties of structures or structural components containing defects. This Technical Specification describes a laboratory test method for determination of the fracture toughness of paper materials and a numerical method to predict the fracture strength and fracture strain of notched paper webs for a given reference paper web geometry called ISO paper web geometry. The specified methods are based on nonlinear fracture mechanics theory (J-integral theory).[1] [2] [3]

The experimental procedure for determining the fracture toughness of this Technical Specification consists of two material tests: tensile testing and fracture toughness testing. Both these tests are performed following ISO 1924-3, with the exception that 50 mm wide test pieces containing 20 mm-wide centre notches are used in the fracture toughness test.

For material ranking and material development purposes, it is advantageous to define a notched reference geometry for predictions of fracture strength (stress at break) and fracture strain (strain at break). Such notched reference geometry makes it easier to compare fracture properties of different paper materials and to communicate results in reports and articles. The main application of fracture mechanics to paper materials is related to breaks in continuous web handling operations, such as in manufacture, winding, and printing. The characteristic dimensions of paper webs in such operations generally are in the order of metres, while defects in the paper webs commonly have a characteristic size in the order of millimetres. Furthermore, the most severe defects from a web break perspective are located in the region of the edges of the paper web. In this Technical Specification, a 2 m long and 1 m wide paper web, containing a 10 mm edge notch, is used as the notched ISO paper web geometry for predicting and ranking of the fracture properties of paper materials. The terms ISO fracture strength and ISO fracture strain are used to indicate that the fracture properties are determined for this particular notched ISO paper web geometry following this Technical Specification. A successful experimental validation of the procedure for determining the fracture properties for the assigned ISO web geometry has been performed.[1] [2] [3]

NOTE 1 The determined fracture toughness may also be utilized to predict fracture properties of paper webs and paper products that have different dimensions and shapes than the introduced ISO paper web geometry. The procedure for such predictions is given in References [1], [2], and [3].

NOTE 2 The fracture toughness alone does not constitute sufficient information to determine the fracture behaviour of structures or structural components. Consider the stress/strain curves for two materials, A and B, obtained by tensile testing of notched test pieces (see Figure 1). The exemplified materials have *equal fracture toughness* but *different fracture strengths and fracture strains*. Materials A and B, which have different stress/strain behaviours, could for instance originate from machine direction (MD) and cross-machine direction (CD) of a particular paper grade or could be two papers of different origin. Clearly, materials A and B are expected to behave very differently in converting operations, although they have equal fracture toughness. This example illustrates that the fracture toughness cannot be used to rank the fracture properties of papers that show different stress/strain behaviour. However, the ISO fracture strength and ISO fracture strain, according to this Technical Specification, can be used to accurately rank the fracture properties of materials A and B.

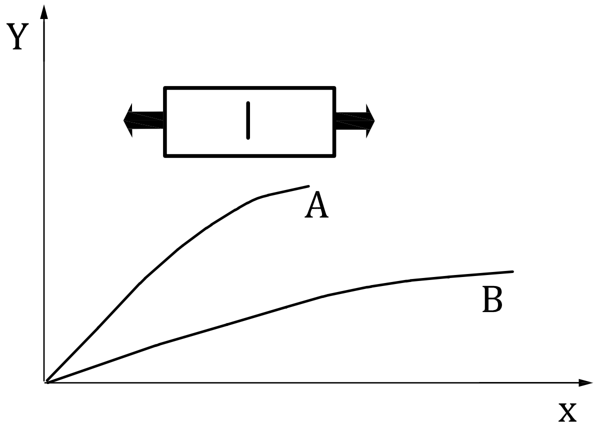


Figure 1 — Stress/strain curves for two materials, A and B, obtained by tensile testing of notched test pieces

Paper and board — Determination of fracture toughness — Constant rate of elongation method (1,7 mm/s)

1 Scope

This Technical Specification describes a method for determining the fracture toughness of paper and board using a tensile testing machine operated with a constant rate of elongation. This Technical Specification also describes the determination of the fracture strength and fracture strain of a notched paper web with an assigned standard web geometry. This information is used to rank the fracture properties of paper materials.

This Technical Specification is applicable to all kinds of paper and paperboard, except for certain special grades, such as creped paper and other paper materials that significantly deviate from exhibiting monotonically decreasing tangential stiffness during tensile testing. This Technical Specification does not apply to corrugated fibreboard.

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 186, *Paper and board — Sampling to determine average quality*

ISO 187, *Paper, board and pulps — Standard atmosphere for conditioning and testing and procedure for monitoring the atmosphere and conditioning of samples*

ISO 536, *Paper and board — Determination of grammage*

ISO 1924-3, *Paper and board — Determination of tensile properties — Part 3: Constant rate of elongation method (100 mm/min)*

3 Terms and definitions

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

3.1
tensile stiffness
E^b
maximum slope of the curve obtained when tensile force per unit width is plotted versus strain

[SOURCE: ISO 1924-3:2005, definition 3.8]

3.2
tensile strength
σ_{T}^{b}
maximum tensile force per unit width that paper and board will withstand before breaking under the conditions defined in this Technical Specification

[SOURCE: ISO 1924-3:2005, definition 3.1]

3.3
tensile energy absorption
W_T^b
amount of energy per unit surface area (test length × width) of a test piece when it is strained to the maximum tensile force

[SOURCE: ISO 1924-3:2005, definition 3.6]

3.4
strain at break
ε_T
strain at the maximum tensile force

[SOURCE: ISO 1924-3:2005, definition 3.5]

3.5
strain-hardening exponent
N
mathematically determined exponent describing the non-linear part of the stress/strain curve of the test material

Note 1 to entry: The strain–hardening exponent is dimensionless.

3.6
strain-hardening modulus
E_0^b
mathematically determined modulus describing the non-linear part of the stress/strain curve of the test material

Note 1 to entry: The strain–hardening modulus is expressed in newtons per metre (N/m).

3.7
apparent tensile strength
σ_{cr}^b
tensile strength of the centre-notched fracture toughness test piece

Note 1 to entry: The apparent tensile strength is reported in newtons per metre (N/m).

3.8
apparent strain at break
ε_{cr}
strain at break of the centre-notched fracture toughness test piece

Note 1 to entry: The apparent strain at break is dimensionless and usually reported as a percentage.

3.9
fracture toughness
J_{cr}^b
energy release rate at structural instability of notched paper or board panels under in-plane tensile loading

3.10
ISO fracture strength
σ_{ISO}^b
tensile strength of the edge-notched ISO paper web geometry used in this Technical Specification

3.11
ISO fracture strain
ε_{ISO}
strain at break of the edge-notched ISO paper web geometry used in this Technical Specification

4 Principle

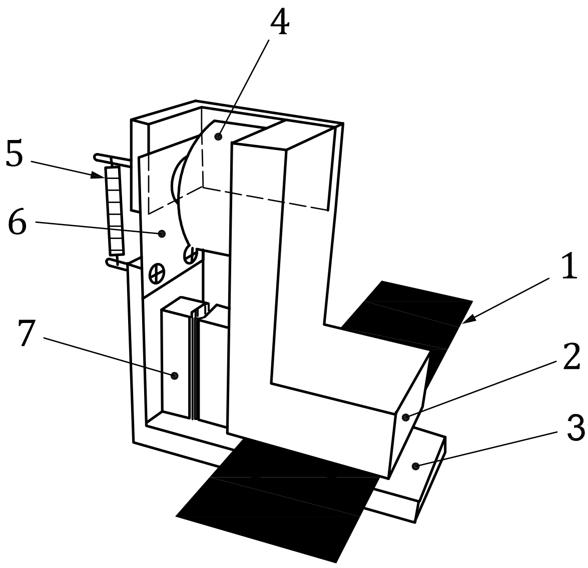
Two different kinds of test pieces, un-notched and notched, of given dimensions are subjected to constant rate of elongation using a tensile testing machine recording the tensile force and elongation. From the recorded data of the un-notched test pieces, the tensile strength, strain at break, tensile energy absorption, and tensile stiffness are determined. From the recorded data of the notched test pieces, the apparent tensile strength and apparent strain at break are determined. The parameters of the un-notched test pieces in combination with the parameters of the notched test pieces are used to calculate the fracture toughness of the material. The required calculations are treated in Clause 9.

5 Apparatus

5.1 Tensile testing machine, as described in ISO 1924-3. The tensile testing machine shall be capable of testing both 15 mm wide and 50 mm wide test pieces.

5.2 Anti-buckling guide, used to keep the notched region of the fracture toughness test piece flat during the fracture toughness test. The anti-buckling guide shall consist of two supports with parallel, flat, smooth low-friction surfaces, preferably made of steel or aluminium that shall cover the total width of the test piece and a length of 15 mm on each side of the notch. A compression force of (0,6 ± 0,2) N shall be applied to the fracture toughness test piece by the supports, before the separation of the supports is fixed. The fixed separation of the supports shall then be retained during the reminder of the fracture toughness test.

One possible solution to prevent out-of-plane buckling of the fracture toughness test piece is shown in Figure 2. The paper test piece (1) is placed between a stationary upper support (2) and a movable lower support (3). The lower support, which is free to slide vertically on roller bearings (7), is brought into contact with the test piece. The specified compression force is applied by the spring (5) to the paper test piece via the lower support. The position of the lower support is then fixed by the pneumatic cylinder (4) via the thin metal blade (6).



Key

1 paper test piece
2 upper support
3 lower support
4 pneumatic cylinder
5 spring
6 thin metal blade
7 roller bearings

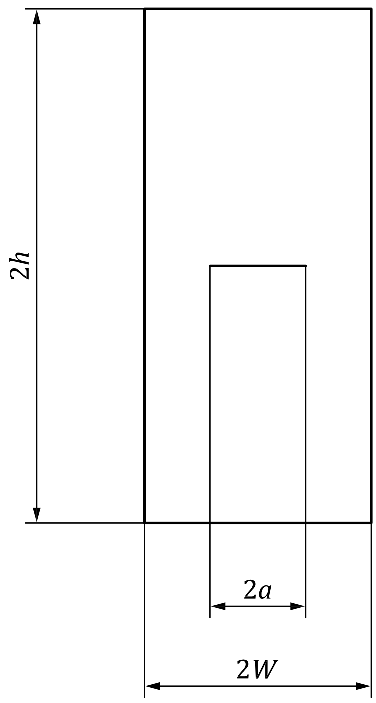
Figure 2 — Illustration of one possible solution to achieve anti-buckling

5.3 Computer, means for numerical calculation of fracture toughness and predictions of fracture strength and fracture strain, in accordance with the formulae given in this Technical Specification.

5.4 Cutting device(s), used for cutting tensile and fracture toughness test pieces. The cutting device(s) shall be able to cut (15 ± 0,1) mm wide tensile test pieces and (50 ± 0,1) mm wide fracture toughness test pieces (2*W*), respectively.

5.5 Device for making a notch, used to manufacture a centre-notch in each fracture toughness test piece. The device shall be able to produce a (20 ± 0,1) mm long straight centre-notch (2*a*). The notch shall be oriented perpendicular to the loading direction with a precision of ± 5 and have a central location with respect to both the width and the length of the test piece. The end of the notch shall be situated (15 ± 0,1) mm from the edge of the test piece. The position of the notch in the length direction shall be (50 ± 5) mm (*h*) from each clamp in the testing apparatus. A description of the test piece is given in Figure 3.

NOTE One possible device that is able to cut the notch with the required precision consists of a sharp razor blade mounted in a punch press.



Key

2h test piece length between clamps

2a notch length

2W test piece width

Figure 3 — The characteristic geometry of the fracture toughness test piece

6 Calibration and adjustment of apparatus

The tensile testing machine (5.1) shall be calibrated according to ISO 1924-3 and instructions given by the manufacturer of the testing apparatus.

The proper function of the anti-buckling guide shall be checked before the fracture toughness testing. Ensure that the anti-buckling guide is applying a compression force of (0,6 ± 0,2) N to the fracture toughness test piece before the separation of the supports is fixed. A calibration weight or a force measurement instrument may be used for controlling the compression force. If necessary, adjust the applied force.

7 Sampling and preparation of test pieces

7.1 Sampling

If the tests are being made to evaluate a lot, select the sample in accordance with ISO 186. If the tests are made on another type of sample, ensure that the specimens taken are representative of the sample received.

7.2 Conditioning

Condition the samples at (23 ± 1) °C and (50 ± 2) % relative humidity (r.h.) as specified in ISO 187.

These tests, like other mechanical tests, are very sensitive to changes in the moisture content of the test pieces. Handle the test pieces carefully and never touch the part of the test pieces to be placed between the clamps with bare hands. Keep the test pieces away from moisture, heat, and other influences that may change their moisture content.

The specimens shall be kept in the conditioning atmosphere until all test pieces have been prepared. Keep the test pieces in the conditioning atmosphere throughout the test.

NOTE In addition to the climate specified in this Technical Specification, ISO 187 also specifies another climate, (27 ± 1) °C and (65 ± 2) % r.h. The test pieces may be conditioned in this climate or in any other constant climate, followed by testing in the same climate. If so, the testing is not conducted in accordance with this Technical Specification and the used climate should be reported.

7.3 Determination of grammage

Determine the grammage of the samples according to ISO 536.

7.4 Preparation of test pieces for tensile testing

Prepare test pieces for the tensile testing as described in ISO 1924-3, using the test piece width (15 ± 0,1) mm. Ensure the test pieces are long enough to protrude from the clamps.

7.5 Preparation of test pieces for fracture toughness testing

Prepare test pieces for the fracture testing as described in ISO 1924-3, using a test piece width of (50 ± 0,1) mm. Ensure the test piece is long enough to protrude from the clamps. Make a centrally placed notch according to 5.5.

Cut a sufficient number of test pieces to enable at least 10 valid fracture toughness tests in the principal in-plane material direction of interest; i.e. the machine direction (MD) or cross-machine direction (CD) for anisotropic papers or an arbitrary in-plane direction for isotropic laboratory sheets.

8 Procedure

Two types of material tests are required to determine the fracture toughness of a paper material in the principal in-plane material direction of interest.

8.1 Tensile testing

Using the test pieces for tensile testing (see 7.4), perform the tensile tests according to ISO 1924-3. Record the force and elongation during the test. Determine the tensile stiffness, tensile strength and strain at break, and tensile energy absorption.

8.2 Fracture toughness testing

Using the test pieces for fracture toughness testing (see 7.5), perform the fracture toughness tests according to ISO 1924-3, with the three exceptions that wider test pieces are used, that the test pieces contain centre notches, and that out-of-plane buckling of the test pieces is prevented in the notched region of the test pieces. Record the force and elongation. Determine the apparent tensile strength and the apparent strain at break.

NOTE The denotation "*apparent*" in the parameters *apparent tensile strength* and *apparent strain at break*, respectively, are introduced to mark that these parameters are determined without considering that the fracture toughness test piece contains a centre notch. Clearly, the presence of the centre notch will weaken the test piece, resulting in that the apparent tensile strength will be lower than the tensile strength of the material, and the apparent strain at break will be lower than the strain at break of the material.

9 Calculations

9.1 General

The procedure for determining the fracture toughness utilizes both the tensile test data and the fracture toughness test data.

The fracture properties of paper materials cannot be determined based on the fracture toughness alone. Determination of the ISO fracture strength and ISO fracture strain makes it possible to determine the fracture properties of papers and boards and further facilitates the communication of the results in reports and articles. The terms ISO fracture strength and ISO fracture strain, which are predicted for a 2 m long and 1 m wide ISO paper web geometry containing a 10 mm edge crack, are used to indicate that these fracture properties are determined according to this Technical Specification.

The calculations in the following clauses are facilitated by computer assistance.

9.2 Tensile testing and evaluation of tensile properties

Table 1 — Nomenclature for determination of tensile properties

ε	strain, dimensionless
σ^b	stress, in newtons per metre
b	test piece width, in metres
E^b	tensile stiffness, a material parameter, in newtons per metre
σ_T^b	tensile strength, a material parameter, in newtons per metre
ε_T	strain at break
W_T^b	tensile energy absorption, a material parameter, in joules per square metre
E_0^b	strain-hardening modulus, a material parameter, in newtons per metre
N	strain-hardening exponent, a material parameter, dimensionless

The tensile material behaviour is modelled by Formula (1).[1] [2] [3]

$$\varepsilon = \frac{\sigma^b}{E^b} + \left(\frac{\sigma^b}{E_0^b}\right)^N \quad (1)$$

NOTE 1 The theory assumes that the stress/strain curve can be described by the material model in Formula (1). Most paper grades are accurately described by this model. The theory will become gradually less precise as the deviation between the measured stress/strain curve and the model increases. The theory in this Technical Specification is intended for treating materials that exhibit a monotonically decreasing tangential stiffness during tensile testing. The theory is therefore less well suited for certain special grades, such as creped paper, which cannot be described accurately by Formula (1).

After performing the tensile testing according to ISO 1924-3, calculate the tensile stiffness E^b, tensile strength σ_T^b, tensile energy absorption W_T^b, strain at break ε_T, and the coefficient of variation for each of these parameters following ISO 1924-3.

Determine the strain hardening exponent, *N*, and the strain-hardening modulus, E_0^b, using Formulae (2) and (3).

$$N = \frac{(\sigma_T^b)^2 - 2E^b W_T^b}{(\sigma_T^b)^2 + 2E^b (W_T^b - \sigma_T^b \varepsilon_T)} \tag{2}$$

$$E_0^b = \frac{\sigma_T^b}{\left(\varepsilon_T - \frac{\sigma_T^b}{E^b}\right)^{\frac{1}{N}}} \tag{3}$$

NOTE 2 It is advisable that the accuracy of the model, when calibrated by the determined material parameters E^b, E_0^b, and *N*, is checked by plotting the behaviour of the model together with the stress/strain curves determined experimentally from the tensile testing.

9.3 Fracture toughness testing and evaluation of fracture toughness

Table 2 — Nomenclature for determination of fracture toughness

σ_{cr}^b	apparent tensile strength from the fracture toughness test, in newtons per metre
ε_{cr}	apparent strain at break from the fracture toughness test, dimensionless
$\sigma_{ns,cr}^b$	critical net-section stress from the fracture toughness test, in newtons per metre
$2W$	width of the fracture toughness test piece, in metres ($2W$ = 0,050 m)
$2a$	notch length of the fracture toughness test piece, in metres ($2a$ = 0,020 m)
J_{cr}^b	fracture toughness, in joules per metre
f_{el}	linear elastic geometry parameter for the expression of the fracture toughness, dimensionless
f_{nl}	non-linear geometry parameter for the expression of the fracture toughness, dimensionless
E^b	tensile stiffness, a material parameter, in newtons per metre
E_0^b	strain-hardening modulus, a material parameter, in newtons per metre
N	strain-hardening exponent, a material parameter, dimensionless

After performing the fracture toughness test according to ISO 1924-3 for the fracture toughness test pieces with dimensions according to Figure 3, determine the apparent tensile strength, σ_{cr}^b, and the apparent strain at break, ε_{cr}. Calculate the coefficient of variation for each of the parameters.

Determine the critical net-section stress, $\sigma^{b}_{\text{ns,cr}}$, according to Formula (4).

$$\sigma^{b}_{\text{ns,cr}} = \frac{\sigma^{b}_{\text{cr}}}{1-\frac{a}{W}} = \frac{\sigma^{b}_{\text{cr}}}{0{,}6} \tag{4}$$

Determine the fracture toughness, J^{b}_{cr}, given by Formula (5).

$$J^{b}_{\text{cr}} = \frac{a(\sigma^{b}_{\text{ns,cr}})^2}{E^b} f_{el} + \frac{a(\sigma^{b}_{\text{ns,cr}})^{N+1}}{(E^{b}_{0})^N} f_{nl} \tag{5}$$

where

$$f_{el} = 1{,}409\,6 \tag{6}$$

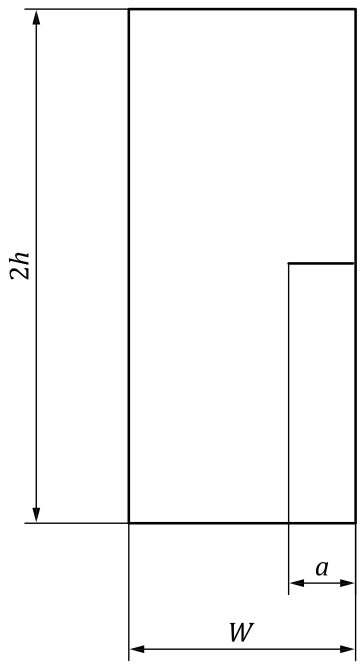
$$f_{nl} = \frac{N^{0{,}549\,4}}{0{,}245\,9N + 0{,}461\,2} \tag{7}$$

9.4 Determination of ISO fracture strength and ISO fracture strain

Table 3 — Nomenclature for determination of ISO fracture strength and ISO fracture strain

W	width of the ISO fracture geometry, in metres (W = 1 m)
$2h$	length of the ISO paper web geometry, in metres ($2h$ = 2 m)
a	notch length of the ISO paper web geometry, in metres (a = 0,010 m)
J^{b}_{cr}	fracture toughness, in joules per metre
f_{el}	linear elastic geometry parameter for the expression of the ISO paper web geometry, dimensionless
f_{nl}	non-linear geometry parameter for the expression of the ISO paper web geometry, dimensionless
$\sigma^{b}_{\text{ns,cr}}$	critical net-section stress of the ISO paper web geometry, in newtons per metre
E^b	tensile stiffness, a material parameter, in newtons per metre
E^{b}_{0}	strain-hardening modulus, a material parameter, in newtons per metre
N	strain-hardening exponent, a material parameter, dimensionless
g_{el}	linear elastic geometry parameter for the compliance expression of the ISO paper web geometry, dimensionless
g_{nl}	non-linear geometry parameter for the compliance expression of the ISO paper web geometry, dimensionless
σ^{b}_{ISO}	ISO fracture strength of the ISO paper web geometry, in newtons per metre
ε_{ISO}	ISO fracture strain of the ISO paper web geometry, dimensionless

An edge-notched paper web is used as the ISO paper web geometry. The characteristic dimensions of the ISO paper web geometry are shown in Figure 4.



Key

$2h$ web length (2 m)

a notch length (0,010 m)

W theoretical width (1 m)

Figure 4 — The ISO paper web geometry

Formula (8) defines the relation between the fracture toughness, the tensile material parameters, and the critical net-section stress for the ISO paper web geometry.

$$J_{\mathrm{cr}}^{b} = \frac{a\left(\sigma_{\mathrm{ns,cr}}^{b}\right)}{E^{b}} f_{el} + \frac{a\left(\sigma_{\mathrm{ns,cr}}^{b}\right)^{N+1}}{\left(E_{0}^{b}\right)} f_{nl} \tag{8}$$

where

$$f_{el} = 3{,}782\ 4 \tag{9}$$

$$f_{nl} = -4{,}680\ 7\times10^{-5} N^{4} + 3{,}427\ 6\times10^{-3} N^{3} - 1{,}071\ 4\times10^{-1} N^{2} + 2{,}094\ 4N + 1{,}785\ 6 \tag{10}$$

NOTE Formula (8) is identical to Formula (5), except that the magnitudes of the geometry parameters, f_{el} and f_{nl}, differ, which will result in a different relation between the fracture toughness of the material and the critical net-section stress.

Use an iterative numerical method, such as the Newton-Raphson method, to solve Formula (8) for the critical net-section stress, $\sigma_{\mathrm{ns,cr}}^{b}$.

Calculate the ISO fracture strength using Formula (11).

$$\sigma_{\mathrm{ISO}}^{b} = \sigma_{\mathrm{ns,cr}}^{b} (1 - \frac{a}{W}) = 0{,}99 \sigma_{\mathrm{ns,cr}}^{b} \quad (11)$$

Calculate the ISO fracture strain using Formula (12)

$$\varepsilon_{\mathrm{ISO}} = \frac{\sigma_{\mathrm{ISO}}^{b}}{E^{b}} \left(1 + \frac{1}{\left(1 - \frac{a}{W}\right)} g_{el} \right) + \left(\frac{\sigma_{\mathrm{ISO}}^{b}}{E_{0}^{b}} \right)^{N} \left(1 + \frac{1}{\left(1 - \frac{a}{W}\right)^{N}} g_{nl} \right) \quad (12)$$

where

$$g_{el} = -1{,}151\,4 \times 10^{-2} \quad (13)$$

$$g_{nl} = 3{,}797\,8 \times 10^{-7} N^{4} - 2{,}747\,9 \times 10^{-5} N^{3} + 8{,}153\,1 \times 10^{-4} N^{2} - 1{,}194\,5 \times 10^{-2} N - 1{,}915\,8 \times 10^{-2} \quad (14)$$

9.5 Indexed parameters

If required, the parameters may be reported in indexed form using the formulae in Table 4.

Table 4 — Nomenclature for indexed properties

w	grammage, in kilograms per square metre according to ISO 536
σ_{cr}^{w}	apparent tensile strength index of the centre-notched fracture toughness test piece, in newton metres per kilogram; $\sigma_{\mathrm{cr}}^{w} = \frac{\sigma_{\mathrm{cr}}^{b}}{w}$
E_{0}^{w}	strain-hardening modulus index, in newton metres per kilogram; $E_{0}^{w} = \frac{E_{0}^{b}}{w}$
J_{cr}^{w}	fracture toughness index, in joule metres per kilogram; $J_{\mathrm{cr}}^{w} = \frac{J_{\mathrm{cr}}^{b}}{w}$
$\sigma_{\mathrm{ISO}}^{w}$	ISO fracture strength index, in newton metres per kilogram; $\sigma_{\mathrm{ISO}}^{w} = \frac{\sigma_{\mathrm{ISO}}^{b}}{w}$

10 Report

The test report shall include the following information:

a) a reference to this Technical Specification (i.e. ISO/DTS 17958:2013);

b) the date and place of testing;

c) the full identification of the material tested;

d) the direction of test (machine direction or cross-machine direction), or random direction for laboratory sheets;

e) the conditioning atmosphere used;

f) if required, the conditioned grammage, *w*, of the material;

g) the determined tensile stiffness, E^b;

h) the determined nonlinear material parameters, N, and E_0^b;

i) the apparent tensile strength and apparent strain at break for the fracture toughness test pieces determined according to ISO 1924-3 (see 9.3);

j) the fracture toughness, J_{cr}^b, (see 9.3) and fracture toughness uncertainty (see Annex A);

k) the ISO fracture strength, σ_{ISO}^b, and ISO fracture strength uncertainty (see Annex A);

l) the ISO fracture strain, ε_{ISO}, (see 9.4) and ISO fracture strain uncertainty (see Annex A);

m) if required, indexed properties according to Table 4;

n) the number of un-notched test pieces;

o) the number of notched test pieces;

p) any departure from the standard procedure and any other circumstances that may have affected the result.

Annex A
(normative)

Uncertainty determination

A.1 General

The ISO fracture strength and ISO fracture strain are calculated by intricate mathematical relations. Scientifically accurate estimates of the statistical variation of these predicted parameters based on the statistical variation of the experimentally determined material parameters from the tensile testing and fracture toughness testing tend to become highly complex.

A simplified approach for the estimations of the confidence limits for ISO fracture strength and ISO fracture strain, based on the coefficient of variation for the apparent tensile strength and the apparent strain at break, is therefore proposed. The number of test pieces, *n*, for the apparent tensile strength is used.

Table A.1 — Nomenclature for precision

n	number of test pieces
s_x	standard error
t	*t* factor, see statistical tables. $t \approx 2{,}2$ when ten test pieces are used (see statistical tables)
σ_{cr}^{b}	apparent tensile strength
$s(\sigma_{\text{cr}}^{b})$	estimated standard deviation for the apparent tensile strength
$C_{\text{V}}(\sigma_{\text{cr}}^{b})$	coefficient of variation for the apparent tensile strength
ε_{cr}	apparent strain at break
$s(\varepsilon_{\text{cr}})$	estimated standard deviation for the apparent strain at break
$C_{\text{V}}(\varepsilon_{\text{cr}})$	coefficient of variation for the apparent strain at break
σ_{ISO}^{b}	ISO fracture strength
$s(\sigma_{\text{ISO}}^{b})$	estimated standard deviation for the ISO fracture strength
$C_{\text{V}}(\sigma_{\text{ISO}}^{b})$	coefficient of variation for the ISO fracture strength
ε_{ISO}	ISO fracture strain
$s(\varepsilon_{\text{ISO}})$	estimated standard deviation for the ISO fracture strain
$C_{\text{V}}(\varepsilon_{\text{ISO}})$	coefficient of variation for the ISO fracture strain

A.2 Fracture toughness statistics

The confidence limits for the apparent tensile strength are

$$\left[\sigma_{\mathrm{cr}}^{b} - t\, s_x , \sigma_{\mathrm{cr0}}^{b} + t\, s_x\right] \tag{A.1}$$

where the standard error is

$$s_x = \sqrt{\frac{s(\sigma_{\mathrm{cr}}^{b})^2}{n}} \tag{A.2}$$

where

$$s(\sigma_{\mathrm{cr}}^{b}) = C_{\mathrm{V}}(\sigma_{\mathrm{cr}}^{b}) \times \sigma_{\mathrm{cr}}^{b}$$

The confidence limits for the fracture toughness are determined by inserting the lower and upper confidence limits, respectively [Formula (A.1)], into the fracture toughness calculation procedure in Formulae (4) to (7).

A.3 ISO fracture strength statistics

By definition,

$$C_{\mathrm{V}}(\sigma_{\mathrm{ISO}}^{b}) = \frac{s(\sigma_{\mathrm{ISO}}^{b})}{\sigma_{\mathrm{ISO}}^{b}} \tag{A.3}$$

$$C_{\mathrm{V}}(\sigma_{\mathrm{cr}}^{b}) = \frac{s(\sigma_{\mathrm{cr}}^{b})}{\sigma_{\mathrm{cr}}^{b}} \tag{A.4}$$

We assume that

$$C_{\mathrm{V}}(\sigma_{\mathrm{cr}}^{b}) = C_{\mathrm{V}}(\sigma_{\mathrm{ISO}}^{b}) \tag{A.5}$$

which means that

$$s(\sigma_{\mathrm{ISO}}^{b}) = \sigma_{\mathrm{ISO}}^{b} \times C_{\mathrm{V}}(\sigma_{\mathrm{cr}}^{b}) \tag{A.6}$$

Calculate the confidence limits by simple statistics.

$$\left[\sigma_{\mathrm{ISO}}^{b} - t\, s_x , \sigma_{\mathrm{ISO}}^{b} + t\, s_x\right] \tag{A.7}$$

where the standard error is

$$s_x = \sqrt{\frac{s(\sigma_{\mathrm{ISO}}^{b})^2}{n}} \tag{A.8}$$

A.4 ISO fracture strain statistics

By definition,

$$C_{\mathrm{V}}(\varepsilon_{\mathrm{ISO}}) = \frac{s(\varepsilon_{\mathrm{ISO}})}{\varepsilon_{\mathrm{ISO}}} \tag{A.9}$$

$$C_V(\varepsilon_{cr}) = \frac{s(\varepsilon_{cr})}{\varepsilon_{cr}} \tag{A.10}$$

We assume that

$$C_V(\varepsilon_{cr}) = C_V(\varepsilon_{ISO}) \tag{A.11}$$

which means that

$$s(\varepsilon_{ISO}) = \varepsilon_{ISO} \times C_V(\varepsilon_{cr}) \tag{A.12}$$

Calculate the confidence limits by simple statistics.

$$\left[\varepsilon_{ISO} - t\, s_x, \varepsilon_{ISO} + t\, s_x\right] \tag{A.13}$$

where the standard error is

$$s_x = \sqrt{\frac{s(\varepsilon_{ISO})^2}{n}} \tag{A.14}$$

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