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Papers and boards

Fracture toughness

Constant rate of elongation method (1,7 mm/s)

0 Introduction

The fracture toughness may be important for the prediction of web breaks in the re-winder, in a printing press or in other situations where in-plane fracture occurs during the manufacture and converting of different paper products.

This SCAN-test Method describes one possible measuring and calculation procedure for determining the fracture toughness. The measuring procedure consists of two parts; the tensile testing procedure and the fracture toughness testing procedure. In the two procedures, the test span length is 100 mm and the rate of elongation is 1,7 mm/s.

The recommended test piece width is 15 mm in the tensile testing procedure and 50 mm, with a 20 mm notch in the centre of the test piece, in the fracture toughness testing procedure.

The procedure takes advantage of the high testing rate and the high calculation capacity of modern computerised tensile testing machines.

Note − This method is based on ISO 1924-3, which is an alternative method to ISO 1924-2 (EN ISO 1924-2) for the determination of tensile properties. ISO 1924-3 differs from ISO 1924-2 in the following respects:

The tensile stiffness and tensile stiffness index are included.

The test span length, i.e. the distance between the clamping lines, has been changed from 180 mm to 100 mm, irrespective of the kind of sample to be tested.

The rate of elongation has been increased in order to reduce the testing time and make it possible to test a larger number of samples within a given time period.

The calculation procedure is complicated and must be computerized (5.3). From the tensile test data, a relationship between *J*-integral value and elongation is established. The critical elongation is evaluated from the fracture toughness test data. From a knowledge of the critical elongation, the critical *J*-integral value, which is the fracture toughness, is evaluated.

1 Scope

This SCAN-test Method specifies a method for measuring the fracture toughness of papers and boards, using a tensile testing machine operating with a constant rate of elongation.

The Standard is applicable to all kinds of paper and board but not for low density papers, such as crepe paper, or for corrugated fibreboard.

The theoretical derivation for the calculation of fracture toughness is described in the Annex.

2 References

ISO 187	Paper, board and pulps – Standard atmosphere for conditioning and testing and procedure for monitoring the atmosphere and conditioning of samples (EN 20187)
ISO 536	Paper and board – Determination of grammage (EN ISO 536)
SCAN-P 9	Papers and board – Identification of machine and cross direction
ISO 1924-3	Papers and board – Determination of tensile properties – Constant rate of elongation method (100 mm/min) (SCAN-P 67)

Note – SCAN-test has withdrawn a number of test methods and refers instead to the corresponding ISO and/or EN Standards.

3 Definitions

For the purpose of this Method, the following definitions apply:

3.1 *Fracture toughness,* J^b_{Ic} – The incremental work done per notch-length growth, in a test piece containing a notch, when the test piece is strained to a critical elongation.

3.2 *Fracture toughness index,* J^w_{Ic} – The fracture toughness divided by grammage.

3.3 *Elongation,* δ – The increase in length of a test piece.

3.4 *Critical elongation,* δ_c – The elongation at the maximum force.

Note – The definitions of the terms used in the tensile test are given in ISO 1924-3.

4 Principle

From the tensile test data, obtained from un-notched test pieces in accordance with ISO 1924-3, a *J*-integral versus elongation curve is constructed for a notched test piece of a given size.

Note – The tensile curves in both machine direction (MD) and cross direction (CD) are needed to obtain the *J*-integral versus elongation curve in any of the two directions.

A notched test piece is strained to break and the critical elongation is determined. The fracture toughness is defined as the *J*-integral value at the mean critical elongation, *Figure 1*.

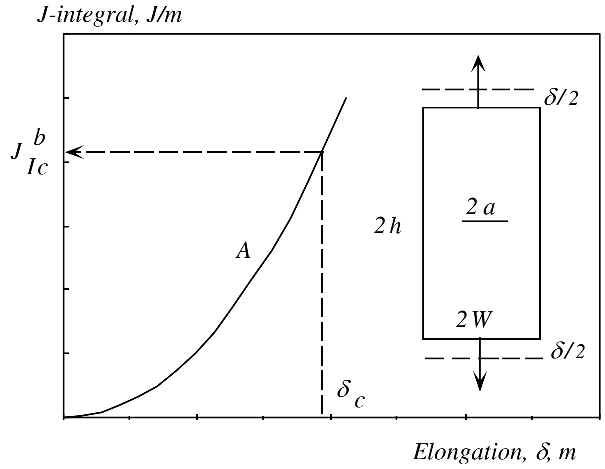

Figure 1. From tensile test data, a J-integral-elongation curve (A) is constructed.

The mean critical elongation (δ_C) determines the critical J-integral value, which is the fracture toughness.

5 Apparatus

5.1 *Tensile testing machine,* as described in ISO 1924-3. The width of the two clamps shall be easy to change between 15 mm and 50 mm.

Note – Building blocks can be used instead of changing the clamps. In that case, only the clamps with a width of 50 mm are needed, and two building blocks are used to centre the 15 mm wide test pieces during the tensile test. To be able to centre the test piece, each building block shall have a width of 17,5 mm.

5.2 *Anti-buckling guide,* made for instance of steel or of aluminium, to keep the notched test pieces flat during the test. The guide shall have two parallel, flat and smooth surfaces with a low friction, and cover a length of 30 mm and the total width in the centre of the test piece. Before the fracture toughness test, the smooth surfaces shall be brought into contact with the test piece with a force of (0,6 ± 0,2) N. The distance shall then be locked and kept locked during the test.

5.3 *Computer,* means for numerical calculation of the fracture toughness in accordance with the equations given in the Annex.

5.4 *Device for cutting the test pieces,* with test piece widths of 15 mm and 50 mm.

5.5 *Device for making a notch* in each 50 mm wide test piece. The notch in each test piece can be made by means of a sharp blade, preferably mounted in a punch press.

The notch shall be (20 ± 0,1) mm and placed in the centre of the test piece, perpendicular to the long edge of the test piece, see *Figure 1.*

6 Calibration and adjustment of apparatus

The apparatus shall be calibrated according to instructions given by the manufacturer of the testing apparatus. The test span and the rate of separation of the clamps shall be calibrated according to ISO 1924-3.

Check that the antibuckling guide (5.2) is loading the test piece with a force of (0,6 ± 0,2) N by using a known weight or a force measurement instrument. If necessary adjust the loading force.

7 Sampling and preparation of test pieces

7.1 *Sampling.* The sampling procedure is not covered by this Method.

7.2 *Conditioning.* Condition the samples as specified in ISO 187. If the fracture toughness index is to be calculated, determine the grammage of the samples as described in ISO 536.

> *Note 1* – This test, like other mechanical tests, is very sensitive to changes in the moisture content of the test piece. Handle the test pieces carefully and never touch with the bare hand the part of the test piece to be placed between the clamps. Keep the test piece away from moisture, heat and other influences that may change its moisture content.

7.3 *Preparation of test pieces for the tensile testing.* The preparation of test pieces for the tensile test is described in ISO 1924-3.

7.4 *Preparation of test pieces for the fracture toughness testing*. Test pieces for the fracture toughness test are prepared in the same way as for the tensile test. However, the test piece width for the fracture toughness test is (50,0 ± 0,1) mm.

Cut a sufficient number of test pieces to enable at least 20 tests to be made in both the MD and in the CD .

Make a notch in each test piece with a notch-length of (20 ± 1) mm by using the device for making a notch (5.5).

> *Note 2* – Several test pieces can be cut simultaneously provided the test pieces formed fulfil the requirements specified above and that the test pieces formed give the same results as test pieces cut singly.

8 Procedure and evaluation of results

8.1 *Tensile test.* The purpose of the tensile test is to construct a representative mean force-elongation curve for the MD and CD, from which the material parameters can be calculated.

For the tensile test, follow the instructions given in ISO 1924-3. The test piece width is 15 mm.

Evaluate the nominal elongation, the nominal force and the maximum slope from the test data obtained as follows:

Figure 2 shows the principle for calculating properties from the tensile test. The figure illustrates how individual curves which are not representative for the material properties of the sample are deleted before the construction of the mean curve. Four curves are shown to illustrate the principle.

All calculations are to be made from zero elongation of each curve, i.e. the point where the tangent of the curve, with a slope equal to the maximum slope of the curve, intersects the elongation axis.

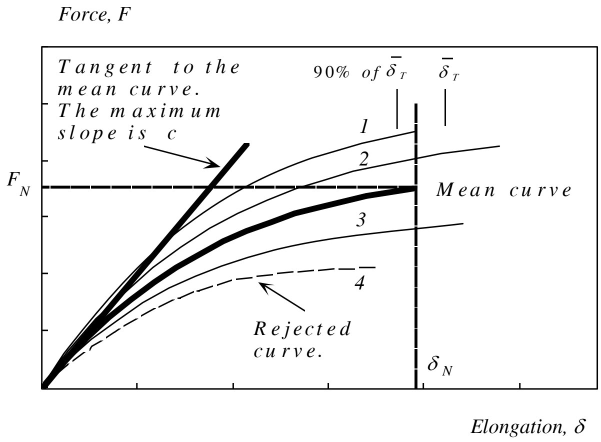

Figure 2. Principle for calculating properties from the tensile test.

δ_N *is the nominal elongation;*
c *is the maximum slope;*
F_N *is the nominal force;*
$\bar{\delta}_T$ *is the mean elongation at break.*

Calculate the mean elongation at break, $\bar{\delta}_T$.

Delete those tensile curves which have an elongation at break less then 90 % of the mean elongation at break (Curve 4 in *Figure 2*). Determine the smallest elongation of the remaining curves. The smallest elongation is named the nominal elongation, δ_N , (Curve 1 in *Figure 2*).

Determine the mean force versus elongation curve by means of the remaining curves (by calculating the mean force at each elongation increment up to the nominal elongation).

Determine the nominal force, F_N , of the mean curve as the force at the nominal elongation.

Determine the maximum slope, *c*, of the mean curve preferably by linear regression analysis over a number of force-elongation values. The elongation increment shall then be 0,1 mm and the linear regression shall contain at least 10 force-elongation values.

8.2 *Fracture toughness.* Make sure that the anti-buckling guide (5.2) is in function. Ensure that the test piece does not bend when it passes over the two anti-buckling guide surfaces.

Perform the fracture toughness test using the notched test pieces prepared as described in 7.4 and *Figure 1*. Test at least 20 test pieces in the MD and 20 in the CD.

9 Calculation

The calculation procedure to obtain the parameters must be computerized. The theoretical derivation for the calculation of fracture toughness is described in the Annex.

For paper and board, calculate the results separately for the MD and CD .

In order to specify the kind of result reported, the suffixes MD and CD shall be used to express MD and CD respectively. As an example $J^w_{Ic,MD}$ is used for fracture toughness index in the MD, $J^w_{Ic,CD}$ is used for fracture toughness index in the CD.

9.1 Tensile testing

Tensile data are needed for the evaluation of fracture toughness. To enable strength calculations by means of fracture toughness results, report tensile stiffness according to ISO 1924-3 and parameters p and Φ according to equations [A3] and [A8].

9.2 Fracture toughness

The fracture toughness, J^b_{Ic} , is obtained from the equation:

$$J^b_{Ic} = \frac{(\bar{\beta})^2 \cdot E^b_2}{h(1-\nu_{12}\nu_{21})} f_1 + \frac{2p \cdot h}{p+1} \Phi \cdot \sigma^b_0 (\varepsilon_0)^p \left(\frac{\bar{\beta}}{\varepsilon_0 \cdot h} \right)^{p+1} f_2 \qquad [1]$$

where

J^b_{Ic} is the fracture toughness, in joule per metre.

The other symbols are described in the Annex.

9.3 Fracture toughness index

Calculate the fracture toughness index, J^w_{Ic}, from the following equation:

$$J^w_{Ic} = \frac{1000 \cdot J^b_{Ic}}{w} \qquad [2]$$

where

J^w_{Ic} is the fracture toughness index, in joulesmetres per kilogram;
w is the grammage, in grams per square metre.

10 Report

The test report shall include reference to this SCAN-test Method and the following particulars:

(a) date and place of testing;
(b) identification mark of the material tested;
(c) the direction of the test;
(d) the test results;
(e) the coefficient of variation of the results;
(f) any departure from the procedure described in this SCAN-test Method and any other circumstances that may have affected the result.

11 Precision

11.1 Repeatability

Results from repeated measurements carried out at seven laboratories, under normal laboratory conditions using test pieces from the same gross sample, have a mean coefficient of variation within labs for fracture toughness index as follows:

Paper grade	Grammage, g/m^2	Direction	Mean fracture toughness index, Jm/kg	Mean coeff of variation, % *
Kraft liner	200	MD	14,5	9
		CD	10,7	16
Newsprint	45	MD	6,1	12
		CD	4,5	20
Copy paper	80	MD	10,9	10
		CD	7,9	14

* The laboratories received a diskette containing the program for calculating the coefficient of variation of the fracture toughness.

11.2 Reproducibility

Seven laboratories tested the same paper and boards. The reproducibility, expressed as coefficient of variation between labs, for fracture toughness index was as follows:

Paper grade	Grammage, g/m^2	Direction	Fracture toughness index, Jm/kg	Coeff of variation, %
Kraft liner	200	MD	14,5	8
		CD	10,7	4
Newsprint	45	MD	6,1	6
		CD	4,5	16
Copy paper	80	MD	10,9	7
		CD	7,9	11

12 Literature

12.1 Wellmar, P., Fellers, C., Nilsson, F., and Delhage, L. Crack tip characterization in paper (Accepted for publication in Journal of Pulp and Paper Science.)

Annex – Symbols and calculation procedure

A.1 Symbols used in the calculations

A.1.1 Un-notched test pieces

δ	is the elongation, in metres;
δ_N	is the nominal elongation, in metres;
$\bar{\delta}_T$	is the mean elongation at break, in metres;
F	is the force, in newtons;
F_N	is the nominal force, in newtons;
c	is the maximum slope of the mean force versus elongation curve, in newtons per metre;
U	is the area under the mean force versus elongation curve, in newtonmetres;
k	is a material parameter;
p	is a material parameter;
$A(E)$	is the anisotropy in tensile stiffness;
E^b_{MD}	is the tensile stiffness in MD, in newtons per metre (ISO 1924-3);
E^b_{CD}	is the tensile stiffness in CD, in newtons per metre (ISO 1924-3);
α	is a material parameter;
α_{MD}	is a material parameter in MD;
α_{CD}	is a material parameter in CD;
l	is the test span length, in metres;
Φ	is a material parameter;
f_1	is a dimensionless function;
f_2	is a dimensionless function;
E^b_1	is the tensile stiffness perpendicular to the loading direction, in newtons per metre (ISO 1924-3);
E^b_2	is the tensile stiffness in the loading direction, in newtons per metre (ISO 1924-3).

A.1.2 Notched test pieces

$2W$	is the width, in metres;
$2h$	is the test span length, in metres;
$2a$	is the notch length, in metres;
δ_c	is the critical elongation, in metres;
δ_o	is the zero elongation, in metres;
$\nu_{12}\nu_{21} = (0{,}293)^2$	is the product of the Poisson´s ratios in MD and CD;
σ^b_c	is the critical stress, in newtons per metre;
β	is a parameter, in metres;
$\bar{\beta}$	is the mean value of the parameter β, in metres;
σ^b_0	is the reference stress, in newtons per metres;
ε_0	is the reference strain, in metres per metre;
J^b_{Ic}	is the fracture toughness, in joules per metre;
J^w_{Ic}	is the fracture toughness index, in joulemetres per kilogram;
V_J	is the variance in fracture toughness, in (joule per metre)^2;
V_β	is the variance of the parameter β, in square metres;
CV_J	is the coefficient of variation of the fracture toughness, as a percentage;
w	is the grammage, in grams per square metre.

The calculation and the evaluation procedures are complicated and must be computerized. The above symbols are used in the theoretical derivation for calculation of the fracture toughness.

A.2 Calculation procedure

A.2.1 Work of elongation

Calculate by numerical integration, for the mean force versus elongation curve, the area U under the curve from zero elongation up to the nominal elongation, δ_N, *Figure 2* and equation [A1]:

$$U = \int_0^{\delta_N} F(\delta)d\delta \qquad [A1]$$

A.2.2 Material parameters

Fit the mean force versus elongation curve from zero elongation up to the nominal elongation to equation [A2] by calculating the material parameters p and k from equations [A3] and [A4]:

$$\delta = \frac{F}{c} + k\left(\frac{F}{c}\right)^p \qquad [A2]$$

$$p = \frac{F_N\left(\frac{F_N}{c} - \delta_N\right)}{U - F_N\delta_N + \frac{F_N^2}{2c}} - 1 \qquad [A3]$$

$$k = \frac{\delta_N - \frac{F_N}{c}}{\left(\frac{F_N}{c}\right)^p} \qquad [A4]$$

A.2.3 Anisotropy, parameters and functions in MD and CD

Calculate the anisotropy in tensile stiffness, *A(E)*, from the following equation:

$$A(E) = \frac{E^b_{MD}}{E^b_{CD}} \qquad [A5]$$

Calculate the following material parameters:

When the test direction is MD, use the following equation:

$$\alpha_{MD} = 0{,}293\sqrt{\frac{1}{A(E)}} \qquad [A6]$$

When the test direction is CD, use the following equation:

$$\alpha_{CD} = 0{,}293\sqrt{A(E)} \qquad [A7]$$

Calculate the material parameter Φ in MD and CD according to the following equation:

When MD is the test direction, use $\alpha = \alpha_{MD}$
When CD is the test direction, use $\alpha = \alpha_{CD}$

$$\Phi = \frac{k \cdot l^{p-1} \cdot (2-\alpha)(\alpha^2 - \alpha + 1)^{\frac{p-1}{2}}}{2 \cdot 0{,}914^p} \qquad [A8]$$

Calculate the dimensionless functions f_1 and f_2 according to the following equations:

$$f_1 = 0{,}5617\left(\frac{E_1^b}{E_2^b}\right)^{-0{,}19} \qquad [A9]$$

$$f_2 = 0{,}5 + 0{,}512\, tanh(0{,}206\, p) \qquad [A10]$$

> *Note* – The functions f_1 and f_2 have been determined by using finite element analysis and apply only to this test piece geometry. For other geometries, new calculations have to be made.

A.2.4 Fracture toughness

Record the force-elongation curve for each test piece, *Figure 3*. Determine the zero elongation, δ_0, i.e. the point where the tangent of the curve, with a slope equal to the maximum slope of the curve, intersects the elongation axis. Determine for each test piece the critical elongation.

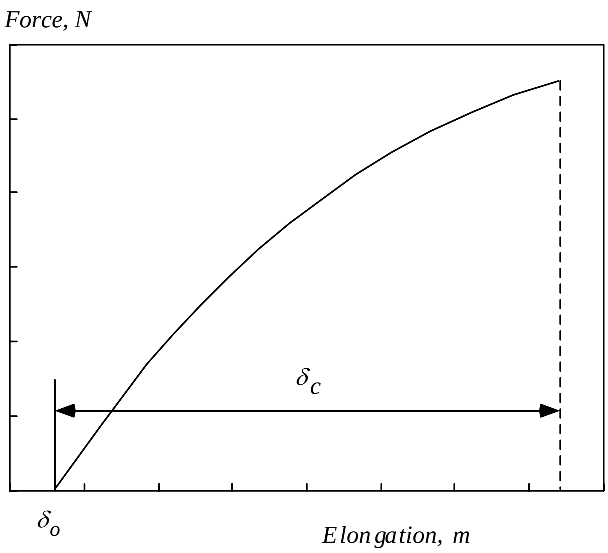

Figure 3. Force-elongation curve for a fracture toughness test piece.

δ_o *is the zero elongation;*
δ_c *is the critical elongation.*

Determine for each test piece, the critical stress, σ_c^b, by numerical inversion of the following equation:

$$\frac{\delta_c}{2} = \frac{1-\nu_{12}\nu_{21}}{E_2^b}\sigma_c^b \cdot h + \Phi \cdot h\left(\frac{1-\nu_{12}\nu_{21}}{E_2^b}\sigma_c^b\right)^p \quad \text{[A11]}$$

Calculate for each test piece the parameter, *β*, from the following equation:

$$\beta = \frac{h(1-\nu_{12}\nu_{21})}{E_2^b}\sigma_c^b \quad \text{[A12]}$$

Calculate the mean value, $\bar{\beta}$, of the parameter *β*.

Calculate the reference stress, σ_0^b, from the following equation:

$$\sigma_0^b = \varepsilon_0 \frac{E_2^b}{(1-\nu_{12}\nu_{21})} \quad \text{[A13]}$$

Note – For papers, the reference strain, ε_0, is set to be 0,003, a value that is not critical for to the calculated fracture toughness.

Finally, calculate the fracture toughness, J_{Ic}^b, from the following equation:

$$J_{Ic}^b = \frac{(\bar{\beta})^2 \cdot E_2^b}{h(1-\nu_{12}\nu_{21})} f_1 + \frac{2p \cdot h}{p+1}\Phi \cdot \sigma_0^b(\varepsilon_0)^p\left(\frac{\bar{\beta}}{\varepsilon_0 \cdot h}\right)^{p+1} f_2 \quad \text{[A14]}$$

A.2.5 Error estimation

The error in the fracture toughness value consists of two factors, the error in the mean force versus elongation curve and the error in the critical elongation. Assuming that the error in this curve is negligible, the error in the fracture toughness is estimated in the following way:

Calculate the variance, V_β, and mean value, $\bar{\beta}$, of the parameter *β*.

Estimate the variance of the fracture toughness from the following equation:

$$V_J = 4\left(\frac{\bar{\beta} \cdot E_2^b}{h(1-\nu_{12}\nu_{21})} f_1 + \frac{p \cdot h}{\bar{\beta}}\Phi \cdot \sigma_0^b(\varepsilon_0)^p\left(\frac{\bar{\beta}}{\varepsilon_0 \cdot h}\right)^{p+1} f_2\right)^2 V_\beta \quad \text{[A15]}$$

Calculate the coefficient of variation, CV_J, of the fracture toughness, as a percentage, from the equation:

$$CV_J = 100 \cdot \frac{\sqrt{V_J}}{J_{Ic}} \quad \text{[A16]}$$

Method

SCAN-test Methods are issued and recommended by KCL, PFI and STFI-Packforsk for the pulp, paper and board industries in Finland, Norway and Sweden.
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