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Fibre-reinforced composites — Measurement of interfacial shear strength by means of a micromechanical single-fibre pull-out test

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Foreword

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This document was prepared by Technical Committee ISO/TC 61, *Plastics*, Subcommittee SC 13, *Composites and reinforcement fibres*.

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.

Introduction

Fibre-reinforced composites have become an indispensable part of modern high-tech applications due to the excellent tensile properties of the reinforcement fibres incorporated in the composite. This requires that the loads in a composite need to be distributed evenly to all fibres by means of a matrix. Therefore, a high interfacial shear strength is required for a good load transfer. Hence, the interfacial shear strength is one of the key parameters in composite technology.

To characterize the interfacial shear strength, composites with unidirectional aligned fibres are manufactured. A tensile test is then performed perpendicular to the fibre orientation (transverse tensile test), or a short beam shear strength test (as defined for instance in ISO 14130 or ASTM D2344) is performed to measure the apparent interlaminary shear strength (ILSS).

However, the maximum stress found in such macromechanical tests does not only depend on the fibre-matrix adhesion strength, it is also governed by the following additional factors: the fibre content, orientation, length, diameter and fibre distribution homogeneity, the pore void of the test specimens, and the mechanical properties of the fibre and the matrix. To achieve repeatable results for the fibre-matrix adhesion strength through macromechanical tests, it is necessary to keep a rigid control of the manufacturing process of the specimen, making the overall testing procedure laborious and difficult to compare across laboratories.

Micromechanical testing techniques have several advantages over the macromechanical methods. By involving only single fibres in the test, most dependencies on the manufacturing process of the test specimen listed above are avoided. Whereas macroscopic methods can only determine the apparent interfacial shear strength, the single-fibre pull-out test as a micromechanical test method also can determine the local interfacial shear strength, the interfacial frictional stress, and the critical interfacial energy release rate. Here, the local interfacial shear strength is essential for composites applications with cyclic load, since it characterizes to which stress a composite can be loaded before the interface between fibre and matrix is damaged. The critical interfacial energy release rate and the interfacial frictional stress have a strong impact on the energy absorption of composites, which is important in crash situations as for example in mobility applications.

This document describes stringent methods for specimen preparation, conditioning, and pull-out testing. Practical trials have shown that following these procedures leads to minimum variability in the test results.

Fibre-reinforced composites — Measurement of interfacial shear strength by means of a micromechanical single-fibre pull-out test

1 Scope

This document specifies a test method for determining the interfacial shear strength between a single fibre and a matrix by means of a pull-out test. The method can be used to measure the critical energy release rate.

The method is applicable to reinforcement fibres, such as carbon fibres, glass fibres, basalt fibres and similar stiff reinforcement fibres and to thermoset, thermoplastic and fine-grained concrete matrices. It can be used for polymeric reinforcement fibres and for other inorganic matrices.

It is not applicable to:

a) elastomeric fibres and elastomeric matrices such as rubber;

b) matrices which cure or melt at temperatures above 400 °C;

c) matrices that show a strong tendency to bubble formation or expansion during the sample-preparation process;

d) foams.

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 1973, *Textile fibres — Determination of linear density — Gravimetric method and vibroscope method*

ISO 2602, *Statistical interpretation of test results — Estimation of the mean — Confidence interval*

EN 12390-2, *Testing hardened concrete — Part 2: Making and curing specimens for strength tests*

3 Terms and definitions

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

ISO and IEC maintain terminology 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
constant-rate-of-extension testing machine
CRE testing machine
tensile testing machine provided with one specimen holder, which is stationary, and one clamp, which moves with a constant speed throughout the test, the entire testing system being virtually free from deflection

[SOURCE: ISO 5079:2020, 3.10, modified — “clamp” was replaced with “specimen holder“.]

3.2
crucible
receptacle, made of aluminium or stainless steel, to hold a drop of matrix into which one single fibre is embedded

3.3
pull-out test
method of pulling out one single embedded fibre from a solidified drop of matrix, carried out with a *CRE testing machine* (3.1)

3.4
force-displacement curve
graphical representation of the force recorded during the *pull-out test* (3.3) over the displacement of the moving clamp of the *CRE testing machine* (3.1)

3.5
maximum force
highest force value taken from the *force-displacement curve* (3.4) appearing just before the complete debonding of the fibre from the solidified matrix during the pull-out

3.6
debonding force
force at which the fibre starts debonding from the solidified drop of matrix, derived from the *force-displacement curve* (3.4)

3.7
interfacial frictional force
force measured after complete debonding, caused by only the friction between the fibre and the solidified matrix, taken from the *force-displacement curve* (3.4)

3.8
embedding depth
selected depth to which the embedding device inserts the fibre into the matrix

3.9
embedded length
resulting length of the fibre in contact with the solidified matrix, corresponds to the displacement at which the fibre completely slips out of the solidified matrix, taken from the *force-displacement curve* (3.4)

3.10
final forming
process, in which the matrix maximizes the wetting of the fibre and the meniscus reaches a steady state

3.11
solidification
process of transformation of the matrix from liquid to solid

Note 1 to entry: The term solidification includes both the commonly used solidification of thermoplastics by cooling as well as the curing of thermosets and concrete matrices.

3.12
fixing
first step of the *solidification* (3.11) of matrices, after which a test specimen can be removed from the embedding device without the risk that the fibre redirects inside the matrix

3.13
curing
process of *solidification* (3.11) of thermoset and concrete matrices

3.14
apparent interfacial shear strength
maximum force (3.5) normalized to the contact area between the fibre and the solidified matrix

3.15
interfacial frictional stress
interfacial frictional force (3.7) normalized to the contact area between the fibre and the solidified matrix

3.16
local interfacial shear strength
debonding force (3.6) related to the contact area of the interface between the fibre and the solidified matrix, without the impact of the friction between the fibre and the matrix

3.17
critical interfacial energy release rate
interfacial toughness
calculated as a function of the crack length (energy-based method), taking the deformation of the fibre and matrix during the pull-out into account

4 Principle

A single fibre is embedded into a drop of matrix at a defined temperature to form a test specimen for the pull-out test by means of an embedding station. If required, the embedding can take place in an inert gas atmosphere. Embedding depth and speed are variable. After embedding, the test specimen is solidified, for instance by heating up to a curing temperature (for example for thermoset matrices) or cooling down to a suitable temperature for matrix solidification (for example for thermoplastic matrices).

After complete solidification and conditioning, the test specimen is transferred into a CRE testing machine for pull-out testing.

During the pull-out test, certain values are measured along the force-displacement curve respectively calculated from these measured values.

5 Abbreviated terms, symbols and dimensions

5.1 Symbols

Table 1 lists symbols used throughout this document.

Table 1 — Test characteristics, symbols, and dimensions

Characteristic	Matrix	Symbol	Unit
Material parameter			
Fibre density	—	ρ	g/cm^3
Fibre linear density	—	ρ_l	dtex
Fibre diameter	—	d_f	µm
Fibre breaking force	—	f_B	cN
Melting temperature	TP	T_M	°C
Solidification temperature	TP	T_S	°C
Testing procedure			
Heating rate to embedding temperature	TS, TP	r_{TE}	K/min
Time at embedding temperature	TS, TP	t_{TE}	s
Embedding temperature	TS, TP	T_E	°C
Embedding depth	TS, TP, C	l_{ED}	µm
Embedding speed	TS, TP, C	v_E	mm/min
Forming time	TS, TP, C	t_F	s

Table 1 *(continued)*

Characteristic	Matrix	Symbol	Unit
Curing temperature	TS, C	T_C	°C
Heating rate to curing temperature	TS, C	r_{TC}	K/min
Time at curing temperature	TS, C	t_{TC}	s
Below-solidification-temperature	TP	T_{BS}	°C
Cooling rate to below-solidification-temperature	TP	r_{TBS}	K/min
Final cooling rate	TS, TP	r_{TF}	K/min
Final withdrawal temperature	TS, TP	T_F	°C
Testing speed for pull-out test	All	V_P	mm/min
Evaluation			
Maximum force	All	F_{max}	cN
Debonding force	All	F_d	cN
Interfacial frictional force	All	F_b	cN
Embedded length	All	l_e	µm
Apparent interfacial shear strength	All	τ_{app}	MPa
Interfacial frictional stress	All	τ_f	MPa
Local interfacial shear strength	All	τ_d	MPa
Alternative local interfacial shear strength	All	$\tau_{d,alt}$	MPa
Shear-lag parameter	All	β	—
Residual thermal stresses	All	τ_T	MPa
Critical energy release rate	All	G_{ic}	J/m^2

5.2 Abbreviated terms

Table 2 lists abbreviated terms used throughout this document.

Table 2 — Materials and abbreviated terms

Material	Abbreviation
Fibres	
Carbon fibre	CF
Recycled carbon fibre	rCF
Glass fibre	GF
Natural fibre	NF
Matrices	
Thermoset	TS
Thermoplastic	TP
Concrete	Concrete
Polypropylene	PP
Polyamide 6	PA6
Polyether ether ketone	PEEK
Polyether block amide	PEBA
Polyurethane	PU

Table 2 *(continued)*

Material	Abbreviation
Polycarbonate	PC
Epoxy	EP
Vinylester	VE

6 Apparatus

6.1 Fibre diameter determination

6.1.1 General

The diameter of each individual fibre shall be determined close to the position where the fibre is embedded into the matrix. The following methods may be used for the determination of the individual fibre diameter.

NOTE For the sake of simplicity, all calculations within this document assume a circular fibre cross section.

6.1.2 Vibroscopic fibre linear density and diameter test

This method uses a device measuring the linear density according to the vibroscopic principle, which shall be in accordance with ISO 1973. Here, a fibre with a known pretension is excited to its fundamental resonance frequency at a known vibrating length.

For glass fibres, due to a possible impact of the bending stiffness to the resonance curve, a vibrating length of at least 50 mm and a pretension of 3 cN/tex are strongly recommended. For carbon fibres, a vibrating length of minimum 25 mm and a pretension of 1 cN/tex are commonly used.

Based on the selected pretension and vibrating length and on the measured resonance frequency, the linear density ρ_l is calculated following the vibrating string equation. Employing the known fibre density ρ (specified by the fibre producer), the fibre diameter d_f is calculated according to Formula (1):

$$d_f = 10 \cdot \sqrt{\frac{4 \cdot \rho_l}{\pi \cdot \rho}} \quad (1)$$

where

d_f is the fibre diameter, in micrometres (µm);

ρ_l is the fibre linear density, in decitex (dtex, g/1 000 m);

ρ is the fibre density, in gram per square centimetres (g/cm^3).

The determination of the fibre diameter is required to calculate the contact area between the fibre and the matrix.

6.1.3 Optical fibre diameter determination

This method uses an optical assembly to measure the individual fibre diameter directly. Possible principles are a laser-scan micrometre, a laser diffractometer, an optical microscope, or an appropriate device according to ISO 11567.

6.2 Embedding station

This method uses a device for producing test specimens for the pull-out test, by embedding a single fibre into a drop of matrix placed in a crucible. A single fibre with a minimum length of 5 mm is placed into a cannula, after insertion the fibre protrudes out of the cannula. The protruding end is embedded into the

matrix, embedding depth and speed are variable. During embedding and solidification, the fibre can be held with low tension in the cannula by means of a holding air flow such that it can follow a possible shrinkage of the matrix.

The device is equipped with a heating system for the crucible, allowing temperature changes at rates of 0,1 K/min to 99,9 K/min up to a maximum temperature of 400 °C. The heat transfer is given by the contact between the heating system and the bottom side of the crucible. The actual temperature at the top of the matrix might be lower than the displayed actual heater temperature, due to the geometry of the setup. Temperature, temperature rates and duration of heating (time at temperature) can be adjusted.

The device is equipped with an active cooling system which can be enabled, and which rate can be adjusted. The maximum cooling shall allow the device to cool down from 400 °C to 40 °C within 6,5 min (from 100 °C to 40 °C within 3,5 min).

The device is equipped with a triaxial linear table to allow positioning of the fibre relative to the matrix, and a microscope to observe and control the positioning. The fibre can be moved along its axis for embedding using an additional z-axis of the embedding device.

The device is equipped with a system to flush the embedding zone with an inert gas to avoid oxidation of the matrix.

6.3 CRE testing machine

This method uses a device for pull-out testing, equipped with an upper holder for the test specimen mounted to the force-measuring system, and a moveable lower draw-off clamp to pull the single fibre out of the matrix.

The device shall be equipped with a high-precision load cell with a minimum force range higher than the fibre breaking force to be tested and a resolution of 1 µN or better. The distance between the draw-off clamp and the upper specimen holder can be freely adjusted, the testing speed can be adjusted to values between 0,1 mm/min to 100 mm/min.

The draw-off clamp consists of one stationary and one moveable clamp jaw with adjustable clamping pressure. The surface of the clamp jaws in contact with the specimen shall be made of a material to provide correct grip without damaging the fibre, thereby avoiding slippage and jaw breaks.

A high-precision displacement measurement sensor with a resolution of 0,1 µm or better is required. The device is resistant against deformation under load, with a maximum deflection of 0,02 mm/N.

The lateral position of the draw-off clamp is adjustable to match the position of the fibre axis. In this way, the fibre is clamped at minimum shear force even at very low distances between matrix and clamp. Adjustment is carried out by means of a camera with microscopic optics.

During the pull-out test, the displacement of the draw-off clamp and the resulting force is recorded as a force-displacement curve.

7 Test specimen

The test specimen consists of a rotationally symmetric metallic crucible, a drop of a matrix placed into the upper recess of the crucible, and a fibre embedded into the matrix. Figure 1 shows the physical dimensions of the crucible that shall be used for the preparation of the test specimen.

Dimensions in millimetres

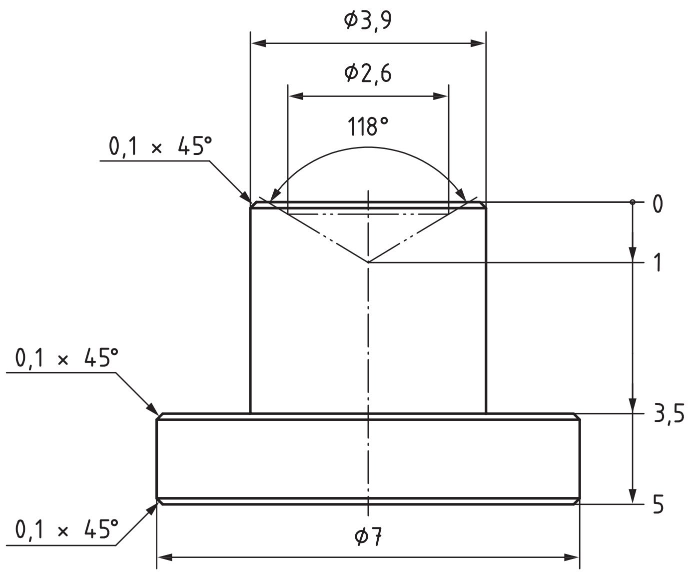
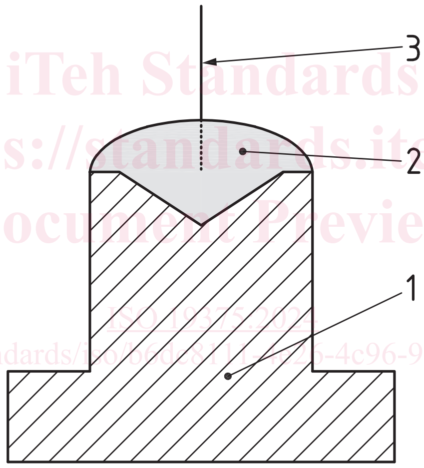


Figure 1 — Test specimen, crucible

Figure 2 shows a schematic lateral section through the test specimen.



Key

1 crucible with recess

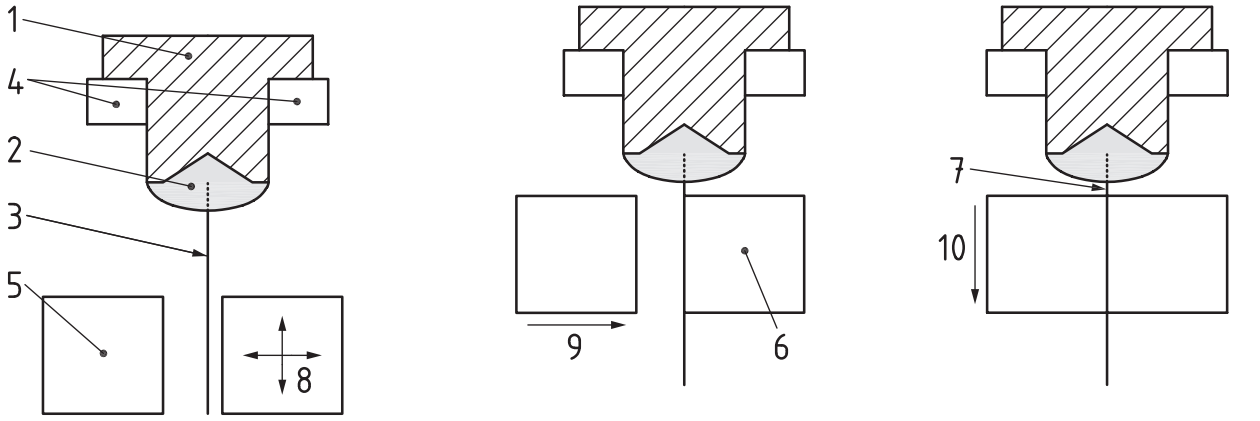
2 matrix drop

3 embedded fibre (dashed line = embedded section)

Figure 2 — Test specimen, lateral section

An appropriate embedding device to create the test specimen is described in 6.2.

After the test specimen has been produced and solidified, it is transferred to the CRE testing machine. Figure 3 shows schematic lateral sections through the test specimen, mounted into the upper test specimen holder and the lower draw-off clamp of the CRE testing machine, described in 6.3.



a) Draw-off clamp adjustment **b) Draw-off clamp open** **c) Draw-off clamp closed**

Key

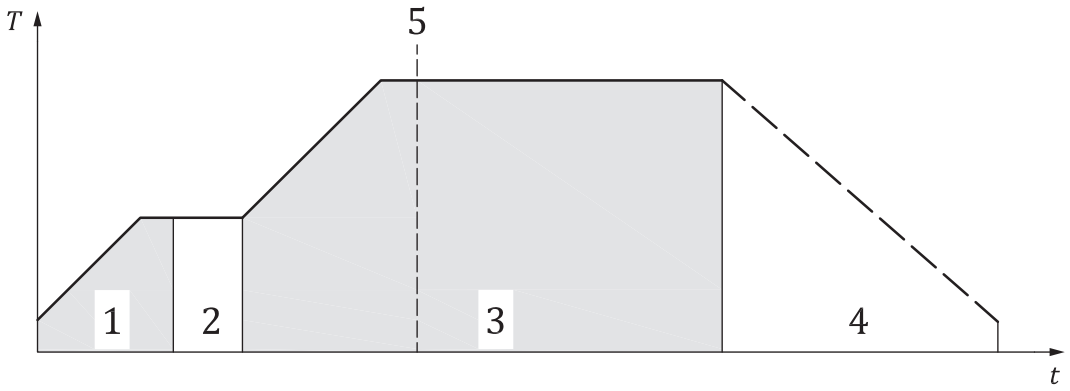
1	crucible with recess	6	stationary jaw of draw-off clamp
2	matrix drop	7	free fibre length
3	embedded fibre (dashed line = embedded section)	8	lateral + vertical adjustment
4	test specimen holder = measuring clamp	9	closing direction of movable clamp jaw
5	movable jaw of draw-off clamp	10	draw-off direction

Figure 3 — Test specimen in CRE testing machine, lateral section

8 Procedure

8.1 Overview

Fibre embedding and matrix solidification are carried out using complex temperature profiles, described in 8.2 to 8.10. Figure 4 and Figure 5 schematically illustrate those temperature profiles for thermoset respectively thermoplastic matrices.



Key

T temperature

t time

1 heating to and holding embedding temperature for degassing (heating rate to embedding temperature, time at embedding temperature, embedding temperature)

2 positioning, embedding and final forming (embedding temperature, forming time)