
**Tensile tests for discontinuously reinforced
metal matrix composites at ambient
temperatures**

*Essais de traction pour composites à matrice renforcée de manière
discontinue de métal à températures ambiantes*

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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 standardisation.

To respond to the need for global collaboration on standardization questions at early stages of technological innovation, the ISO Council, following recommendations of the ISO/IEC Presidents' Advisory Board on Technological Trends, decided to establish a new series of ISO publications named **"Technology Trends Assessments" (ISO/TTA)**. These publications are the results of either direct cooperation with prestandardization organizations or ad hoc workshops of experts concerned with standardization needs and trends in emerging fields.

Technology Trends Assessments are thus the result of prestandardization work or research. As a condition of publication by ISO, ISO/TTAs shall not conflict with existing International Standards or draft International Standards (DIS), but shall contain information that would normally form the basis of standardization. ISO has decided to publish such documents to promote the harmonization of the objectives of ongoing prestandardization work with those of new initiatives in the Research and Development environment. It is intended that these publications will contribute towards rationalization of technological choice prior to market entry.

This Technology Trends Assessment, ISO/TTA 2, has been developed by the Versailles Project on Advanced Materials and Standards (VAMAS) and is published under a Memorandum of Understanding concluded between ISO and VAMAS. It reports the results of the Technical Working Area (TWA) 15 of VAMAS, which has the task of investigating mechanical test methods for metal matrix composites and which retains the responsibility for the technical content of this ISO/TTA. Users of this ISO/TTA who would like information on the research project should refer to a recent report of VAMAS TWA 15 which was prepared by Dr B Roebuck, Dr L N McCartney and Dr J D Lord of the NPL under the leadership of Dr Steve J Johnson at Georgia Tech., Atlanta, USA. The ISO Technical Board approved the publication of this classification as an ISO/TTA in late 1995.

Whilst ISO/TTAs are not standards, it is hoped that they will be used as a basis for standards development in future national and international standardization processes. In the particular case of ISO/TTA 2, the publication has been brought, in the first instance, to the attention of ECISS/TC1, Tensile Testing Standards, for use in its standardisation work.

EXECUTIVE SUMMARY

There is a need for a tensile testing standard for discontinuously reinforced metal matrix composites (MMC). Use of the current ISO standard for metals EN 10002 leads to unsatisfactory uncertainties in the property values measured, particularly for Young's modulus and proportional limit. The measurement of Young's modulus in MMC is important for several reasons:

- a) Improvements in specific stiffness are an important driver in increasing the use of MMC over conventional materials. An accurate knowledge of the engineering value of Young's modulus is vital for preliminary design studies.
- b) Proof stress measurements require a prior knowledge of the Young's modulus. If the material of interest has a high work hardening rate in the early stage of yield then inaccuracies in the Young's modulus can lead to significant inaccuracies in proof stress.
- c) MMC have low proportional limits because of internal residual stresses. It is important to be able to measure the proportional limit accurately and to assess the extent of yield at low strains. An accurate value of Young's modulus is required to obtain reliable values for the proportional limit.
- d) Accurate measurements of Young's modulus are required to give good fits to the constitutive expressions for the stress/strain data.

Following analysis of the results of a UK exercise to examine the sources of uncertainty in the measurement of the tensile properties of SiC particulate reinforced Al alloys a draft procedure was written for tensile tests on particulate MMC at ambient temperatures. The draft procedure recommends appropriate testpiece dimensions, testing rates, methods of gripping and strain measurement techniques. It also defines methods for measuring Young's modulus, proportional limit, proof stress, tensile strength and elongation to failure. Significantly it contains a recommended proforma for the test report in anticipation of future database requirements. The draft procedure forms the basis of this ISO/TTA document. It was validated by two interlaboratory exercises, one through VAMAS (internationally) and one in the UK (led by NPL). The outcome of this validation exercise is also summarised in the Introduction to the ISO/TTA document.

The style of the draft procedure is similar to that adopted for the current EN tensile testing standards, EN10002 pt 1 (tensile tests for metals) and its sister document for Aerospace materials EN2002-1 part 1.

INTRODUCTION - VALIDATION EXERCISE

Two validation exercises were carried out to confirm the utility of the draft procedure:

VAMAS

An intercomparison using the tensile testing draft procedure [1] was instigated under the guidance of the VAMAS Technical Working Area 15 on Metal Matrix Composites. One of the important objectives of VAMAS is to harmonise testing procedures internationally. The current exercise included organisations from the UK, USA, Japan, France, Spain and Germany.

UK MMC Forum

Another intercomparison was organised by NPL through a sub-committee of the UK FORUM on TEST METHODS for MMC. It included a subset of the organisations involved in the first UK exercise [2] which were chosen to be representative of industry, academia and research organisations.

Appropriate testpieces were distributed by NPL to the participating organisations in each exercise together with copies of the draft tensile testing procedure. Each organisation tested 3-4 testpieces. The results were returned to NPL for collation and analysis.

MATERIALS AND TESTPIECES

VAMAS:

The MMC was provided by APMC Ltd (USA) and was in the form of extruded 2009 Al/20% SiC_w. It was machined into dogbone rectangular testpieces (Type T1 [1] - 6 mm x 3 mm cross section; 25 mm gauge length) by NRIM, Japan.

UK Forum:

An MMC and an unreinforced Al matrix alloy were included in this study. The MMC was provided by AMC Ltd (UK) as rolled plate 2124 Al/20% SiC_p. The Al alloy was provided by Alcan International Ltd as extruded bar (Alcan Cospray 2618). Both materials were machined at NPL into similar geometry testpieces as those used in the VAMAS exercise (Type T1 [1]). All the testpieces were machined using diamond (PCD) Tooling.

PARTICIPATION

VAMAS:

NPL	UK	Bordeaux Univ	France
DRA (Farnborough)	UK	BMW	Germany
BAe (Warton)	UK	DLR	Germany
NIST	USA	TUHH	Germany
NASA	USA	Honda	Japan
Inasmet	Spain	NRIM	Japan

UK Forum:

NPL
DRA (Farnborough)
Lucas
Hi-Tec

ERA
BAe (Warton)
Oxford Univ
Sheffield Univ

In reporting the results, all the VAMAS participants were identified (by agreement); in the UK exercise participants remained anonymous and coded.

DISCUSSION OF RESULTS**GENERAL COMMENTS**

It is significant that all the participants were able to use the draft procedure and results proforma without any major problems and this clearly validated the draft procedure as a satisfactory written document. A number of comments were made on the tests and results by some of the participants and these remarks were used to make small changes to the procedure outlined in this document.

YOUNG'S MODULUS AND STRAIN MEASUREMENT METHOD

The draft procedure for tensile testing [1] allowed three different types of analysis method to be used to calculate Young's modulus. These are referred to as M1, M2 and M3 and there are two subsets of M2 - M2A and M2B. These methods can be summarised as follows.

M1 - Graphical

From a straight line drawn parallel to the initial portion of a load/strain curve, ideally plotted as close as possible to 45° to the strain axis on A3 paper.

M2 - Chordal (using computer software)

From a straight line between two arbitrarily chosen limits on the initial portion of the stress/strain curve.

- M2A - direct straight line between the two points.
- M2B - linear regression fit to the data between the points.

M3 - Tangent (using computer software)

This is the NPL recommended method [3], based on the derivative of the quadratic polynomial fitted locally to the stress/strain data.

All three methods were used by the various participants. Data were obtained using either single or double sided strain measurement with either strain gauges or extensometers.

VAMAS

It was clear that for the most part the use of double sided strain measurement systems gave more reproducible and more accurate results.

Typically the standard deviations (SD) obtained using double sided strain gauges were less than 1% and less than 2% for the double sided extensometry. However, for the single sided systems the standard deviations were much larger, sometimes significantly greater than 5%.

The M1 method in general gave less scatter than the M2 (computer-based) method. However, this was not true in every case because the NASA results obtained using the M2 method were as repeatable and accurate as the results from NPL using the M3 method. The reason for this discrepancy can possibly be explained through examination of the upper and lower limits used by the different participants:

Participant	Method of Analysis	Upper and lower limits N mm ⁻²	Standard Deviation kN mm ⁻²	Deviation from mean kN mm ⁻²
NASA	M2	0-275	0.4	+0.2
Inasmet	M2	0-100	1.4	-4.9
NRIM	M2	-	5.4	+2.4
BMW	M2	150-250, 175-350	6.6	+7.5
BAe	M2B	25-125	2.4	+ 5.6

Clearly there is a wide range in the values chosen for the upper and lower limits and this may have contributed to greater uncertainties.

Another possible reason for the accurate and repeatable results from the NASA data set was the use of a class 0.5 extensometer. The draft procedure allows the use of two testpiece geometries with nominal gauge lengths of 25 or 50 mm. It might be prudent to recommend, where possible, the use of the larger testpiece (Type T2) for measurements using double sided extensometry. For example, for measurements using the M2 method (between 50 and 250 N mm⁻²) the equivalent strains are about 0.05 and 0.25%. On a gauge length of 25 mm these strains correspond to displacements of 12.5 and 62.5 µm respectively. As can be seen in the following table increasing the gauge length to 50 mm brings about a useful potential increase in accuracy.

Gauge length mm	Displacement, µm M2 method (50-250 N mm ⁻²)		Uncertainty (extensometer class*), µm		Estimated uncertainty in E, %	
	Upper	Lower	Class 0.5 type	Class 1.0 type	Class 0.5 type	Class 1.0 type
25	12.5	62.5	0.5	1.0	±2%	±4%
50	25	125	0.5	1.0	±1%	±2%

* estimates have been used because of the difficulty of comparing values from different available standards.

UK Forum

For the UK FORUM exercise the outcome and uncertainties associated with the different methods were very similar to those reported above for the VAMAS exercise. For example, the measurements made using single sided systems were more likely to be in error than with double sided systems. Also, double sided strain gauges gave more repeatable results than double sided extensometry. However, the use of strain gauges did not always give accurate values for the modulus. Some organisations which used double sided strain gauges had the same systematic deviation (approximately -5 and +5 kN mm⁻² respectively) for tests on both the MMC and Al matrix, thus indicating a common cause. The most likely reason for this is uncertainty in the value of the gauge factor. In a separate exercise [4] it has been shown that differences of 5% can easily be reported from this source. The report format should therefore have a suitable entry for recording the gauge factor if strain gauges are used and

to what accuracy this is known. Clearly gauges of different cost are available and in general the cheaper the gauge the less accurate is the gauge factor.

As in the VAMAS exercise method M1 gave more accurate results than method M2, possibly for similar reasons since the proportional limit for these materials was even lower (~ 250 cf ~ 300 N mm⁻²). Method M3 gave the most accurate and repeatable results, as had been found in the previous UK intercomparison exercise [2].

Summary (Young's Modulus and Strain Measurement Method)

A number of conclusions can be drawn from the two exercises (VAMAS and UK FORUM) concerning the measurement of Young's modulus.

1. The most accurate values were obtained at NPL using a double sided strain measurement system together with the M3 method of analysis. This procedure resulted in standard deviations of about $\pm 0.5\%$ (1 SD) in the measurement of modulus.
2. In general, the use of double sided strain measurement systems resulted in uncertainties of less than $\pm 2\%$ (1 SD) in the measurement of modulus; single sided systems were generally significantly worse, with uncertainties of $\pm 5\%$ (1 SD) or greater.
3. Overall, except for two organisations, the exercise reported uncertainties of less than $\pm 5\%$ (1 SD) in the measurement of modulus. This compares very well with the previous UK exercise where a significant number of uncertainties greater than $\pm 10\%$ (1 SD) were reported. With some modification the use of the draft procedure should ensure that in future tests uncertainties should be kept within $\pm 3\%$ (1 SD) for all methods. The potential exists within the standard procedure for uncertainties to be as low as $\pm 0.5\%$ (1 SD).
4. The results were more dependent on the use of a double sided strain measurement system than on the method of analysis. The chordal method could possibly be modified to specify bounds for the upper and lower limits for the data fit. These limits are likely to be material dependent and necessary guidelines would need to be investigated through collaborative projects between users and suppliers. For example, in aluminium alloy matrix MMC it would be unwise to use values for the upper limit much greater than 250 N mm⁻² because of the low proportional limit in these materials.
5. The finalised test procedure should recommend the use of the larger testpiece (Type T2) where the most accurate measurements are required (to better than $\pm 2\%$) and where only extensometry is available for the tests.
6. The test procedure should also request users to include and use an accurate value for the gauge factor if strain gauges are used.

PROPORTIONAL LIMIT

The uncertainty in the measurement of proportional limit was fairly high as the following summary indicates

Exercise	Proportional Limit (Mean value) N mm ⁻²	Standard Deviation N mm ⁻² (±%)
VAMAS	366	58 (16)
UK FORUM (MMC)	268	48 (18)
UK FORUM (Matrix)	298	72 (24)

These uncertainties were however considerably better than had been observed in the first UK intercomparison [2] where the standard deviation in results had been about ±25%. For most of the organisations using double sided measurement systems the measurements were reasonably repeatable with uncertainties (1 SD) typically about ±3%. However, the reproducibility, between organisations, was less good, increasing the uncertainties to typically ±10%. It was suggested by the Bordeaux University participants that the reproducibility could probably be improved by increasing the value of plastic strain at which the proportional limit is defined to that equivalent to the measurement of a 0.02% proof stress. The data from one test was analysed to examine the variation in proportional limit with a range of selected values of proof stress with the following results

Proof stress, %	Proportional limit N mm ⁻²
NPL procedure, (0.005)	351
0.02	354
0.05	395
0.1	416
0.2	435

Due to the high initial work hardening rate of the MMC there is a very rapid increase in proportional limit for small increments in plastic deformation. If an alternative definition is to be adopted from that in the draft procedure along the lines indicated by Bordeaux University, then 0.002% or 0.005% would be more realistic than 0.02%. It will probably be useful to rewrite the procedure so that this alternative is allowed provided that the % plastic strain is not greater than 0.01%, and that the value chosen is specified in the results sheet.

It is also likely that better reproducibility would have been observed if the method of analysis had been more constrained, particularly M2, (where arbitrary values of stress are chosen, between which the modulus is fitted). For example, the values of proportional limit correlated with the analysis method, since the M2 and M3 methods gave smaller values than M1.

PROOF AND TENSILE STRESS

The values for proof stress showed the least scatter of all the measured properties, with typical uncertainties of $\pm 2-3\%$ (1 SD) for all participants. The tensile strength values had slightly more scatter with uncertainties of 3-5%. However a trend of increasing tensile strength with increasing elongation to failure was noted, particularly in the VAMAS exercise. Thus, with more consistent elongations to failure it might be expected that the uncertainties in tensile strength resulting from the method of measurement could be as low as $\pm 1\%$.

ELONGATION TO FAILURE

The elongation to failure values showed considerable variation in the MMC tests, ie about 2-7% in both the VAMAS and UK FORUM exercises. Even the tests on the Cospray Al alloy showed variations of about 3-12%. Much of this variation was due to testpieces failing outside the gauge length. For example in the VAMAS exercise about 50% of the failures were at or close to the position where the extensometers were attached to the testpieces. The overall uncertainty on elongation including these "invalid tests" was about $\pm 25\%$. The spread in elongation values was much less, about $\pm 10\%$, for those tests in which testpieces failed within the gauge length.

STRAIN RATE EFFECTS

The draft test procedure specifies a maximum stressing rate of $10 \text{ N mm}^{-2} \text{ s}^{-1}$ in the elastic range; this corresponds to a strain rate for the MMC tested in this exercise of about 10^{-4} s^{-1} and is a compromise between sufficient time for data capture and test convenience. Beyond the elastic limit, for measurements of proof stresses, the strain rate can be increased to $2 \times 10^{-4} \text{ s}^{-1}$. The draft procedure does not indicate an appropriate strain rate for testing between the proof stress and tensile strength in those cases where Young's modulus, proof stress and tensile strength are all required to be measured. It only specifies a strain rate of 10^{-3} s^{-1} in the plastic range in those cases where modulus is not required to be measured. Clearly the draft procedure requires some modification to Section 9 to include an upper limit of 10^{-3} s^{-1} for testing in the plastic range in those cases where all the tensile properties are required to be measured.

The procedure does allow other strain rates to be used if specified in a product standard.

RESULTS PROFORMA

The intercomparisons have underlined the usefulness of making a number of small changes to the results proforma. These have been included in the modified procedure which form the basis of this TTA.

UNCERTAINTIES

Typical values for the uncertainties (1 SD) associated with each property measurement can be summarised as follows in comparison with the uncertainties associated with the previous UK intercomparison exercise.

Property	Intercomparison Uncertainties (1 SD)	
	VAMAS and UK FORUM results (New MMC procedure) double sided strain measurement	First UK intercomparison (Existing standards for metals)
Young's modulus	± 2%*	± 7%
Proportional limit	± 20% ⁺	± 28%
Proof stress	± 2%	± 4%
Tensile strength	± 4% [‡]	± 3%
Elongation to Fracture	± 25(10)%**	± 35%

- * Potentially better than ± 1% with the M3 method of analysis and strain gauges with accurately known gauge factors
- ** For all tests; (± 10%) for tests failed in gauge length
- ⁺ Could possibly be reduced further by the use of a x% plastic strain specification for the proportional limit, where x should be less than 0.01 and specified by agreement
- [‡] Probably better than ± 1% for those testpieces that failed in the gauge length.

CONCLUSIONS

The VAMAS and UK FORUM intercomparisons have validated the draft procedure [1] for tensile testing of particulate reinforced MMC at ambient temperatures. Analysis of the results has indicated the need for a small number of changes to the procedure, including the results proforma (Appendix). The original draft procedure has been modified to take account of these changes (proportional limit, strain rate) and will be submitted to the appropriate standards bodies for approval when this TTA has been published and circulated and after taking into account additional comments that this wider dissemination might generate. For example, some changes have been made already as a result of peer review by ISO member countries - on the use of strain gauges, machine grips and testing rate.

The intercomparisons demonstrated that measurement uncertainties were very much reduced by the use of the new test procedure when compared with the first UK intercomparison exercise, which in general followed existing standards for metals. Much of the improvement has clearly been due to the use of double sided strain measurement systems.

REFERENCES

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4. J D Lord and L P Orkney. NPL Report DMM(A)135, January 1995. Strain Gauge Techniques for MMC.

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Tensile tests for discontinuously reinforced metal matrix composites at ambient temperatures

1. SCOPE

This document is an outline procedure for the tensile testing of discontinuously reinforced metal matrix composites (MMC) and defines the mechanical properties which can be determined at ambient temperature, such as Young's modulus, proportional limits, proof stress, tensile strength and elongation to failure. It follows the European standard EN 10002 for the tensile testing of metals and its sister document for Aerospace materials EN 2002-1 Part 1. [refs 1 and 2 in annex C.]

2. PRINCIPLE

The test involves straining a **rectangular** cross-section testpiece by a tensile force, generally to fracture, for the purpose of determining one or more of the mechanical properties defined in section 3.

The test is carried out at ambient temperature between 10°C and 35°C, unless otherwise specified.

A double averaging strain measurement system is recommended for improved accuracy, particularly of modulus [see ref. 3 in annex C]. If a single strain measurement system is used then this must be recorded in the test report.

3. DEFINITIONS

For the purposes of this procedure, the following definitions apply.

3.1 GAUGE LENGTH (L)

Length of the prismatic portion of the testpiece on which elongation is measured during the test. In particular, a distinction is made between:

3.1.1 Original gauge length (L_0)

Gauge length before application of force.

3.1.2 Final gauge length (L_u)

Gauge length after fracture of the testpiece.

3.2 PARALLEL LENGTH (L_c)

Length of the reduced section parallel portion of the testpiece.

3.3 ELONGATION

Increase in the original gauge length (L_0) at the end of the test.

3.4 PERCENTAGE ELONGATION (A)

Elongation expressed as a percentage of the original gauge length (L_o).

3.4.1 Percentage permanent elongation

Increase in the original gauge length of a testpiece after removal of a specified stress expressed as a percentage of the original gauge length (L_o).

3.4.2 Percentage elongation after fracture (A_p)

Permanent elongation of the gauge length after fracture ($L_u - L_o$) expressed as a percentage of the original length (L_o).

3.4.3 Percentage total elongation at fracture (A_t)

Total elongation (elastic plus plastic) of the gauge length at the moment of fracture expressed as a percentage of the original gauge length (L_o).

3.4.4 Percentage elongation at maximum force (A_g)

Increase in the gauge length of the testpiece at maximum force, expressed as a percentage of the original gauge length (L_o). A distinction is made between the percentage total elongation at maximum force (A_{gt}) and the percentage non-proportional elongation at maximum force (A_g).

3.5 EXTENSOMETER GAUGE LENGTH (L_e)

Length of the parallel portion of the testpiece used for the measurement of extension by means of an extensometer (this length may differ from L_o and shall be of any value greater than b (see Table 1) but less than the parallel length (L_c).

3.6 EXTENSION

Increase in the extensometer gauge length (L_e) at a given moment during the test.

3.6.1 Percentage permanent extension

Increase in the extensometer gauge length after removal from the testpiece of a specified stress, expressed as a percentage of the extensometer gauge length (L_e).

3.7 PERCENTAGE REDUCTION OF AREA (Z)

Maximum change in cross-sectional area which has occurred during the test ($S_o - S_u$) expressed as a percentage of the original cross-sectional area (S_o).

3.8 MAXIMUM FORCE (F_m)

The greatest force which the testpiece withstands during the test once the yield point has been passed.

3.9 STRESS (R)

Force (F) at any moment during the test divided by the original cross-sectional area (S_o) of the testpiece.

3.9.1 Tensile strength (R_m)

Stress corresponding to the maximum force (F_m).

3.9.2 Proof strength, non-proportional extension (R_p)

Stress at which the non-proportional extension is equal to a specified percentage of the extensometer gauge length (L_e). The symbol used is followed by a suffix giving the prescribed percentage of the extensometer gauge length, for example $R_{p0.2}$.

3.9.3 Proof strength, total extension (R_t)

Stress at which the total extension (elastic extension plus plastic extension) is equal to the specified percentage of the extensometer gauge length (L_e). The symbol used is followed by a suffix giving the prescribed percentage of the original gauge length for example: $R_{t0.5}$.

3.9.4 Permanent set strength (R_r)

Stress at which, after removal of force, a specified permanent elongation or extension expressed respectively as a percentage of the original gauge length (L_0) or extensometer gauge length (L_e) has not been exceeded. The symbol used is followed by a suffix giving the specified percentage of the original gauge length or of the extensometer gauge length (L_e), for example: $R_{r0.2}$.

3.10 STRAIN (ϵ)

Strain is defined as the increase in length divided by the original gauge length. It can be measured using extensometers or strain gauges.

3.10.1 Extensometry

Increase in extensometer gauge length at any moment during the test divided by the original gauge length. For double sided extensometers the strain is expressed as the average of measurements taken from opposite sides of the testpiece.

3.10.2 Strain gauges

Change in length of the strain-sensitive part of the resistive element of the strain gauge divided by the original length of the same part. For gauges mounted on opposite sides of the testpiece, strain is expressed as the numerical average of the two gauges.

3.11 YOUNG'S MODULUS OF ELASTICITY (E)

The Young's modulus is defined as stress (R) divided by strain (ϵ) in the elastic linear region at the start of the force/extension curve.

3.12 PROPORTIONAL LIMIT (PL)

The proportional limit is defined as the stress at which the elastic region of the force/extension curve finishes; it marks the point where the linear relation between stress (R) and strain (ϵ) changes to non-linear (plastic) behaviour.

3.13 SECANT MODULUS (SM)

The secant modulus is defined as the slope of the line between the origin of the stress/strain curve and any point on the curve.

3.14 TANGENT MODULUS (TM)

The tangent modulus is defined as the slope of the stress/strain curve at the point of interest on that curve.

4. SYMBOL DESIGNATIONS

An abbreviated list of important symbols and corresponding designations is given in Table 1. Further symbols corresponding to the dimensions of the testpiece are given in Table A1 of Annex A.

Table 1 - Symbols and Designations
Abbreviated List

Reference	Symbol	Unit	Designation
Testpiece	a	mm	Thickness of flat testpiece
	b	mm	Width of parallel length of flat testpiece
	L _c	mm	Parallel length
	L _o	mm	Original gauge length
	L _e	mm	Extensometer gauge length
Strain	A _t	%	Percentage total elongation at fracture
Force	F _m	N	Maximum force
Strength	R _p	N mm ⁻²	Proof strength
	R _m	N mm ⁻²	Tensile strength
	PL	N mm ⁻²	Proportional limit
Modulus	E	kN mm ⁻²	Young's modulus
	SM	kN mm ⁻²	Secant modulus
	TM	kN mm ⁻²	Tangent modulus

Note: 1 N mm⁻² = 1 MPa

5. TESTPIECES

5.1 SHAPE AND DIMENSIONS

5.1.1 General

The shape and dimensions of the testpieces to a large extent will depend on the shape and dimensions of the products of which the mechanical properties are to be determined. However, for this test procedure for discontinuously reinforced metal matrix composites it is recommended that rectangular testpieces are used.

The testpiece is usually obtained by machining a sample from the product, pressed blank or casting. However, products of constant thickness and as-cast testpieces may be subjected to test without being machined in the through-thickness direction.

Testpieces, the original gauge length of which is related to the original cross-sectional area by the equation $L_o = k \sqrt{S_o}$, are called proportional testpieces. The internationally adopted value for k is 5.65.

The original gauge length shall be not less than 20 mm. For this procedure it is preferred that a gauge length of either 25 mm is adopted [Type 1 testpieces] for a testpiece 6 mm wide by 3 mm thick (nominal), or a gauge length of 50 mm for 12 mm wide by 6 mm thick (nominal), [Type 2 testpieces]. If the testpiece is taken from a product that is less than 3 mm thick it is recommended that the width remains at 6 mm.

The dimensional tolerances of both Type 1 and 2 testpieces shall be in accordance with those given in Annex A.

5.1.2 Machined testpieces

Machined testpieces shall incorporate a transition radius between the gripped ends and the parallel length. The dimensions of this transition radius are important and it is recommended that for tests in accordance with this procedure the radius is either 12 or 24 mm, as defined in Annex A.

The gripped ends may be of any shape to suit the grips of the testing machine. The parallel length (L_c) shall always be greater than the original gauge length (L_o). L_c should be at least equal to $L_o + 1.5 \sqrt{S_o}$ where S_o is the original cross sectional area. For this procedure it is recommended that L_c is 36 mm (Type 1) or 72 mm (Type 2) - see Annex A.

5.2 PREPARATION OF TESTPIECES

The parallel length section of the testpieces shall be prepared to the final dimensions using diamond tooling, taking due care to minimise the introduction of residual stresses and/or damage by careful use of machining techniques. Spark machining (EDM) can be used first of all to blank the testpiece shape from a larger block if necessary.

6. DETERMINATION OF ORIGINAL CROSS-SECTIONAL AREA (S_o)

The original cross-sectional area shall be calculated from measurements of the appropriate dimensions. The accuracy of this calculation depends on the nature and type of the testpiece, (Annex A).

7. MARKING THE ORIGINAL GAUGE LENGTH (L_0)

Each end of the original gauge length shall be marked by means of pencil or ink lines, but not by notches, marks or scribed lines, which could result in premature fracture.

The original gauge length shall be measured to an accuracy of $\pm 1\%$.

In some cases, it may be helpful to draw on the surface of the testpiece, a line parallel to the longitudinal axis, along which the marks are drawn.

8. ACCURACY OF TESTING APPARATUS

The testing machine shall be verified in accordance with EN 10002-2 and shall be of grade 1 or better.

9. CONDITIONS OF TESTING

9.1 TESTING RATE OF THE MACHINE

The testing machine can be controlled through either crosshead displacement control or direct strain (in-situ extensometry) control. The test report should state which method was used. It is **not recommended** that machines should be controlled by a strain output from strain gauges mounted directly on the testpiece. The preferred mode of test is by servo control using direct output from the extensometry system. If crosshead control is used, strain rate should be monitored through the region of yield and the values noted in the test report.

9.1.1 General

Unless otherwise specified in a product standard, the rate of the machine shall comply with the following requirements.

9.1.2 Modulus and Proof strengths (R_p and R_t)

Within the elastic range and the plastic range up to the proof strength (non-proportional extension or total extension) the straining rate shall not exceed 0.0002 s^{-1} . The strain rate can be slower in the elastic region if required. The objective is to ensure that sufficient data points are captured within the elastic region to enable an accurate value for modulus to be calculated.

9.1.3 Tensile strength (R_m)

9.1.3.1 In the elastic range

If the test does not include the determination of a proof stress or modulus, the rate of the machine may reach the maximum permitted in the plastic range.

9.1.3.2 In the plastic range

The strain rate shall not exceed 0.001 s^{-1} .

9.2 METHOD OF GRIPPING

The testpiece must be given adequate grip-length to ensure that there is no slipping in the test and that the stress is distributed uniformly in the test section [see ref. 4 in annex C].

Every endeavour shall be made to ensure that testpieces are held in such a way that the force is applied as axially as possible. This is of particular importance when testing low ductility materials or when determining proof strength (non-proportional extension), proof strength (total extension), yield strength or elastic modulus.

9.3 ALIGNMENT OF TESTPIECES

Accurate alignment of the testpiece is very important for the measurement of modulus. It is recommended that a multi-strain gauged reference testpiece is used to check the alignment of the test machine to ensure strains due to bending from rotation or translation of grips are minimised.

Inaccuracies in strain measurement due to small misalignments or curvature of testpieces can be reduced by using a double sided strain measurement system. It is highly recommended that this practice be universally adopted if the modulus is to be measured in the tensile test. It is recommended that a set square or similar fixture be used to align the testpiece with respect to the grips in the vertical plane.

9.4 STRAIN MEASUREMENT SYSTEM

The preferred method of strain measurement is to use a double sided system. For reasons of cost the recommended method is to use double sided extensometry rather than strain gauges. However, extensive interlaboratory testing has shown that with good testing practice even higher accuracy can be obtained with longitudinal strain gauges bonded to each side of the testpiece [see ref. 5 in annex C]. But, it is recognised that there is no standard for ensuring that strain gauges can be applied consistently and that quoted gauge factors are sufficiently accurate.

The method adopted shall be stated in the test report including the extensometer class if extensometry is used. If a double sided system is not available and a single sided strain measurement device is used then this must also be stated in the test report.

Strain gauges are only suitable for measurement of the full set of mechanical properties if the testpiece failure strains are less than about 3%. For more ductile materials it is necessary to use extensometry to obtain the full stress/strain curve; although if gauges are used then a nominal figure for the tensile strength can be obtained from the load at failure and the cross sectional area of the original testpiece, and the elongation at failure can be obtained directly from the marked testpiece.

10. DETERMINATION OF PERCENTAGE ELONGATION AFTER FRACTURE (A_p)

10.1 Percentage elongation after fracture shall be determined in accordance with the definition given in 3.4.

For this purpose, the two broken pieces of the testpiece are carefully fitted back together so that their axes lie in a straight line. **If fractography is to be performed, it is recommended that this is performed before measurement of A_p to prevent damage to the fracture surfaces.** Special precautions shall be taken to ensure proper contact between the broken parts of the testpiece when measuring the final gauge length. This is particularly important in the case of testpieces having low elongation values.

Elongation after fracture ($L_u - L_0$) shall be determined to the nearest 0.25 mm with a measuring device with 0.1 mm resolution, and the value of percentage elongation after fracture shall be rounded to the nearest 0.5%. If the specified minimum percentage elongation is less than 5%, it is recommended that special care is taken when determining elongation. If failure occurs outside the original gauge length, L_0 , this should be reported.

10.2 For machines capable of measuring extension at fracture using an extensometer, it is not necessary to mark the gauge lengths. The elongation is measured as the total extension at fracture, and it is therefore necessary to deduct the elastic extension in order to obtain percentage elongation after fracture.

In principle, this measurement is only valid if fracture occurs within the extensometer gauge length (L_e). The measurement is valid regardless of the position of the fracture cross-section if the percentage elongation after fracture at least reaches a specified value and this shall be stated in the test report.

10.3 The property should be quoted to two significant figures.

11. DETERMINATION OF PROOF STRENGTH (NON-PROPORTIONAL EXTENSION) (R_p)

11.1 For method M1, the proof strength (non-proportional extension) is determined from the force/extension diagram by drawing a line parallel to the straight portion of the curve in the elastic-region and at a distance from this equivalent to the prescribed non-proportional percentage, for example 0.2%. The point at which this line intersects the curve gives the force corresponding to the desired proof strength (non-proportional extension). The latter is obtained by dividing this force by the original cross-sectional area of the testpiece (S_0).

Accuracy in drawing the force-extension diagram is essential, particularly in the linear elastic region of the curve. A method for doing this is described in section 13.

11.2 The proof strength may be obtained without plotting the force/extension curve by using automatic devices, such as computer based data acquisition systems directly from the stress/strain curve.

11.3 The property should be quoted to three significant figures.

12. DETERMINATION OF PROOF STRENGTH (TOTAL EXTENSION) (R_t)

12.1 For method M1, the proof strength (total extension) is determined on the force/extension diagram by drawing a line parallel to the ordinate axis (force axis) and at a distance from this equivalent to the prescribed total percentage extension. The point at which this line intersects the curve gives the force corresponding to the desired proof strength. The latter is obtained by dividing this force by the original cross-sectional area of the testpiece (S_0).

12.2 This property may be obtained without plotting the force/extension diagram by using automatic devices such as computer based data acquisition systems directly from the stress/strain curve.

12.3 The property should be quoted to three significant figures.

13. DETERMINATION OF YOUNG'S MODULUS (E)

One of three methods shall be used to determine the Young's modulus. The three methods; M1, M2 and M3 are outlined in sections 13.1 to 13.3. The method adopted shall be quoted in the test report. **The modulus should be quoted to the nearest 0.5 kN mm⁻².**

13.1 METHOD M1 - GRAPHICAL METHOD

The load and strains (single or averaged) shall be plotted on a chart recorder using, to minimise errors, A3 graph paper. **The plot should occupy a significant proportion of the paper and the angle between the plot and the strain axis should be as close as possible to 45°.** A straight line shall be drawn parallel to the initial portion of the load/strain curve. The slope of this line, (when the load has been divided by the testpiece cross-section to convert to values of stress) is the Young's modulus.

13.2 METHOD M2 - CHORDAL METHOD

This method shall in general be adopted when machine dedicated software is available to calculate modulus values. **It is strongly recommended that the software is validated/calibrated by the use of reference testpieces of known stiffness.**

13.2.1 Two values of stress are chosen on the stress/strain plot to mark the lower and upper limits of a chordal modulus. The two values of stress are arbitrarily chosen by inspection of the stress/strain curve and must be quoted in the test report. A straight line is drawn between the two points using a validated software procedure. The slope of this line corresponds to the Young's modulus value. This method shall be identified as method M2A.

13.2.2 Two values of stress are chosen in the stress/strain plot to mark the lower and upper limits of the chordal modulus. The two values of stress are arbitrarily chosen by inspection of the stress/strain curve and must be quoted in the test report. A straight line regression fit is made to the experimental data between these two chosen values of stress. The slope of the fitted line corresponds to the value of Young's modulus. This method shall be identified as method M2B.

13.3 METHOD 3 - TANGENT METHOD

The full procedure for this method is given in Reference 3 in annex C. Essentially the following steps are followed.

- i) The stress/strain data is captured using a computer based acquisition system. It is recommended that the data acquisition system collects at least 200(X) data points up to a total strain of 1.0%.
- ii) a quadratic polynomial is sequentially fitted to the data, point by point along the curve, by least squares regression analysis. A n point fit is recommended where n is 15X/200.
- iii) the fitted polynomial is differentiated at each point to obtain a value for the tangent modulus
- iv) the tangent modulus is plotted against stress
- v) the best horizontal fit to the tangent modulus/stress curve is obtained either
 - a) by operator choice - moving a horizontal cursor on the monitor screen, or

- b) automatically by sequentially examining the data in sets of m data points along the curve to find the most horizontal portion, where m is $5X/200$
- vi) the horizontal fit is taken as the first choice of Young's modulus
- vii) this value is used to define a new origin for the stress/strain data
- viii) the data are replotted and a secant modulus/stress curve is calculated
- ix) step v) is repeated but using the secant modulus/stress plot
- x) The most horizontal portion of the secant modulus/stress plot is taken to be the final value of Young's modulus.

The value obtained in Step x, is the Young's modulus of elasticity. This method shall be identified as Method M3.

14. DETERMINATION OF PROPORTIONAL LIMIT (PL)

The following method shall be used to obtain a value for the proportional limit. It is based on the use of software-based systems. It is not recommended that this property is obtained graphically. **The value obtained should be quoted to three significant figures.**

Draw a line parallel to the Young's modulus curve offset by not more than 0.01% strain. The point at which this line intersects the stress-strain curve gives the force corresponding to the proportional limit (PL). The value obtained should be quoted in association with the value of the offset plastic strain.

In practice, for typical discontinuously reinforced MMC the proportional limit does not change by more than about 10 Nmm^{-2} for values of offset strain between 0.0005% and 0.002%. A value for the proportional limit can in principle be obtained at any specified value of proof stress less than 0.01% but this must be noted in the report proforma. It is recommended that for consistency of use a value of offset strain of 0.005% should be used.

15. DETERMINATION OF TENSILE STRENGTH

The tensile strength is the largest stress value that is obtained on the stress/strain curve. **The value obtained should be quoted to three significant figures.**

16. TEST REPORT

It is recommended that the proforma given in Annex B is used for the test report and shall contain the following information, preferably in tabular form for eventual computerisation of data bases as indicated in Annex B.

- reference to this procedure
- nature of the material, if known
- identification of the testpiece
- type of testpiece
- location and direction of sampling of testpieces
- characteristics measured and results, using the proforma given in Annex B.

Annex A
(This annex forms an integral part of the procedure)

Testpiece dimensions

Types of testpiece to be used in the case of sheets and flat sections of thickness equal to or greater than 3 mm, and bars and sections of thickness equal to or greater than 4 mm. For testpieces from these products less than 3 mm thick it is recommended that all dimensions remain the same as those for testpieces from further products except the thickness.

A.1 Shape of the testpiece

In general, the testpiece is machined and the parallel length shall be connected by means of transition radii to the gripped ends which may be of any suitable shape for the grips of the test machine.

The transition radius shall be at least 12 mm for testpieces of rectangular cross-section (3 x 6 mm) and 24 mm for testpieces of rectangular cross-section (6 x 12 mm).

A.2 Dimensions of the testpiece

For tensile tests on particulate reinforced MMC it is recommended that one of two testpiece types are used, Type 1 (T1) or Type 2 (T2). Figure A1 shows the testpiece geometry. Both sizes are commensurate with the standard EN 10002 pt 1. The dimensions are given in Table A1.

Table A1
Dimensions of testpiece

Type	Total length mm	Transition radius mm	Width of grip ends mm	Length of grip ends mm	Parallel length mm	Original gauge length mm	Width of parallel length mm	Thickness of parallel length mm
	L_t	r	W_g	L_g	L_c	L_o	b	a
T1	100	12	12	25	36	25	6	3
T2	200	24	24	50	72	50	12	6

A.2.1 Parallel length of machined testpiece

The parallel length (L_c) shall be at least equal to:

$$L_o + 1.5 \sqrt{S_o}$$

For this procedure it is recommended that L_c is 36 mm (Type 1) or 72 mm (Type 2).

A.2.2 Length of unmachined testpiece

The free length between the grips of the machine shall be adequate for the gauge marks to be a reasonable distance from these grips.

A.3 Preparation of testpieces

When measuring the dimensions of each testpiece the tolerances on shape given in Table A.2 can be used as a guideline but finally the tolerances on thickness and width shall be such that the cross-sectional area of the testpiece does not vary by more than $\pm 1\%$ from the nominal.

The testpieces shall be prepared so as to minimise the effects of changes to the properties of the metal composite. **Diamond tooling is recommended.**

Table A2
Tolerances on dimensions of testpiece, mm

Type	Nominal width/thickness	Machining tolerances	Shape tolerancet
T1	6/3	± 0.05	0.05
T2	12/6	± 0.1	0.10

† Maximum deviation between measurements of a dimension along the parallel length.

A.4 Determination of the cross-sectional area (S_0)

The original cross-sectional area shall be calculated from measurements of the appropriate dimensions, with an error not exceeding $\pm 0.2\%$ on each dimension for testpieces thicker than 3 mm. For tests on thinner material, the uncertainty associated with the measurement of the thickness dimension should be assessed and used to calculate and express the uncertainty which this contributes to the measurement of stress (R).

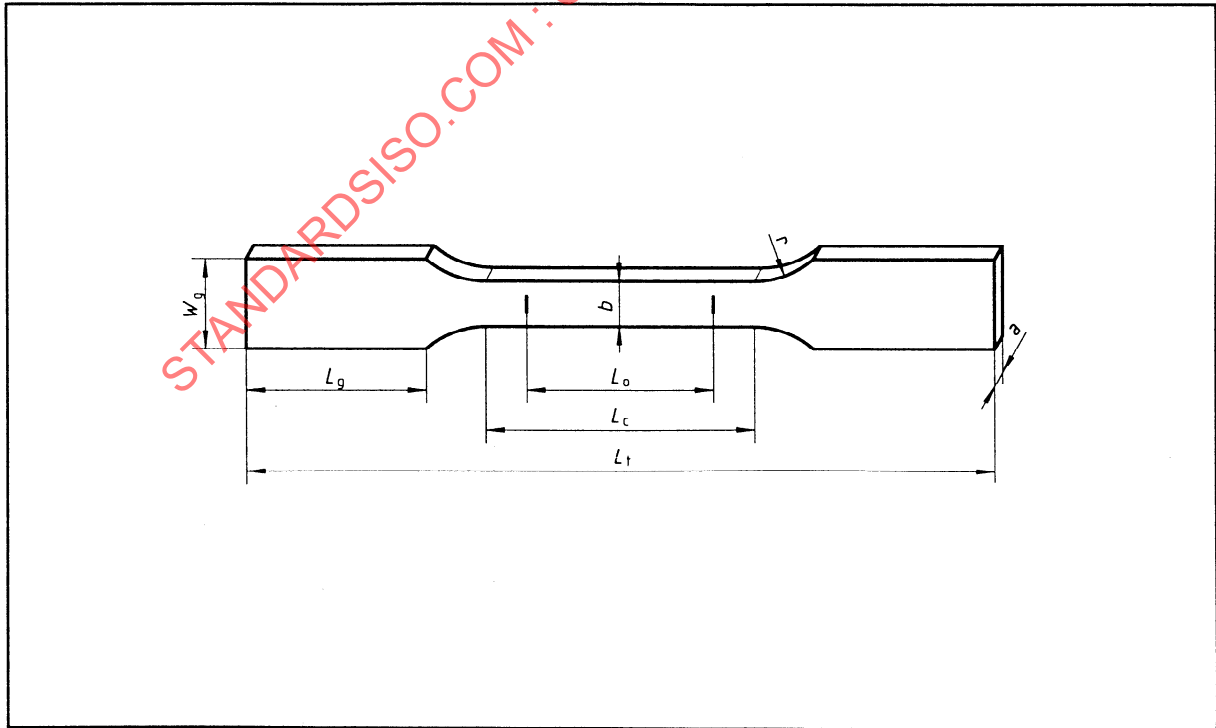


Fig A1 Rectangular testpiece geometry

Annex B

Test Report

It is recommended that the test report is in tabular form as follows (typical values have been given for illustration).

Table B1
Particulate Metal Matrix Composites
Tensile Test Report

Material and testpiece information

Reference	Description	Input value
Material	Source Identifier Composition Form Heat treatment	BP Metal Composites BP 217 SiC particulate reinforced Al alloy Extruded plate (15 mm × 50 mm) T6 heat treatment
Testpiece preparation	Orientation (relative) Method Geometry Applicable standard(s)*	Longitudinal with respect to extrusion direction Diamond machined from spark machined blank Rectangular, 3 mm thick by 6 mm wide A*
Testpiece information	Testpiece identification Testpiece width (average) Tolerance on width Testpiece thickness Tolerance on thickness Total length Gauge length (if extensometry used) Cross-sectional area Uncertainty in cross-sectional area (estimated)	BP RR 07 6 mm ± 0.01 mm 3 mm ± 0.01 mm 100 mm - 18 mm ² ± 0.02 mm ²

Testing organisation

Organisation:- Name:- Date:-	National Physical Laboratory Teddington, Middlesex, UK TW11 0LW (example)
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