TECHNOLOGY TRENDS ASSESSMENT

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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

Reference number
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CONTENTS

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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 ACMC 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	ERA
DRA (Farnborough)	BAe (Warton)
Lucas	Oxford Univ
Hi-Tec	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 ±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 ±2% (1 SD) in the measurement of modulus; single sided systems were generally significantly worse, with uncertainties of ±5% (1 SD) or greater.

3. Overall, except for two organisations, the exercise reported uncertainties of less than ±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 ±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 ±3% (1 SD) for all methods. The potential exists within the standard procedure for uncertainties to be as low as ±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 ±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 ±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 ± 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 ±25%. The spread in elongation values was much less, about ±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 N mm^{-2} 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 $2x10^{-4}$ 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.

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3. B Roebuck, J D Lord, P M Cooper and L N McCartney. Data Acquisition and Analysis of Tensile Properties for MMC, ASTM J. Testing and Evaluation (JTEVA), 22 (1), 1994, 63-69.

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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_o)

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_o) at the end of the test.