VAMAS

Technical Working Area 15
Metal Matrix Composites

Validation of a Draft Tensile Testing Standard for Discontinuously Reinforced MMC

VAMAS and UK MMC FORUM Intercomparisons

by

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ABSTRACT

A draft tensile testing standard for discontinuously reinforced metal matrix composites (MMC) has been validated by use in two intercomparisons, one in the UK and one internationally through VAMAS. The UK exercise used UK sourced testpieces of SiC particulate reinforced Al alloy and the VAMAS exercise measured the properties of a USA sourced SiC whisker reinforced Al alloy. The validation exercise confirmed the utility of the draft standard, (in particular the report proforma and the guidelines on modulus measurement) and quantified the uncertainties in property measurement associated with different strain measurement methods.

CONTENTS

INTRODUCTION

There is a need for a better tensile testing standard for discontinuously reinforced metal matrix composites (MMC). Use of the current ISO standard for metals 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 [1]. 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 give 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 Ramberg-Osgood constitutive expression for the stress/strain data [2].

Following analysis [3] 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 [4]. The draft procedure recommends appropriate testpiece dimensions, testing rates, methods of gripping and strain measurement techniques. It also defines methods for the measurement of Young's modulus, proportional limit, proof stress, tensile strength and elongation to failure. Significantly it contains a recommended proforma for the test report (Appendix) in anticipation of future database requirements. 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. Two validation exercises have been carried out to examine the utility of the draft procedure:

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An intercomparison using the tensile testing draft procedure was instigated under the guidance of the VAMAS [5] 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. The material for the tests was supplied by the USA (SiC_W reinforced 2009 Al alloy - ACMC Ltd).

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 [3] which were chosen to be representative of industry, academia and research organisations. The MMC material for these tests was supplied by AMC Ltd (SiC_p reinforced 2124 Al alloy). For comparison, tests were also performed on a monolithic matrix material supplied by Alcan International Ltd (Alcan Cospray 2618).

Appropriate testpieces were circulated 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 and was in the form of extruded 2009 Al/20% SiC_W. It was machined into dogbone rectangular testpieces (Type T1 [4] - 6 mm x 3 mm cross section; 25 mm gauge length) by NRIM, Japan.

UK Forum:

The MMC was provided by AMC Ltd 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 [4]). 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 have been identified (by agreement) whereas in the UK exercise participants are anonymous and coded.

RESULTS

VAMAS:

Details of the test conditions and methods of analysis are given in Tables 1 and 2; including machine type, testpiece code, grip type, alignment fixture, strain rate, control mode, strain measurement type, data acquisition details and failure position.

Table 3 gives individual results for Young's modulus, tensile strength, proportional limit, proof stress and elongation.

Table 4 gives mean values and standard deviations for each organisation and for all the results for each tensile property. For the modulus measurements two of the NIST testpieces were considered to give values which were assessed as outliers, ie 141 and 166.5 kN mm^{-2} compared with the mean of about 104 kN mm^{-2}. As this would leave only two measurements, all the NIST results were therefore omitted from the calculation of mean values.

A breakdown of the results of the modulus measurements according to the method of strain measurement and method of analysis is given in Tables 5 and 6 respectively.

Plots of the tensile property values (Young's modulus, tensile strength, proportional limit, proof stress and elongation to failure) are given in Figs 1-3. Also included in Fig 3 is a plot of tensile strength against elongation to failure.

UK FORUM:

Details of the test conditions and methods of analysis are given in Tables 7 and 8 in the same format as for the VAMAS tests.

Tables 9 and 10 give individual results and overall means and standard deviations for the MMC and matrix alloy for the tensile properties. The results from organisation 1 were excluded from the analysis because they include several obvious outliers.

Tables 11-14 give a breakdown of the results of the modulus measurements according to strain measurement and method of analysis for the MMC and the matrix alloys.

Plots of the tensile property values are given in Figs 4-9.

DISCUSSION

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 validates the draft procedure as written. A number of comments were made on the tests and results by some of the participants and these remarks will be used to make small changes to the procedure before it is submitted to the appropriate standards bodies, possibly as a further part to the EN10002 series. However, the final route for wider dissemination has yet to be decided.

Follow-up remarks by participants are included in specific technical sections on

Young's Modulus
Strain Measurement Method
Proportional Limit

Proof Stress
Tensile Strength
Elongation to Failure

Where possible the VAMAS and UK Forum outcomes are discussed together.

OUTLIERS

In both the VAMAS and UK FORUM exercises two separate organisations reported values, particularly for Young's modulus, which were clearly outliers. The data sets from these two organisations have been excluded from the analysis of mean values. The NIST data (VAMAS) included two values of Young's modulus 141 and 166.5 kN mm^{-2} which are obviously not in line with the average value of 104.4 kN mm^{-2}. Furthermore, organisation 1 (UK Forum) reported values greater than 100 kN mm^{-2} for the Cospray Al alloy (average 72.5 kN mm^{-2}) and 134.5 kN mm^{-2} for the MMC (average 100 kN mm^{-2}). These values were separated from the average values by considerably more than 4 standard deviations and were clearly due to measurement method problems.

YOUNG'S MODULUS AND STRAIN MEASUREMENT METHOD

The draft procedure for tensile testing [4] allows 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 plotted at 45° ± 2° to the strain axis on A3 paper.

M2 - Chordal (using computer software)

> From a straight line between two arbitrarily chosen upper and lower limits on the initial portion of the stress/strain curve.
>
> M2A - direct straight line between the two points.
> M2B - linear regression fit to data between the points.

M3 - Tangent (using computer software)

> NPL recommended method [6] based on the derivative of the quadratic polynomial fit 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 and either strain gauges or extensometers were used.

Before analysing the results in detail it is worthwhile considering examples of a number of the stress/strain curves obtained by the different organisations. Figs 10-12 show plots from the NPL software (taking averages from each side of the testpiece) for each of the three material types showing the first part of the stress/ strain curve, the calculation of proof stress and proportional limit and the tangent/secant modulus plots for each material from which Young's modulus was calculated. Further good examples of stress/strain data are shown from two different organisations in Fig 13 (double sided extensometry) and Fig 14 (double sided strain gauges). The need for using double sided strain measurement systems is shown in Fig 15 where it can be seen that the stress/strain curve obtained using a single sided system clearly poses problems in defining the linear part of the curve for modulus measurements. Two additional examples of data which are difficult to interpret are shown in Fig 16 which illustrates the difficulty of using the M2 approach and its associated problem of an arbitrarily defined upper and lower limit for the modulus calculation.

Mean values for Young's modulus and the standard deviation from each organisation are shown in Figs 17-19 plotted as a deviation from a "reference" value against the testpiece number or organisational code. The reference value is defined as the mean of the whole population excluding clear outliers (indicated as such in the appropriate Tables). The reference values are given as horizontal lines in Figs 17-19 and have the following values (rounded to the nearest 0.5 kN mm^{-2}):

VAMAS MMC	104.4 kN mm^{-2}
UK Forum MMC	101.1 kN mm^{-2}
UK Forum Al matrix	72.9 kN mm^{-2}

Also included in Figs 17-19 is an indication of the method of analysis (M1, M2 or M3) and strain measurement method (E - extensometers, G - strain gauges; s or d - single or double sided).

VAMAS

It is clear from Fig 17 that for the most part the use of double sided strain measurement systems gives more reproducible and more accurate results. There is only one set of data which is not consistent with this trend and that is the results from BMW using double sided extensometry, where the deviation from the mean and the standard deviation were quite large. Inspection of this data set indicated that values for the start and end of the data fit (by method M2) were quite high, typically 150-300 N mm^{-2}. However, this should in general give lower values than the true value, not higher as was reported. Consequently, although the high scatter could be perhaps explained by the arbitrary nature of the M2 method it does not provide a reason for the large deviation in modulus from the mean.

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

Inspection of the stress/strain curve in Fig 10 shows that 250 N mm^{-2} would be a reasonable upper limit. 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 grade B 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 0.0005 and 0.0025. 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	"B" type	"C" type	"B" type	"C" 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 [3].

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 (Figs 18 and 19). For example, the measurements using single sided systems were more likely to be in error than double sided systems. Also, double sided strain gauges were more repeatable than the use of double sided extensometry. However, the use of strain gauges did not always give accurate values for the modulus. Organisations 2 and 6, 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 [7] 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 [3].

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. Taking the three exercises together 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 uncertainties 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) but single sided strain measurement systems sometimes significantly resulted in uncertainties of ±5% (1 SD) or greater.

3. Overall, except for two organisations, the exercise reported uncertainties of less than ±5% (1 SD). 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 a value (and uncertainty) 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

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

These uncertainties were however considerably better than had been observed in the first UK intercomparison [3] 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 ±3%. However, the reproducibility, between organisations, was less good, increasing the uncertainties to typically ±10%. It was recommended 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. Analysis of typical NPL data indicated that this would significantly increase the value of proportional limit. Fig 20 shows the initial part of the stress/strain curve for one of the VAMAS testpieces (NPL set) with a proof stress of 0.02% selected (435 N mm^{-2}). Also shown is the proportional limit obtained by the NPL draft procedure (351 N mm^{-2}) the difference is large, about 80 N mm^{-2}). The NPL draft procedure indicates a method by which the proportional limit is obtained at approximately 0.0005% proof stress. The same data 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
0.002	354
0.005	395
0.01	416
0.02	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, particularly M2, had been more constrained with well defined upper and lower limits for the measurement, specified beforehand. The values of proportional limit also changed systematically with the different methods of analysis. For example, M2 and M3 gave lower values than M1.

PROOF AND TENSILE STRESS

The values for proof stress showed the least scatter, 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, Fig 3. Thus, with more consistent elongations to failure it might be expected that the uncertainties in tensile strength measurement 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 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 modification of 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

These intercomparisons have underlined the usefulness of making a number of small changes to the results proforma. These have been included in the new recommended results proforma (see Appendix).

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 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 [4] 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 draft procedure will be modified to take account of these changes (proportional limit, strain rate) and submitted to the appropriate standards bodies for approval.

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, 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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Table 1

VAMAS - Details of Test Conditions and Data Analysis

	Machine	Testpiece numbers	Grips	Special Alignment Fixtures	Control Mode	Strain Rate or crosshead speed	
NRIM	Instron 1195	013 041 061	wedge		c'head displ	0.55 mm min^{-1}	
Inasmet	Instron 6025	004 020 021	wedge	set square	c'head displ	0.7 mm min^{-1}	
NPL	Instron 1197	007 035 040 054	wedge	universal joint	c'head displ	1 mm min^{-1}	
Honda	Shimazu Autograph AG-2STD	015 048 056 069	wedge loaded on radius	special fixture	c'head displ	1.5 x 10^{-4} s^{-1} for E	
Bordeaux University	Adamel L'Homargy DY26	025 030 045 068	wedge	'upper spheric pair'	c'head displ	7 x 10^{-5} s^{-1}	
NASA	MTS 810	014 037 043 059	hydraulic wedge	alignment brackets	c'head displ	0.22 mm min^{-1}	
BMW	Zwick 1485	006 057 063 072			c'head displ	2 x 10^{-4} s^{-1}	
TUHH	Zwick 1445/1474	010 024 036 051	flat		c'head displ	Not given	
DLR	Instron 4505	009 011 027 064	flat		c'head displ	7 x 10^{-5} s^{-1} for E	
DRA	Zwick 1474	028 034 052 058	wedge	steel rule	strain rate control	5 x 10^{-5} s^{-1}	
NIST	Satec	001 031 042 047	wedge			Not given	
BAe	Zwick 1784	002 019 033 053	wedge		strain control	2 x 10^{-3} min^{-1}	

Table 2

VAMAS - Details of Strain Measurement and Data Analysis Methods

	Strain measurement	single/double sided	Data Acquisition system, sampling frequency	Modulus method	Failure Position from centre (mm)
NRIM	Strain gauge (triaxial) 1 mm	Single	Computer, 10 Hz	M2?	No details given
Inasmet	Extensometer 25 mm gauge length	Double	In house PC based system, 0.8 Hz	M2B	2 under extensometer contact points, 1 in centre
NPL	Strain gauge (long) 3 mm	Double	Multi channel unit + PC with in-house software, 2 Hz	M3	Gauge length failures
Honda	Strain gauge (long) 5 mm + Extensometer 25 mm gauge length	Double Single ext	Chart recorder	M1	All failed between 18 - 21 mm of the centre, outside of gauge length
NASA	Extensometer (ASTM Class B-1) 25 mm gauge length	Double	PC based data acquisition, 0.5 Hz	M2B (0 - 275 Nmm^{-2})	2 failed inside gauge length, 2 just outside
Bordeaux University	Strain gauge (long) 3.2 mm	Double	PC and dedicated software, 0.5 Hz	M1	1 failed near centre, others 14 - 18 mm from centre, just outside gauge length
BMW	Extensometer 30 mm gauge length	Double	PC	M2A	Shear failure, but position not specified
TUHH	Extensometer and strain gauges 25 mm gauge length	Single (ext) and gauge Double (gauge)	Chart recorder + PC	M2	Shear failure, 2 in gauge length, 2 outside
DLR	Extensometer 25 mm gauge length	Double	No details specified	M1	'semi-brittle failure', all between 9-18 mm of centre, possibly at extensometer contacts

Table 2 (continued)

	Strain measurement	single/double sided	Data Acquisition system, sampling frequency	Modulus method	Failure Position from centre (mm)
DRA	Extensometer, BS 3846 Grade C, 20 mm gauge length	Double	XY recorder	M1	semi-brittle failure, three 10-12 mm from centre one at centre
NIST	Extensometer 25 mm gauge length	Single	Computer data logger	M2?	No details given
BAe	Extensometer, Grade C 25 mm gauge length	Double	Computer, Zwick software	M2B	2 failed near centre, others ~18 mm from centre possibly at extensometer contacts

Table 3 - VAMAS Individual Results

Organisation	Testpiece codes	Young's Modulus (kN mm^{-2})	Tensile strength (N mm^{-2})	Proportional limit (N mm^{-2})	0.2% Proof stress (N mm^{-2})	Elongation (%)
NRIM	013	99.0	680		476	
	041	108.0	663		495	
	061	112.0	680		498	
Inasmet	004	100.0	641	376	483	3.5
	020	97.0	668	357	485	4.4
	021	100.0	643	352	460	3.6
NPL	007	105.0	684	351	487	5.6
	035	104.0	675	354	493	6.6
	040	104.5	683	331	498	6.1
	054	103.5	668	335	505	5.1
Honda	015	101.0	645	382	465	2.0
	048	99.5	636	376	501	3.0
	056	99.0	654	406	511	2.0
	069	99.0	652	351	516	3.0
Bordeaux University	025	103.0	589	432	505	
	030	103.0	666	416	484	
	045	103.0	653	420	490	
	068	101.5	675	446	512	5.4
NASA	014	104.5	680	360	492	5.2
	037	104.5	673	345	507	4.3
	043	104.0	680	361	502	5.3
	059	103.5	674	358	514	6.4
BMW	006	118.5	679		484	4.7
	057	111.0	676		516	4.3
	063	115.0	677		516	5.7
	072	101.0	665		519	4.8
TUHH	010	106.0	669	331	475	4.6
	024	108.0	688	372	464	4.4
	036	106.5	645	392	488	3.6
	051	107.0	684	444	511	6.9
DLR	009	105.0	671	275	474	5.4
	011	101.0	678	367	473	5.3
	027	104.0	675	416	500	5.6
	064	102.0	683	429	519	4.2
DRA	028	105.0	671	404	505	5.5
	034	101.0	659	419	498	5.2
	052	100.0	673	436	509	6.0
	058	103.5	667	426	511	5.9
NIST	001	141.0 *	660	180	480	3.4
	031	100.0	690	395	513	4.4
	042	166.5 *	637	420	515	2.7
	047	101.0	643	380	512	2.9
BAe	002	108.0	686	273	505	6.5
	019	110.0	691	277	476	7.0
	033	110.0	678	275	503	5.5
	053	104.0	676	257	515	6.0

NB Modulus values are rounded up or down to the nearest 0.5 kN mm^{-2}

* Outliers

Table 4 - VAMAS Tests (Mean and Standard Deviations)

	Young's Modulus (kN mm^{-2})	Tensile strength (N mm^{-2})	Proportional limit (N mm^{-2})	0.2% Proof stress (N mm^{-2})	Elongation (%)
NRIM	106.3 5.4	674 8		490 10	
Inasmet	99.0 1.4	651 12	362 10	476 11	3.8 0.4
NPL	104.3 0.6	678 7	343 10	496 7	5.9 0.6
Honda	99.6 0.8	647 7	379 20	498 20	2.5 0.5
Bordeaux University	102.6 0.6	646 34	429 12	498 11	5.4 0
NASA	104.1 0.4	677 3	356 6	504 8	5.3 0.7
BMW	111.4 6.6	674 5		509 14	4.9 0.5
TUHH	106.9 0.7	672 17	385 41	485 18	4.9 1.2
DLR	103.0 1.6	677 4	372 60	492 19	5.1 0.5
DRA	102.4 2.0	668 5	421 12	506 5	5.7 0.3
NIST	127.1 28.1	658 21	344 96	505 14	3.4 0.7
BAe	108.0 2.4	683 6	271 8	500 14	6.3 0.6
All values	106.4 11.3	667 19	366 58	497 16	4.8 1.3
Excluding NIST	104.4 4.4	668 18	369 52	496 16	5.0 1.2

Table 5 - Breakdown of Young's modulus results according to strain measurement method (VAMAS)

	Method	Organisation	Mean modulus (kN mm^{-2})	Deviation from global mean	Standard deviation
Strain Gauges	single	NRIM	106.3	1.9	5.4
	double	NPL	104.3	-0.1	0.6
	double	Honda	99.6	-4.8	0.8
	double	TUHH *	106.9	2.5	0.7
	double	Bordeaux	102.6	-1.8	0.6
	Mean		103.9		1.6
Extensometry	double	Inasmet	99.0	-5.4	1.4
	double	NASA	104.1	-0.3	0.4
	double	BMW	111.4	7.0	6.6
	double	DLR	103.0	-1.4	1.6
	double	DRA	102.4	-2.0	2.0
	double	BAe	108.0	3.6	2.4
	Mean		104.7		2.4

Table 6 - Breakdown of Young's modulus results according to analysis method (VAMAS)

	Organisation	Mean modulus (kN mm^{-2})	Deviation from global mean	Standard deviation
M1	Honda	99.6	-4.8	0.8
	Bordeaux	102.6	-1.8	0.6
	TUHH *	106.9	2.5	0.7
	DRA	102.4	-2.0	2.0
	DLR	103.0	-1.4	1.6
	Mean	102.9		1.1
M2	Inasmet	99.0	-5.4	1.4
	NASA	104.1	-0.3	0.4
	BMW	111.4	7.0	6.6
	NRIM	106.3	1.9	5.4
	BAe	108.0	3.6	2.4
	Mean	105.8		3.2
M3	NPL	104.3	-0.1	0.6

TUHH *	2 testpieces - Gd 2 testpieces - mean of extensometer and 1 strain gauge

Table 7

UK Forum Validation Exercise - Details of Strain Measurement and Data Analysis Methods

	Machine	Testpiece nos. (MMC, Al matrix)	Grips	Special Alignment Fixtures	Control Mode	Strain Rate
Org 1	Mand/ESH	L01 L09 L16 L02 L12 L26	Wedge	Square and universl joint	strain/load control	$5 \times 10^{-5}\ s^{-1}$
Org 2	Instron 1121	L02 L07 L15 L11 L19 L25	Wedge	By eye	crosshead displacement	$6 \times 10^{-5}\ s^{-1}$
Org 3	Zwick 1474	T04 T05 T07 L03 L04 L21	Wedge	Steel rule	Strain	$5 \times 10^{-5}\ s^{-1}$
Org 4	Instron 6025	L04 L08 L12 L09 L10 L28	Wedge	Special fixture	crosshead displacement	$\sim 2 \times 10^{-5}\ s^{-1}$
Org 5	Instron 1197	L03 L05 L11 L14 L22 L30	Wedge	Universal joint, by eye	crosshead displacement	1 mm min^{-1}
Org 6	Mand 160 kN Universal	T06 T10 T11 L06 L15 L24	Wedge	Square metal block	i) Strain ii) C'head displ	$3 \times 10^{-5}\ s^{-1}$
Org 7	Zwick 1784	L10 L14 L18 L08 L16 L29	Button	special fixture	strain	$2 \times 10^{-3}\ min^{-1}$

Table 8

UK FORUM VAMAS - Test Details

	Strain measurement	single/double sided	Data Acquisition system, sampling frequency	Modulus method	Failure Position from centre (mm)
Org 1	Extensometer, Grade C 20 mm gauge length	Single	ESH computer system	M2	MMC: 2 inside, 1 outside gauge length Al: 14-17 mm from centre
Org 2	Strain gauges and Extensometer, 25 mm gauge length	Double	Computer and chart recorder, 113 Hz	M2B (s gauges) M1 (ext)	MMC: outside gauge length, 1 at radius Al: 2 in gauge length
Org 3	Extensometer, Grade C 20 mm gauge length	Double	XY recorder	M1	MMC: 1 in centre, 5 mm, near radius Al: 13 mm, centre radius
Org 4	Extensometer, BS 3846 'B' 25 mm gauge length	Single	Instron computer and software, 0.5 Hz	M2B	MMC: 1 under extensometer knife edge, 15 mm, centre Al: 1 under extensometer knife edge, 16 mm, centre
Org 5	Strain gauge (long) 3 mm	Double	Multi channel unit + PC with in-house software, 2 Hz	M3	MMC: Al:
Org 6	i) Strain gauges (6 mm) ii) Extensometer 25 mm gauge length	Double (sg) Single (ext)	Computer based system, Apple + ADU, 1 Hz	M2A	MMC: Brittle, 1 in centre, 2 outside Al: Ductile, outside middle third of gauge length
Org 7	Extensometer 20 mm gauge length	Double	Computer, Zwick software	M2B	

Table 9 - UK Forum Individual Results (Metal Matrix Composite)

Organisation	Testpiece codes	Young's Modulus (kN mm^{-2})	Tensile strength (N mm^{-2})	Proportional limit (N mm^{-2})	0.2% Proof stress (N mm^{-2})	Elongation (%)
1	L01	131.5	566		436	0.4
	L09					
	L16	106.0	608		451	4.1
2	L02 (ext)	102.5				
	L02 (sg)	93.5	605	302	458	
	L07 (ext)	98.5	602			
	L07 (sg)	94.5				
	L15 (ext)	100.0	610			
	L15 (sg)	93.5				
3	T04	104.0	610	255	432	5.5
	T05	100.0	629	200	444	6.8
	T07	105.5	625	321	442	6.0
4	L04	96.0	621	308	444	4.5
	L08	96.0	623	328	440	5.7
	L12	96.0	622	328	440	4.9
5	L03	102.0	635	194	447	5.0
	L05	101.0	628	263	447	4.6
	L11	101.0	610	189	445	3.5
6	T06 (ext)	103.0	623		444	7.0
	T06 (sg)	106.0				
	T10 (ext)	103.0	630		450	6.9
	T10 (sg)					
	T11 (ext)	105.0	598		455	2.1
	T11 (sg)	107.5				
7	L10	99.5	497	250	455	0.5
	L14	104.5	507	265	451	1.0
	L18	112.0	548	278	453	1.5
Mean *		101.1	601	268	447	4.4
Std dev *		4.6	40	48	7	2.1

NB Modulus values are rounded up or down to the nearest 0.5 kN mm^{-2}
* Mean and standard deviation do not include data from Organisation 1

Table 10 - UK Forum Individual Results (2618 Cospray Al Alloy)

Organisation	Testpiece codes	Young's Modulus (kN mm^{-2})	Tensile strength (N mm^{-2})	Proportional limit (N mm^{-2})	0.2% Proof stress (N mm^{-2})	Elongation (%)
1	L02	103.0	450		417	12.3
	L12	181.0	427		381	5.8
	L26	104.0	686		412	17.8
2	L11 (ext)	71.5	444	361	409	9.5
	L11 (sg)	68.5		404	273	
	L19 (ext)	72.0	439	311	399	13.0
	L19 (sg)	67.5				
	L25 (ext)	72.5	443	354	403	
	L25 (sg)	67.5			414	
3	L03	69.0	454	359	420	9.6
	L04	72.0	450	329	410	12.5
	L21	71.5	423	351	391	9.9
4	L09	74.5	450	390	410	10.6
	L10	76.5	443	348	406	5.0
	L28	73.5	448	372	404	9.3
5	L14	73.0	446	257	412	5.6
	L22	72.5	415	216	399	2.4
	L30	72.0	460	251	416	10.5
6	L06 (ext)	76.5	439		399	11.3
	L06 (sg)	77.5				
	L15 (ext)	75.5	440		393	8.9
	L15 (sg)	76.5				
	L24 (ext)	75.0	450		411	12.2
	L24 (sg)					
7	L08	76.0	436	195	404	9.0
	L16	73.0	482	188	441	12.0
	L29	73.5	450	183	415	11.0
Mean		72.9	445	298	408	9.5
Std dev		2.8	14	72	11	2.8

NB Modulus values are rounded up or down to the nearest 0.5 kN mm^{-2}

* Mean and standard deviation do not include data from Organisation 1

Table 11 - Breakdown of Young's modulus results according to strain measurement method (UK Forum - MMC)

	Method	Organisation	Mean modulus (kN mm^{-2})	Deviation from global mean	Standard deviation
Strain Gauges	double	2	93.8	-7.3	0.5
	double	5	101.3	0.2	0.5
	double	6	106.8	5.7	0.8
	Mean		100.6		0.6
Extensometry	single	1	118.8	17.7	12.8
	double	2	100.3	-0.8	1.6
	double	3	103.2	2.1	2.3
	double	4	96.0	-5.1	0.0
	double	6	103.7	2.6	0.9
	double	7	105.3	4.2	5.1
	Mean *		101.7		2.0

Table 12 - Breakdown of Young's modulus results according to analysis method (UK Forum - MMC)

	Organisation	Mean modulus (kN mm^{-2})	Deviation from global mean	Standard deviation
M1	3	103.2	2.1	2.3
	2 (ext)	100.3	-0.8	1.6
	Mean	101.8		2.0
M2	1	118.8	17.7	12.8
	2 (sg)	93.8	-7.3	0.5
	4	96.0	-5.1	0.0
	6 (sg)	106.8	5.7	0.8
	6 (ext)	103.7	2.6	0.9
	7	105.3	4.2	5.1
	Mean *	101.1		1.5
M3	5	101.3	0.2	0.5

* Mean does not include data from Organisation 1

Table 13 - Breakdown of Young's modulus results according to strain measurement method (UK Forum - Aluminium matrix)

	Method	Organisation	Mean modulus (kN mm^{-2})	Deviation from global mean	Standard deviation
Strain Gauges	double	2	67.8	-5.1	0.5
	double	5	72.5	-0.4	0.4
	double	6	77.0	4.1	0.5
	Mean		72.4		0.5
Extensometry	single	1	129.0	56.1	36.5
	double	2	72.0	-0.9	0.4
	double	3	70.8	-2.1	1.3
	double	4	74.8	1.9	1.2
	double	6	75.7	2.8	0.6
	double	7	74.2	1.3	1.3
	Mean *		73.5		1.0

Table 14 - Breakdown of Young's modulus results according to analysis method (UK Forum - Aluminium matrix)

	Organisation	Mean modulus (kN mm^{-2})	Deviation from global mean	Standard deviation
M1	3	70.8	-2.1	1.3
	2 (ext)	72.0	-0.9	0.4
	Mean	71.4		0.9
M2	1	129.0	56.1	36.5
	2 (sg)	67.8	-5.1	0.5
	4	74.8	1.9	1.2
	6 (sg)	77.0	4.1	0.5
	6 (ext)	75.7	2.8	0.6
	7	74.2	1.3	1.3
	Mean *	73.9		0.8
M3	5	72.5	-0.4	0.4

* Mean does not include data from Organisation 1

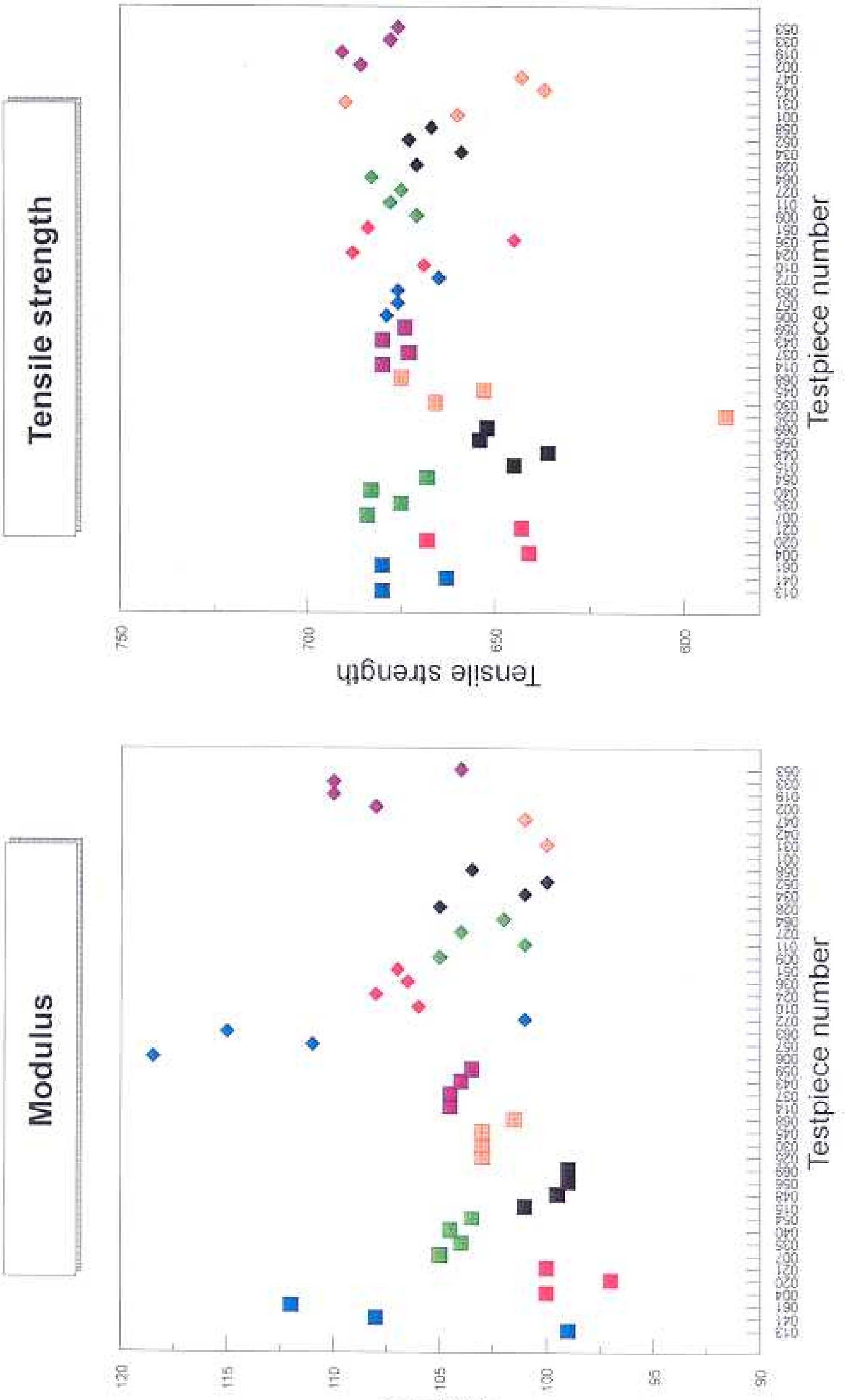


Fig 1 Young's modulus and tensile strength - VAMAS exercise

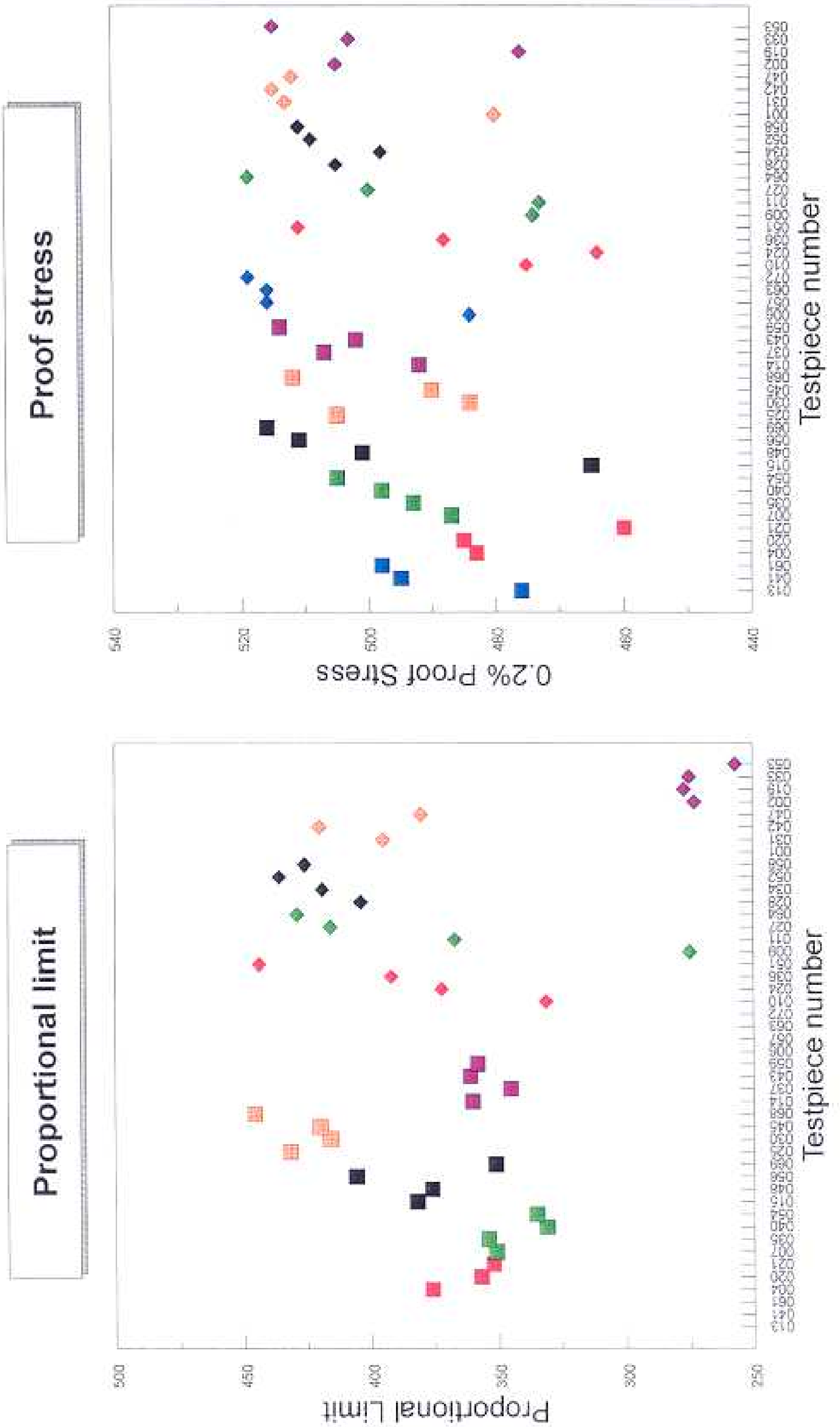


Fig 2 Proportional limit and proof stress - VAMAS exercise

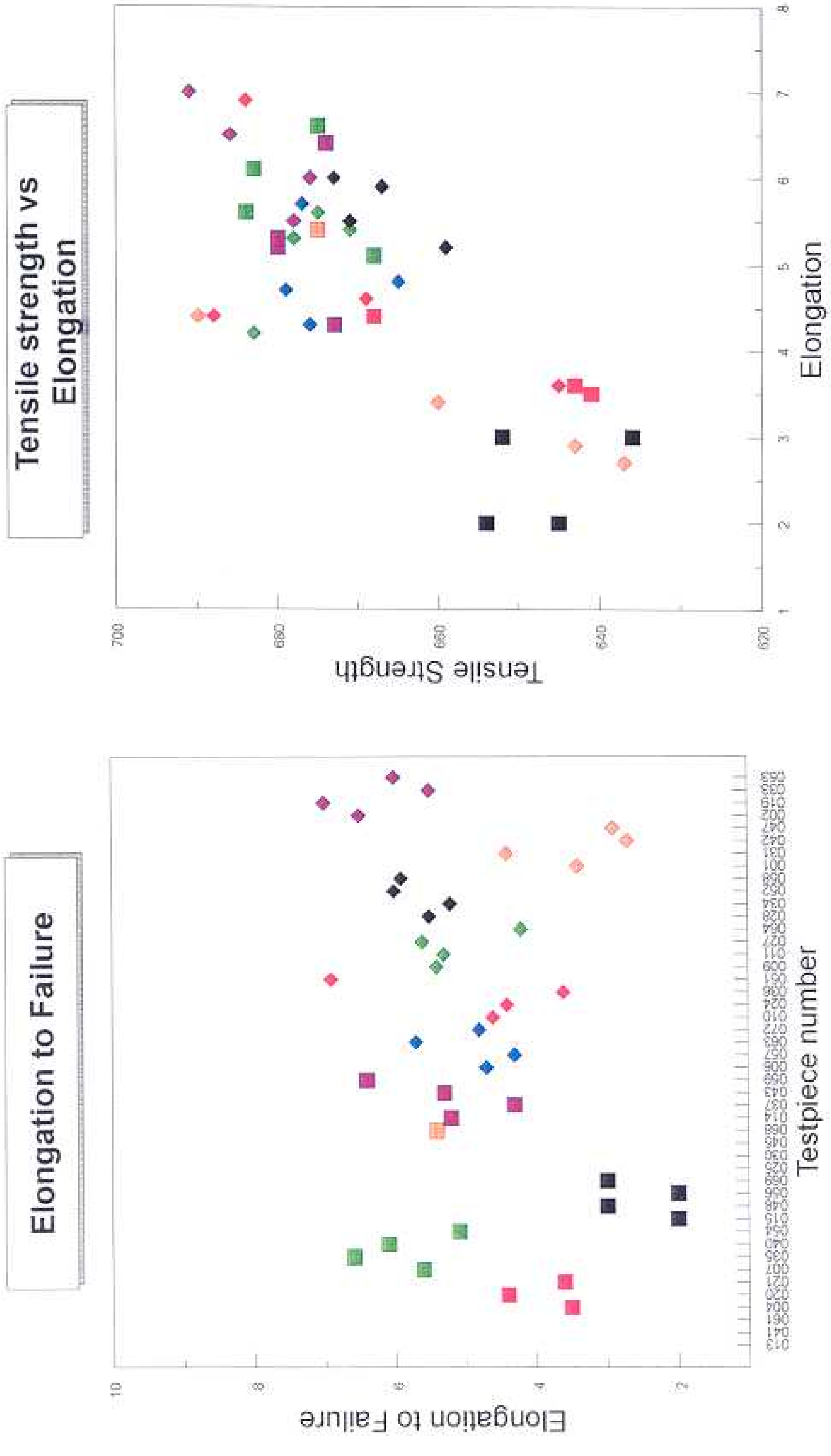


Fig 3 Elongation and tensile strength versus elongation - VAMAS exercise

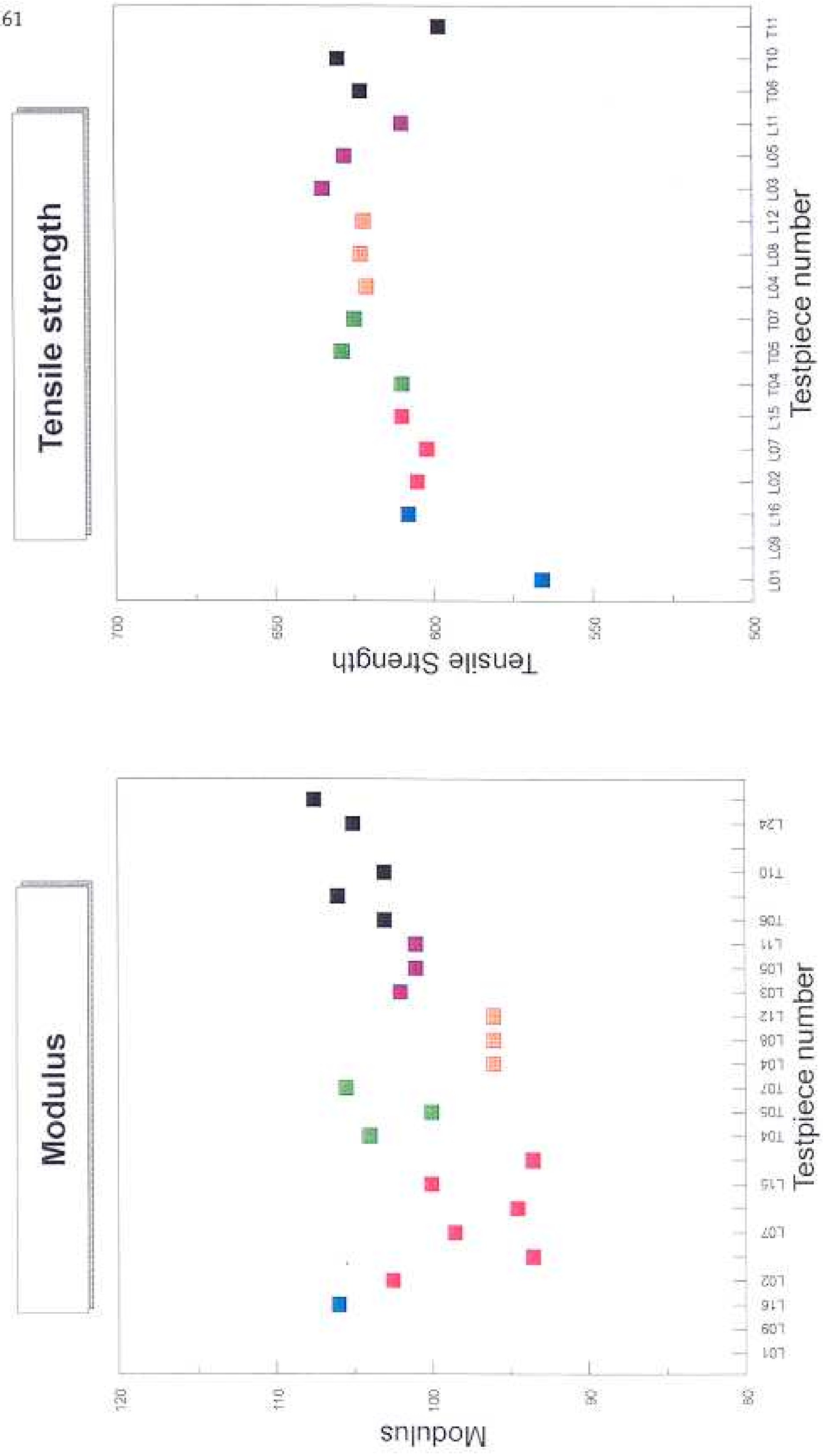
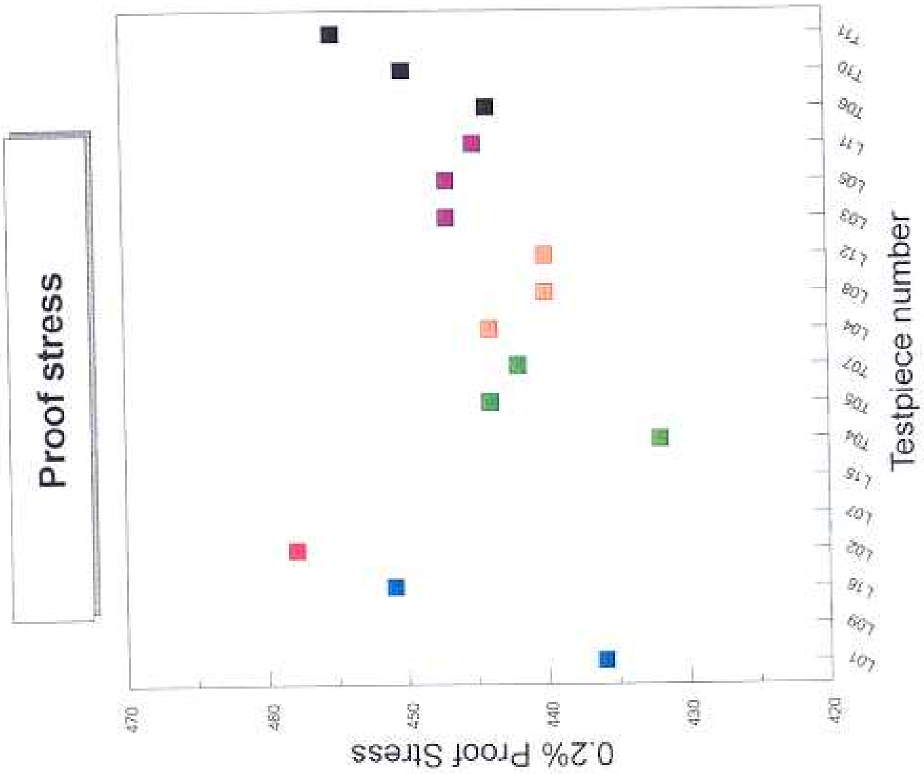


Fig 4 Young's modulus and tensile strength of MMC - UK FORUM



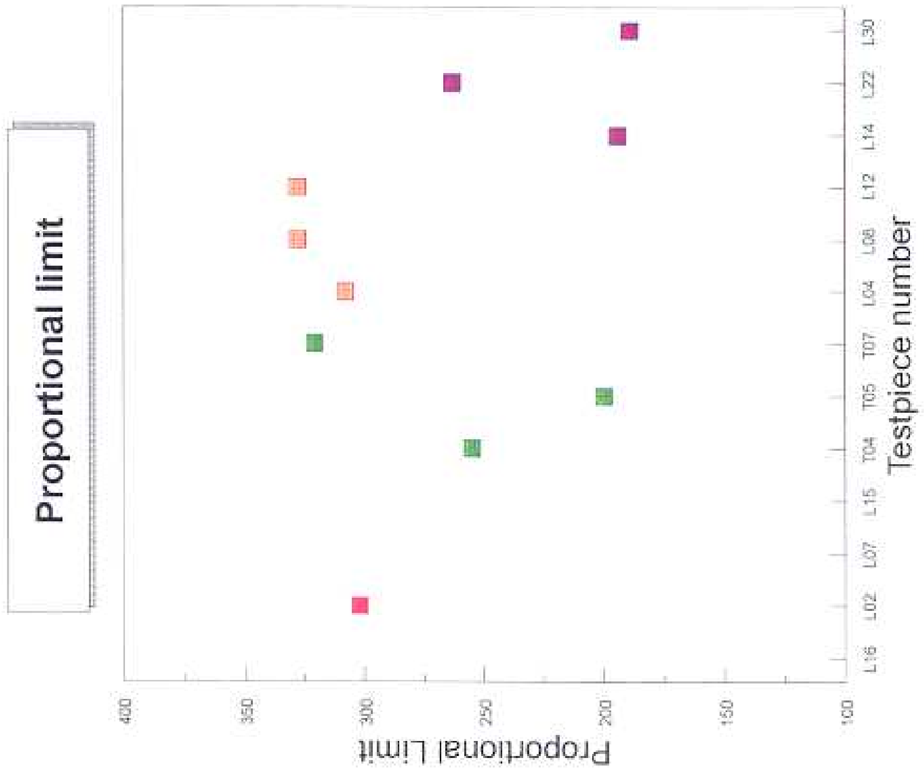


Fig 5 Proportional limit and proof stress of MMC - UK FORUM

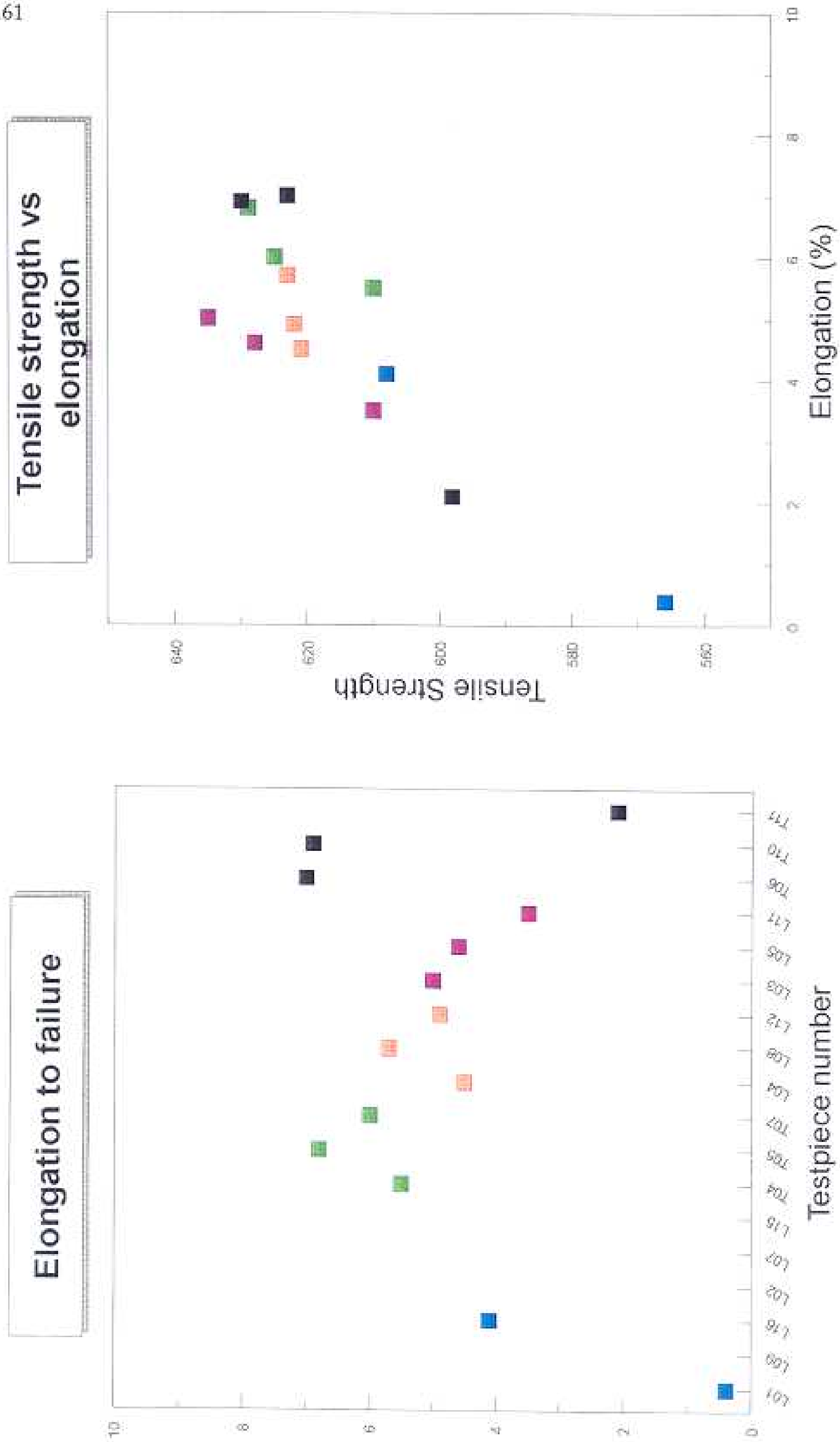


Fig 6 Elongation and tensile strength versus elongation of MMC - UK FORUM

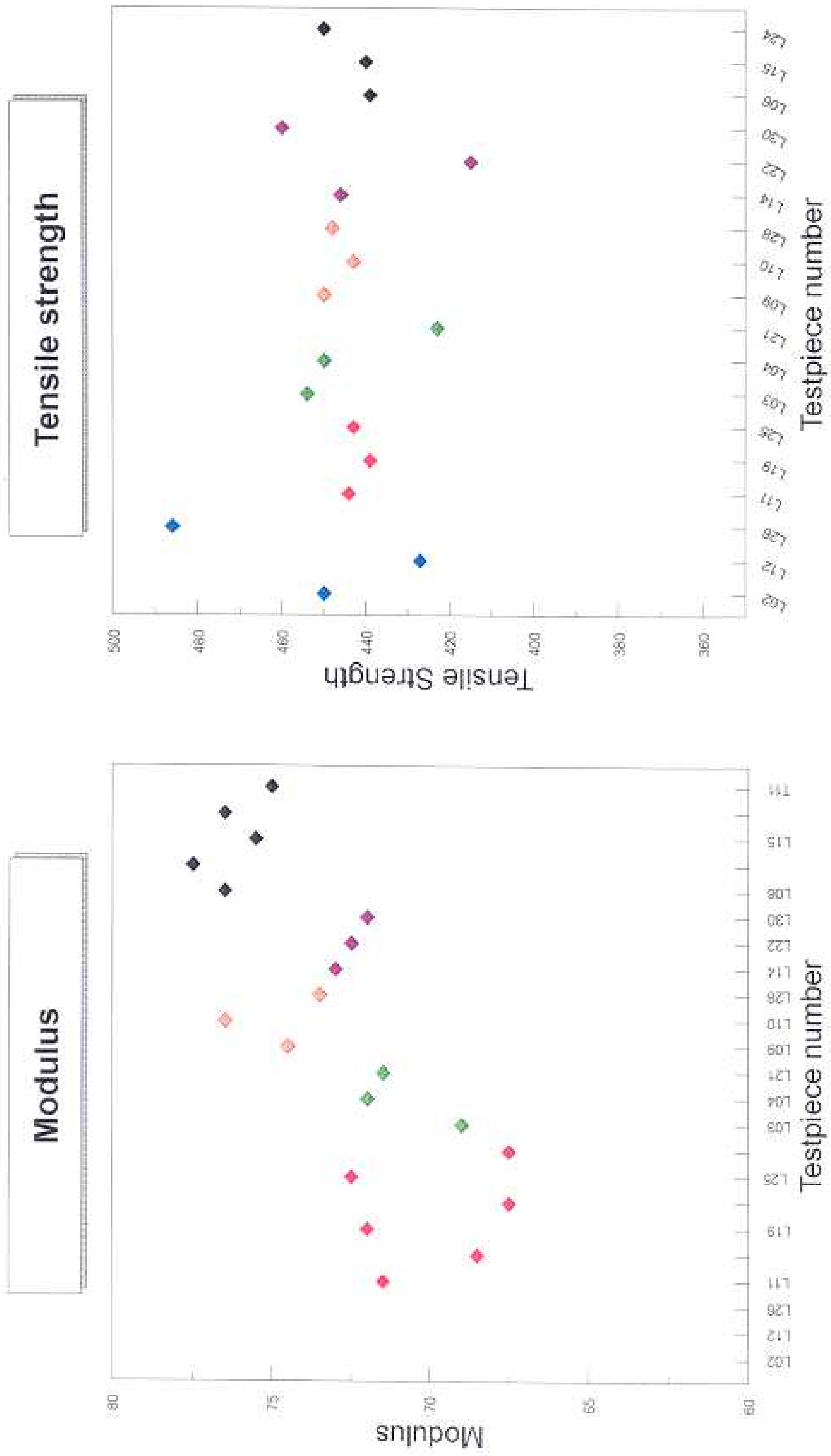


Fig 7 Young's modulus and tensile strength of matrix alloy - UK FORUM

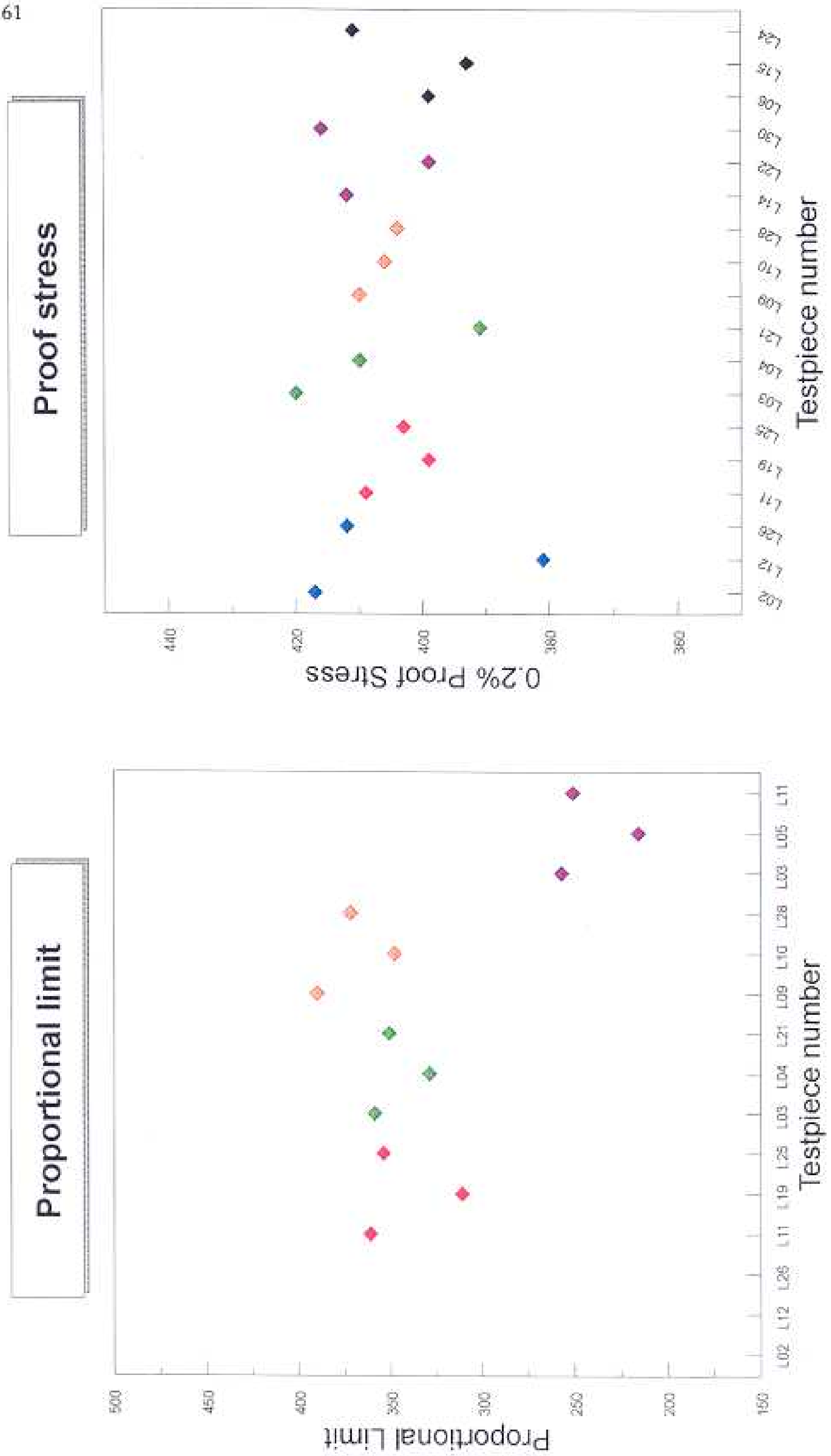


Fig 8 Proportional limit and proof stress of matrix alloy - UK FORUM

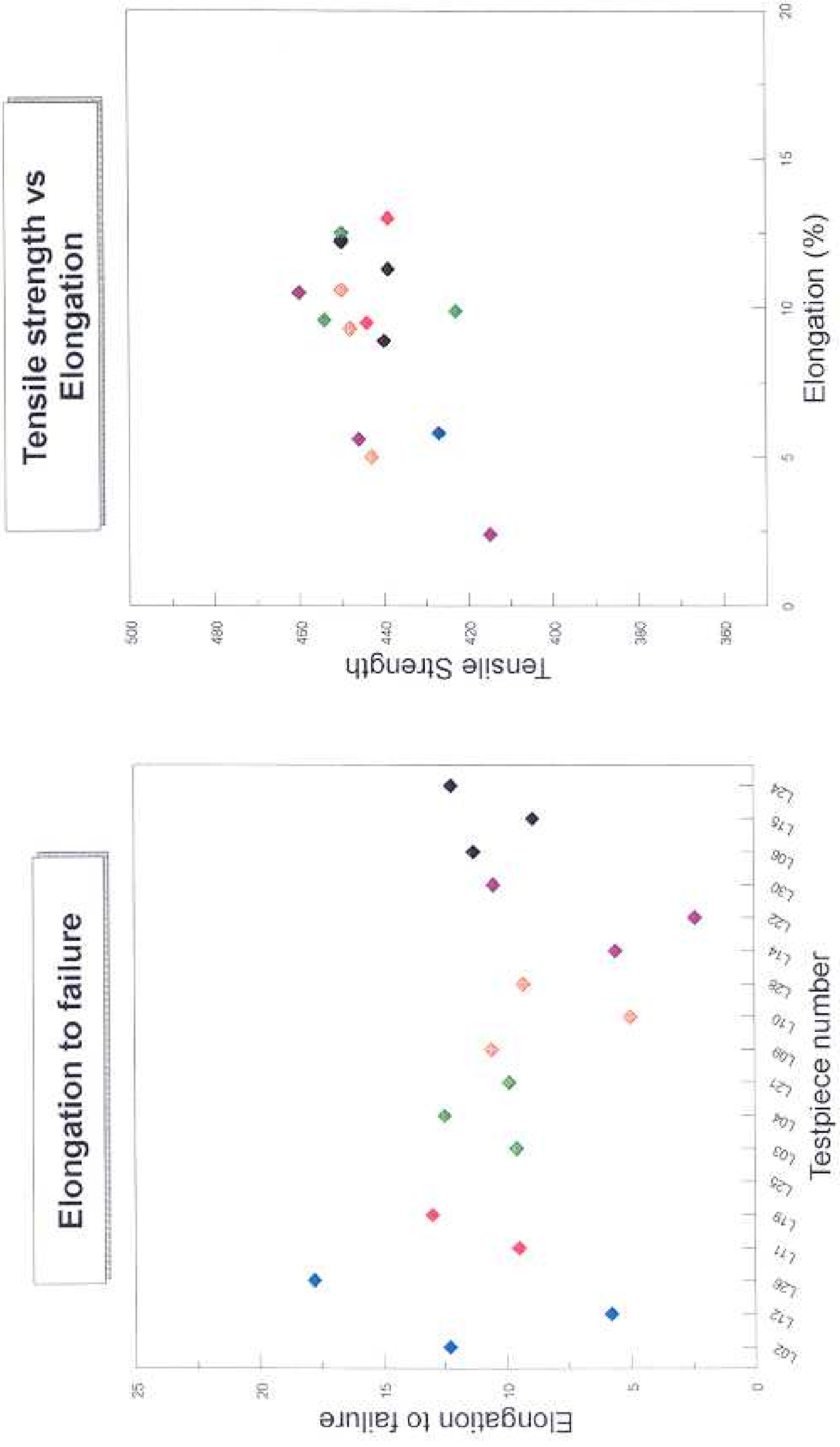


Fig 9 Elongation and tensile strength versus elongation of matrix alloy - UK FORUM

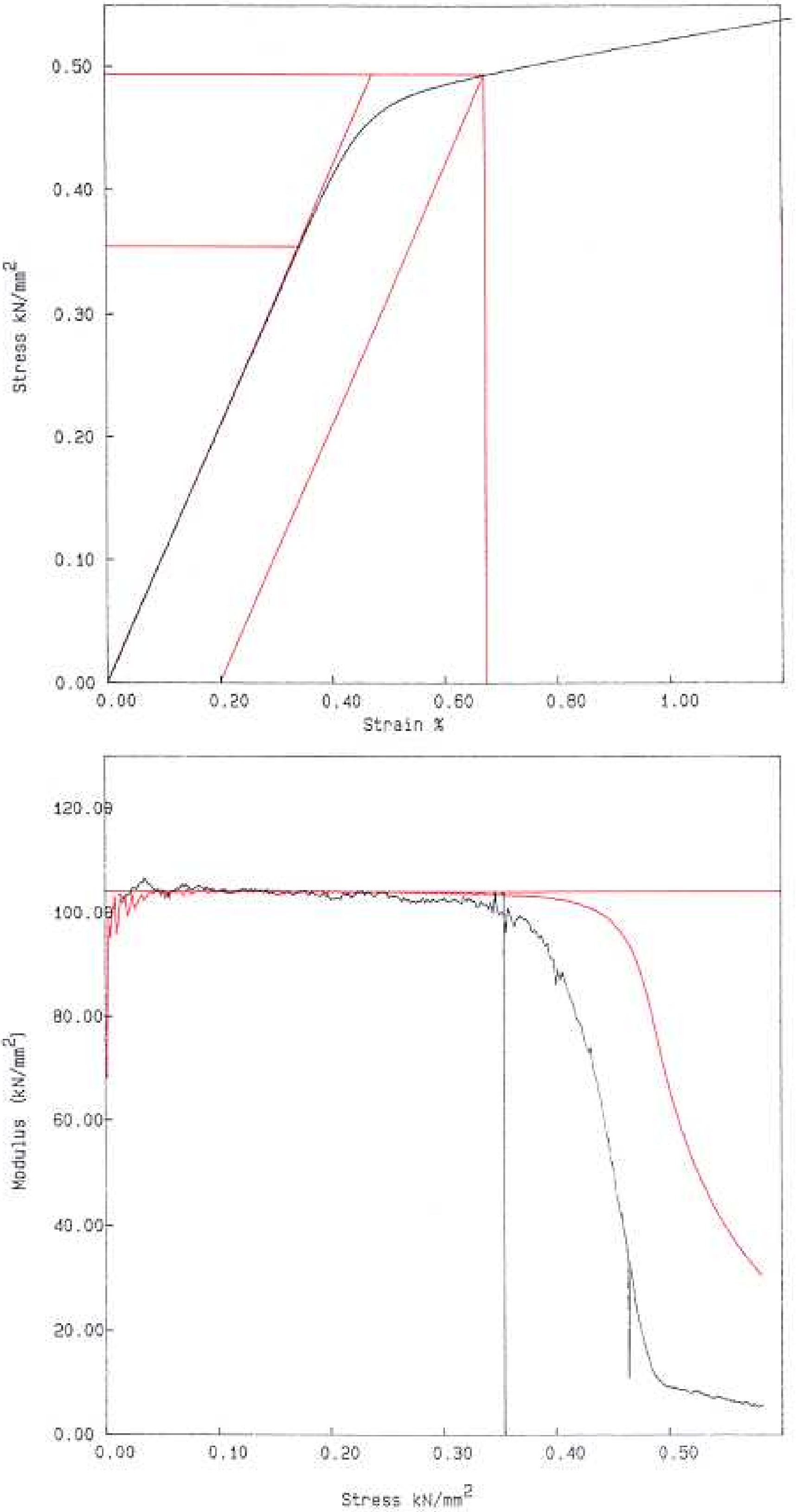


Fig 10 Stress/strain and tangent & secant modulus plots (NPL) - VAMAS Testpiece 035

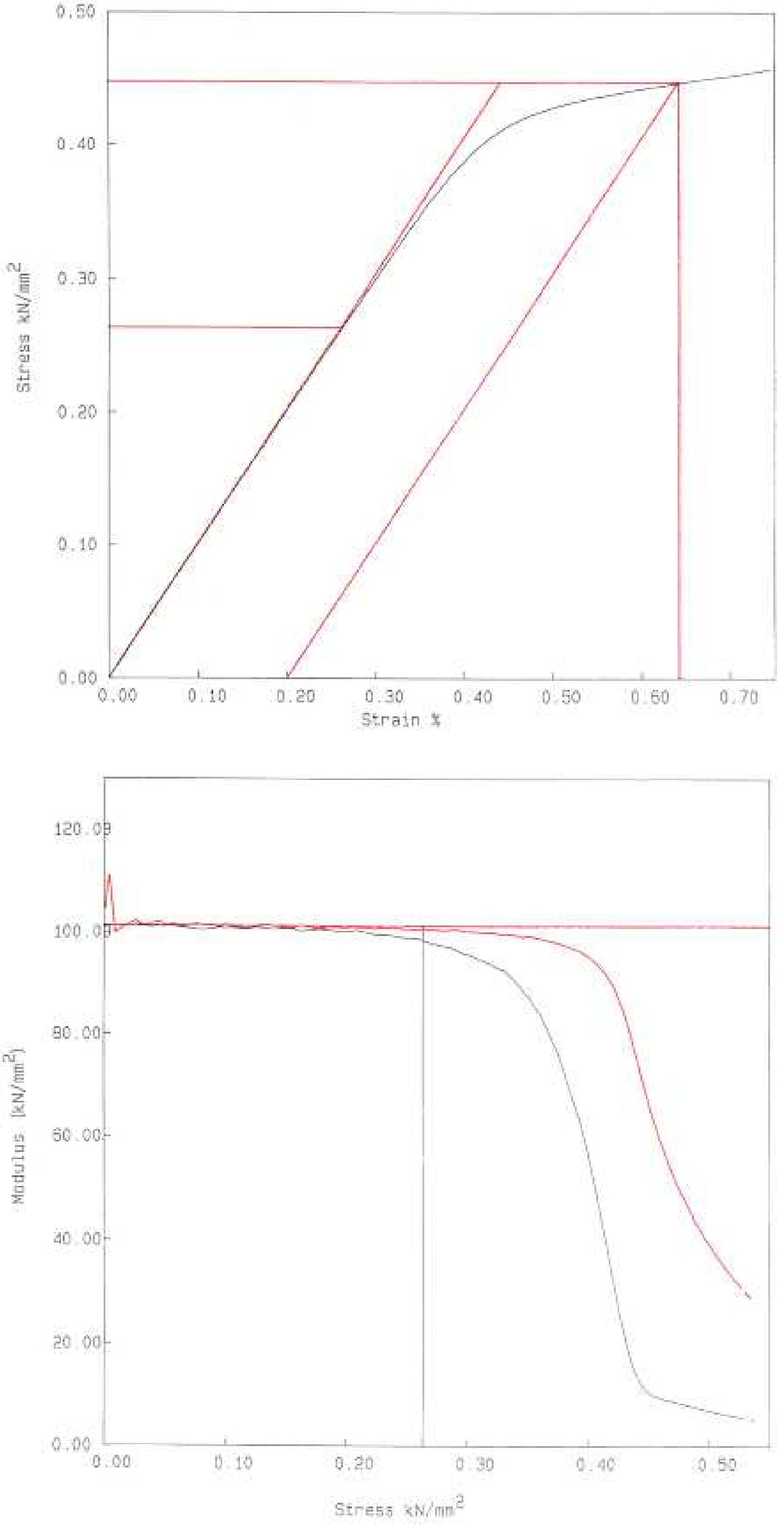


Fig 11 Stress/strain and tangent & secant modulus plots (NPL) - UK FORUM, MMC Testpiece L05

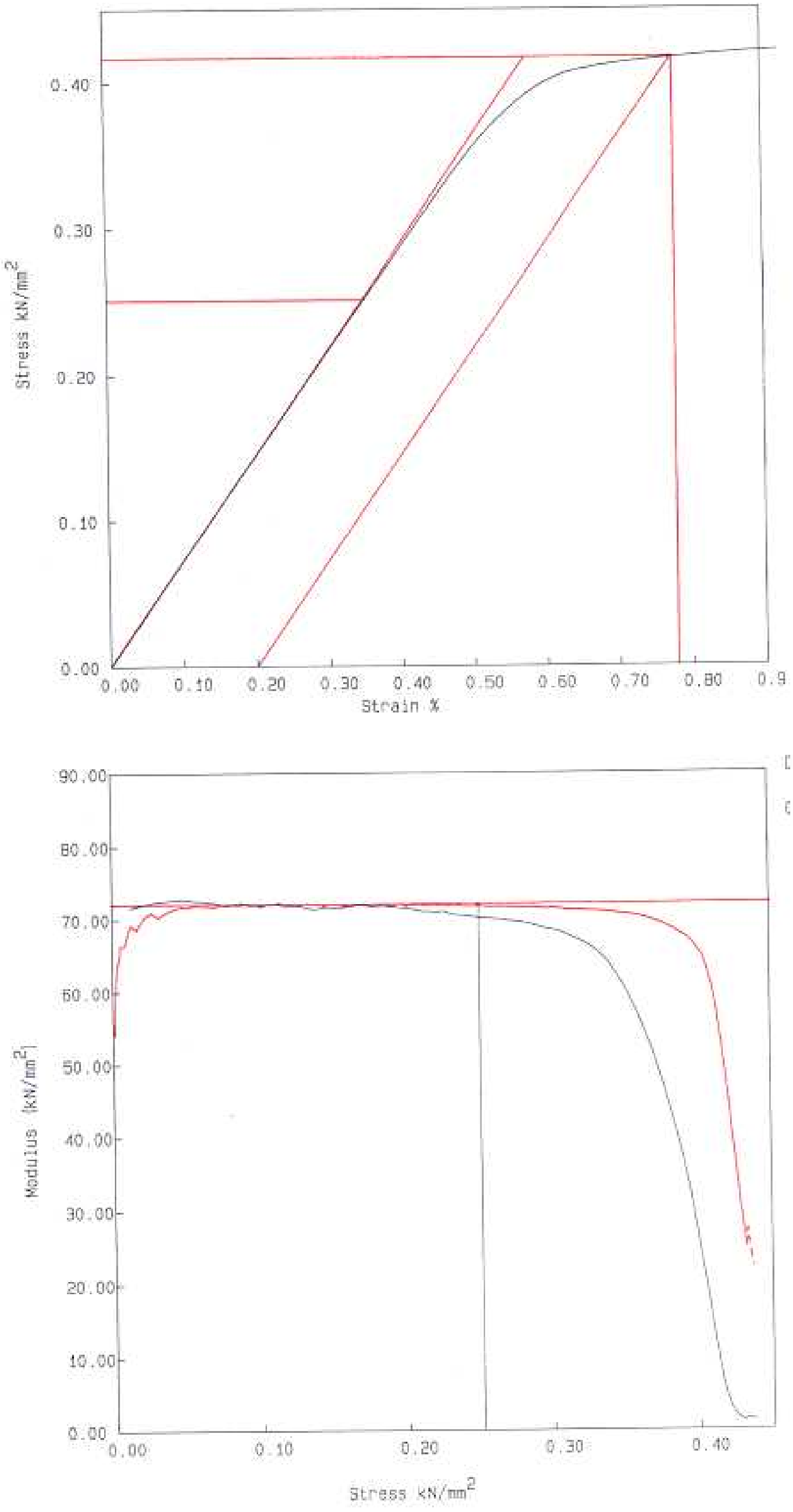


Fig 12 Stress/strain and tangent & secant modulus plots (NPL) - UK FORUM, Al matrix Testpiece L30

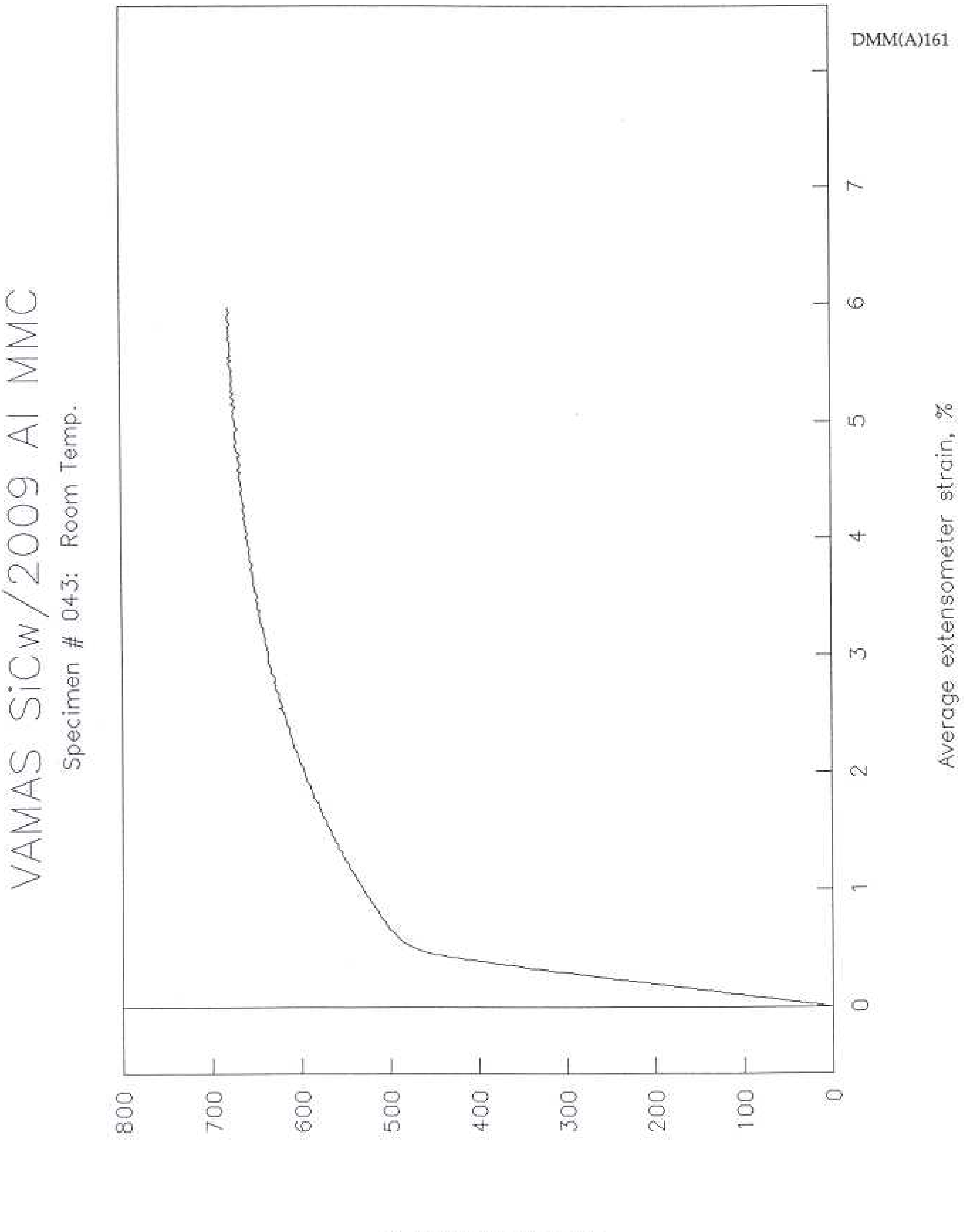


Fig 13 Typical stress/strain plot (NASA - average, from double sided extensometer)

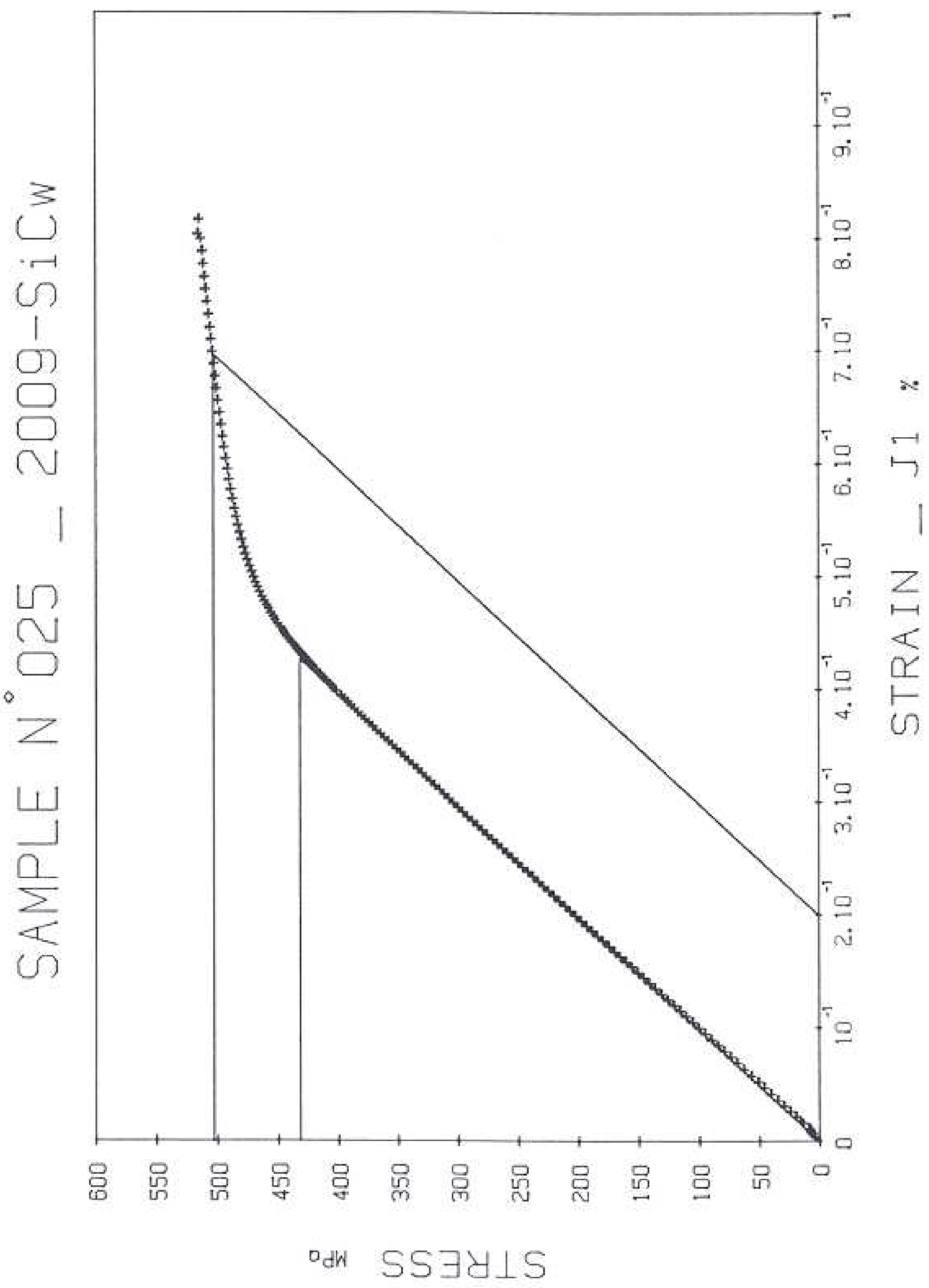
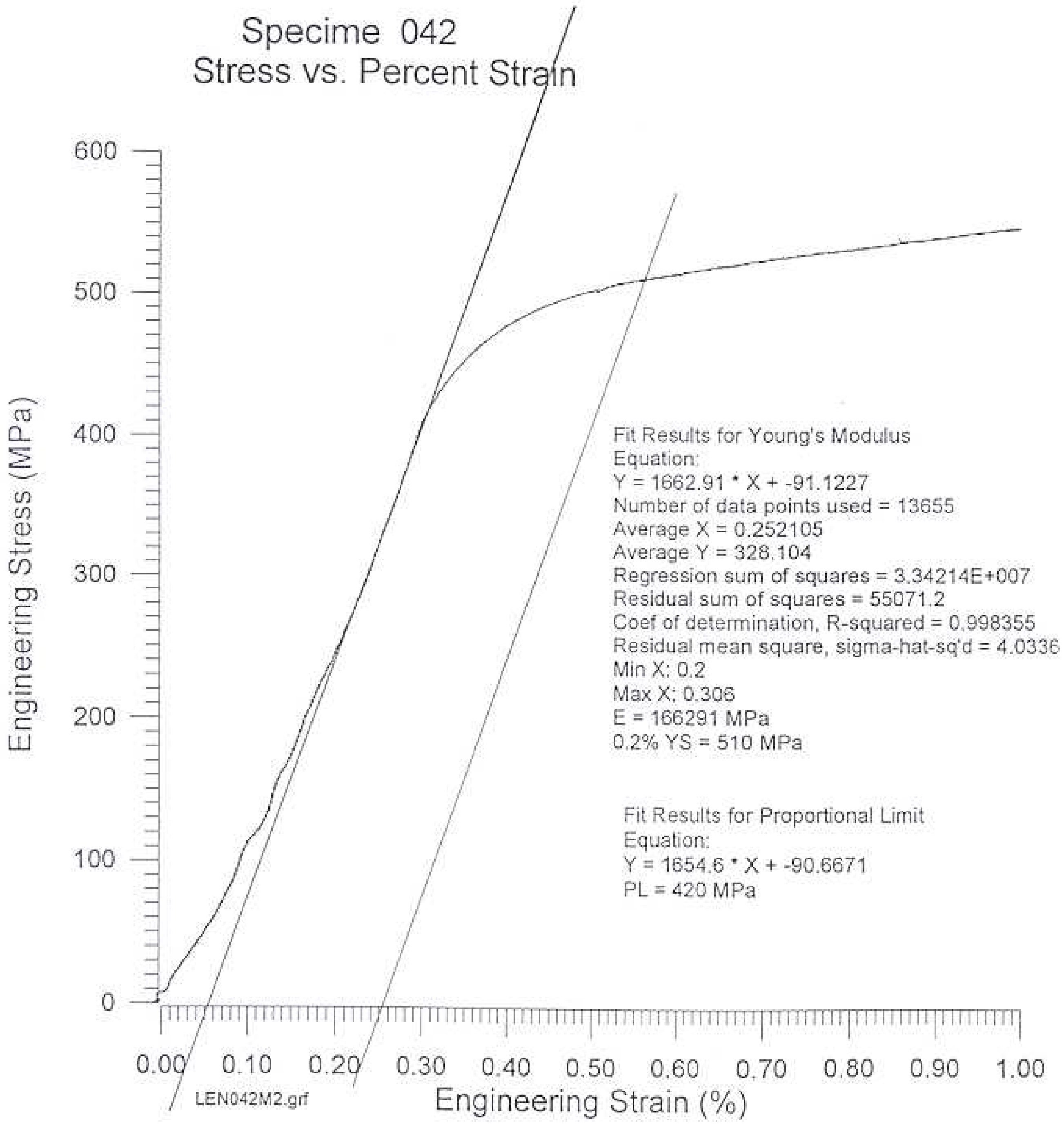


Fig 14 Typical stress/strain plot (Univ Bordeaux - average, from double sided strain gauges)



```
Fit Results for Young's Modulus
Equation:
Y = 1662.91 * X + -91.1227
Number of data points used = 13655
Average X = 0.252105
Average Y = 328.104
Regression sum of squares = 3.34214E+007
Residual sum of squares = 55071.2
Coef of determination, R-squared = 0.998355
Residual mean square, sigma-hat-sq'd = 4.0336
Min X: 0.2
Max X: 0.306
E = 166291 MPa
0.2% YS = 510 MPa
```

```
Fit Results for Proportional Limit
Equation:
Y = 1654.6 * X + -90.6671
PL = 420 MPa
```

Fig 15 Stress/strain plot using single sided extensometer

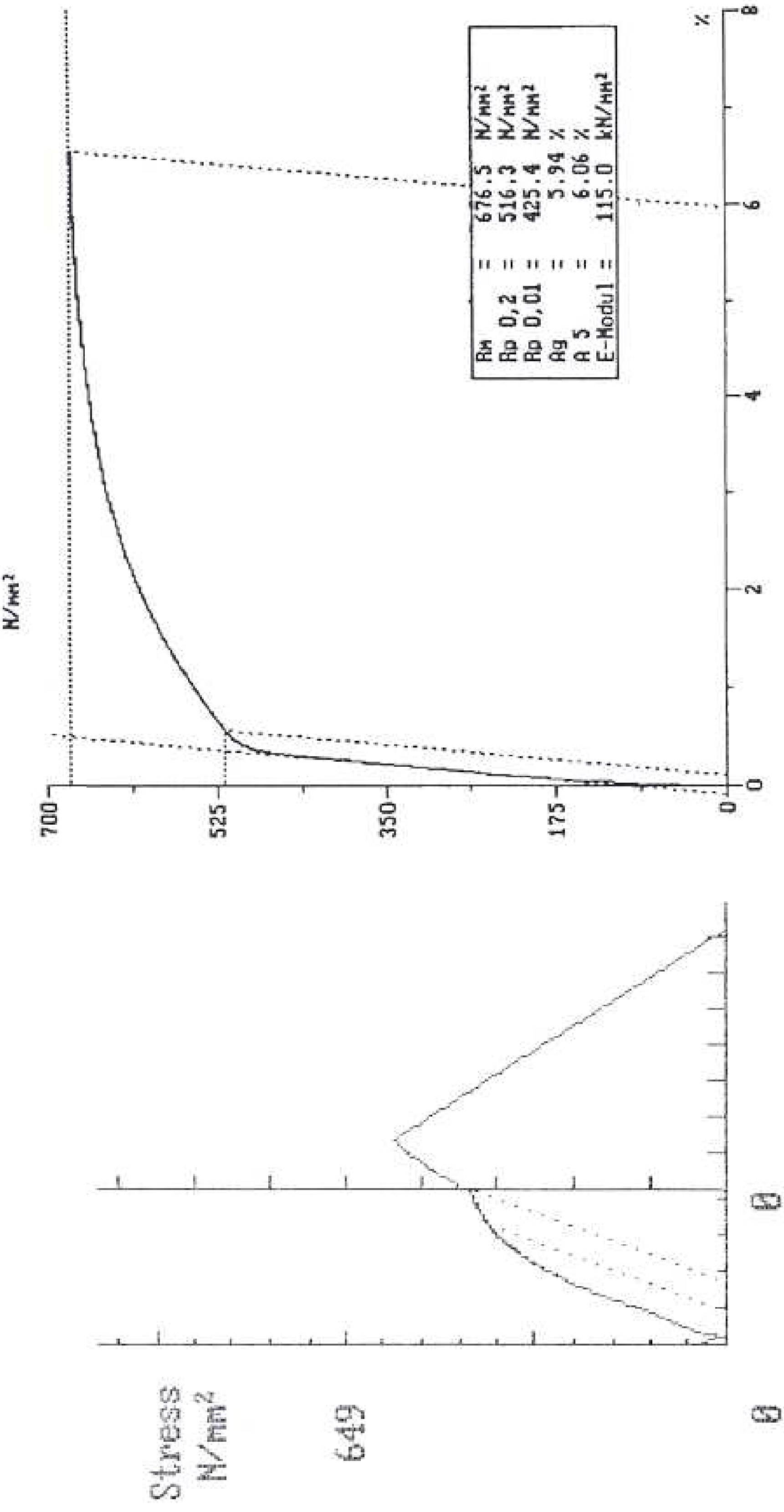


Fig 16 Stress/strain plots showing poorly delineated initial section of the trace.

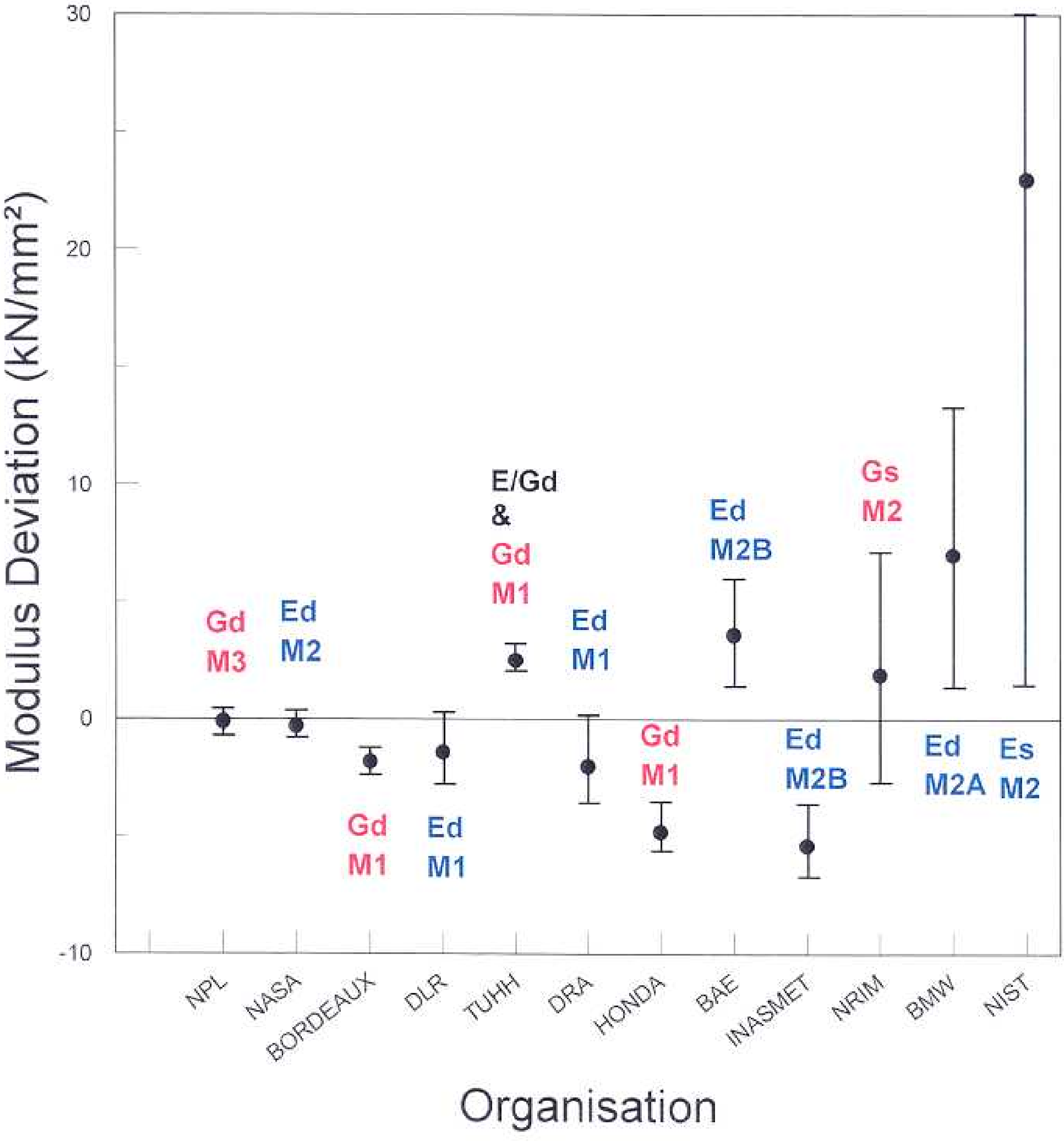


Fig 17 Deviation in Young's modulus values - VAMAS exercise

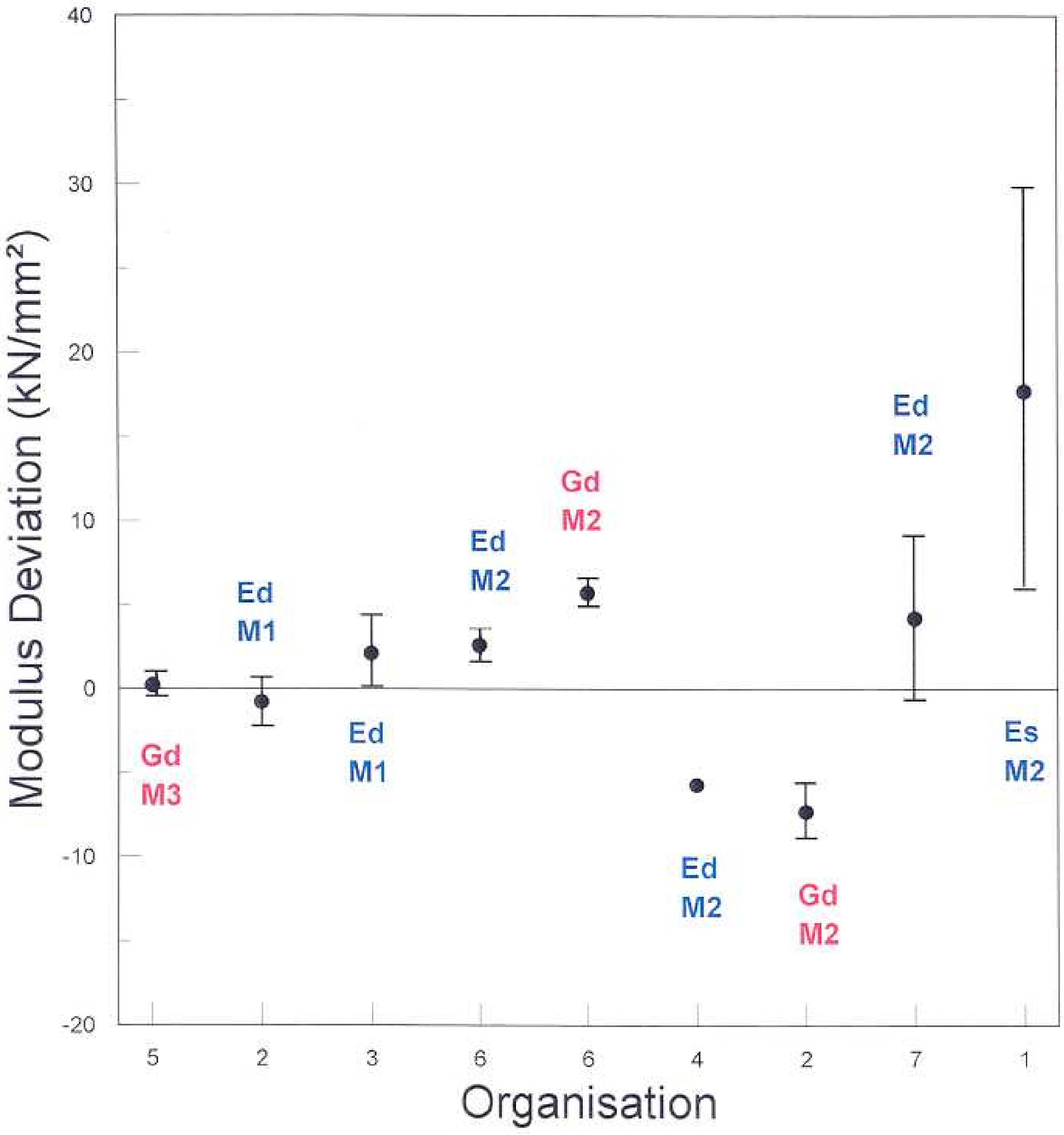


Fig 18 Deviation in Young's modulus values for MMC - UK FORUM

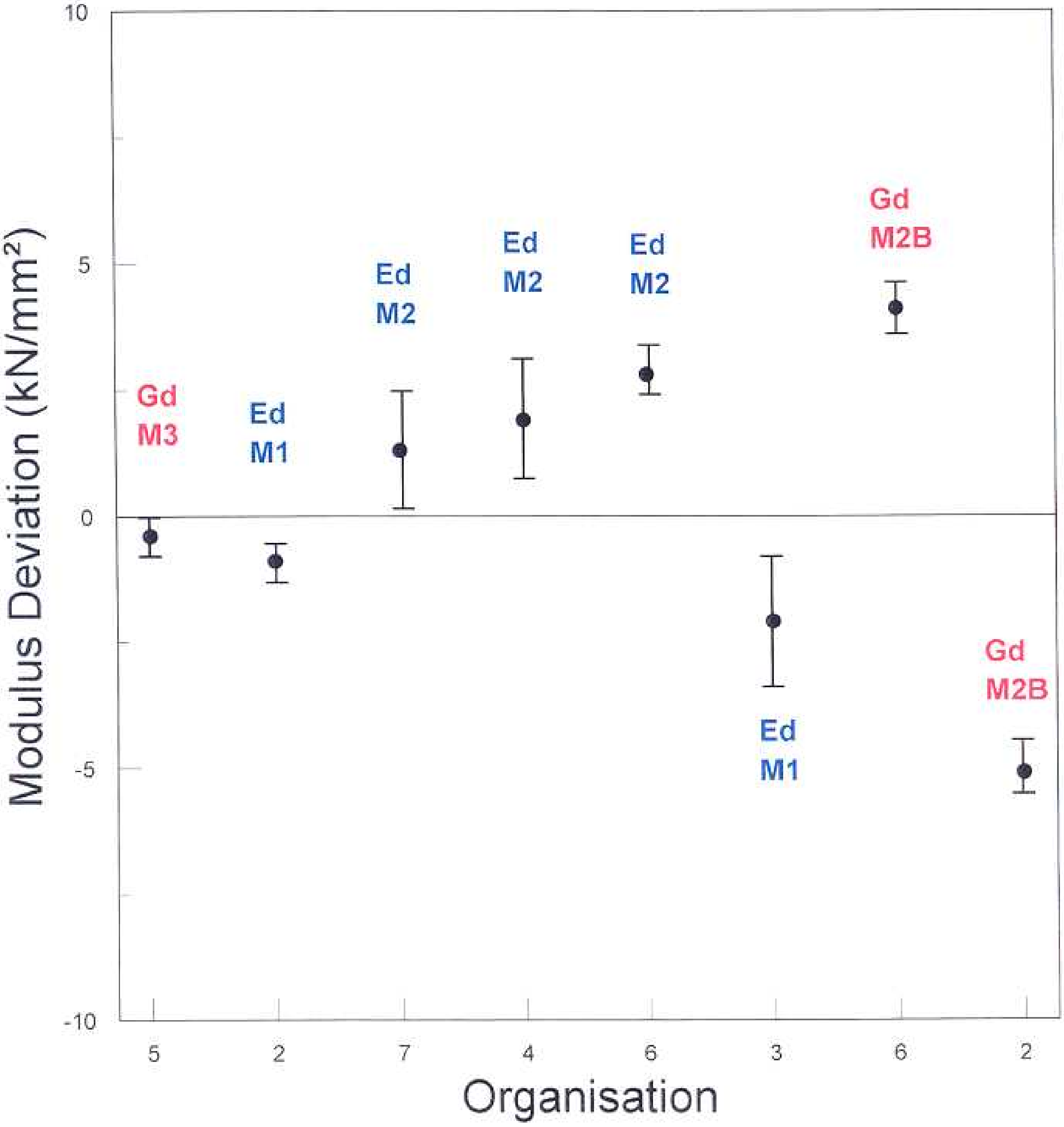


Fig 19 Deviation in Young's modulus values for Al matrix - UK FORUM

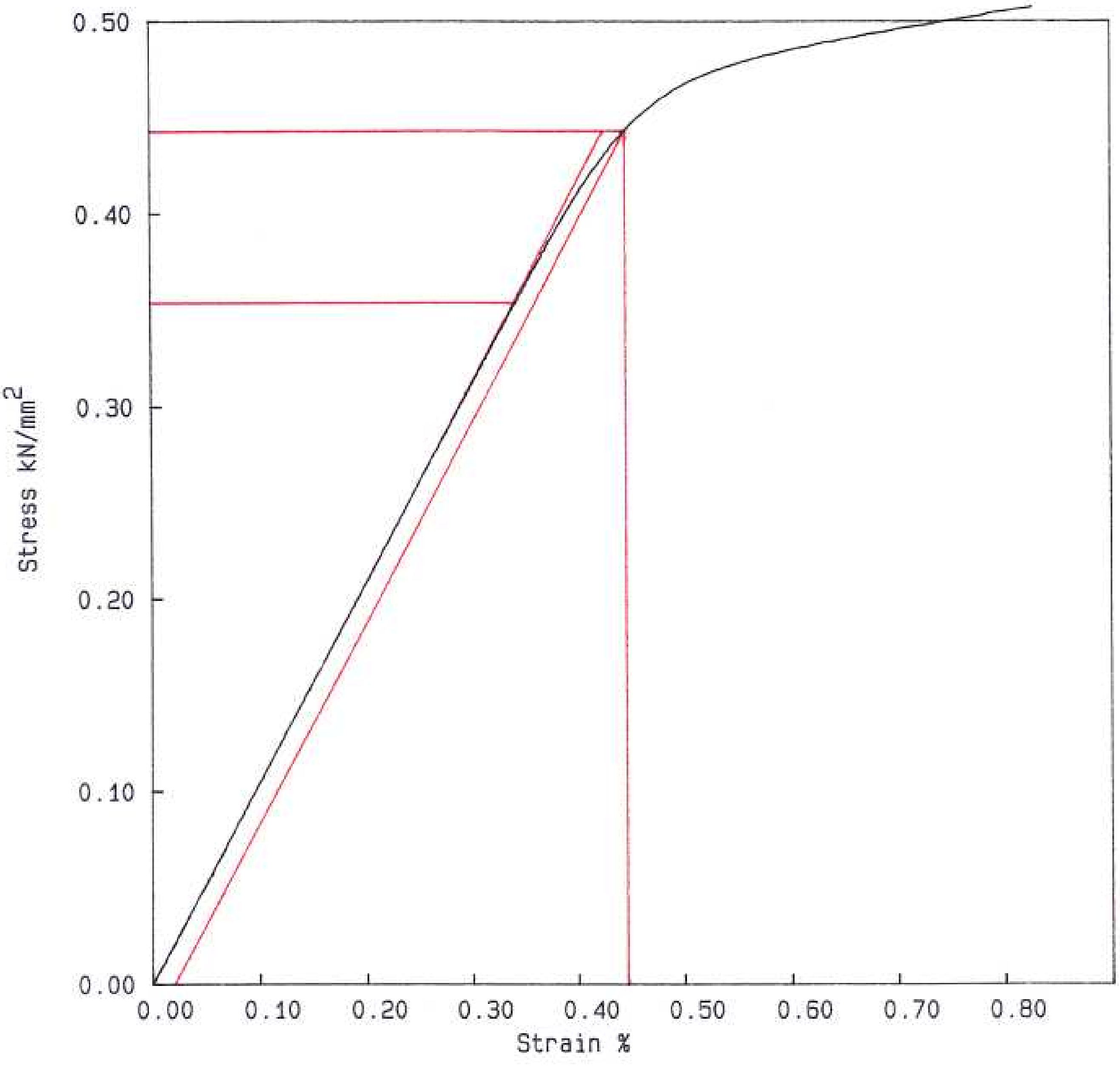


Fig 20 Proof stress selected at 0.02% plastic strain

LIST OF CAPTIONS