RESIDUAL STRESSES IN HIGH VOLUME FRACTION METAL MATRIX COMPOSITES

J. Quinta da Fonseca[1], R. F. Cochrane[1], P.M. Mummery[2] and M. R. Daymond[3]

[1] *Department of Materials, University of Leeds Leeds LS2 9JT, United Kingdom*
[2] *National Physical Laboratory, Queens Road, Teddington, Middlesex, United Kingdom*
[3] *ISIS, Rutherford Appleton Laboratory, Didcot, United Kingdom*

SUMMARY: The work presented is part of an ongoing research project which aims to characterise the deformation properties of high volume fraction metal matrix composite, Hivol. Hivol is a composite with 70% silicon carbide reinforcement in a cast aluminium alloy matrix. This article is an account of residual stress measurements carried out on Hivol samples with different mechanical and thermal histories. The stresses were measured using a neutron diffraction technique. Residual strains were found in as received samples, the low magnitude of which suggest stress relaxation through plastic yielding of the metallic matrix occurs readily. These were found to change when the composite was subject to load and thermal cycling.

KEYWORDS: metal matrix composites, residual, stresses, dimensional stability, neutron diffraction.

INTRODUCTION

The past twenty years have seen metal matrix composites (MMCs) emerge as candidate materials for structural applications. Their main benefits have been the high specific stiffness and increased strength while their principal drawback has been low toughness. As different manufacturing processes were developed, the possibility of introducing high volume fractions of ceramic reinforcement into a metal matrix arose in the form of melt infiltration techniques. This created a composite whose physical properties where quickly appreciated as unique and highly desirable in microelectronics packaging applications: a materials revolution was underway [1]. By varying the volume fraction of reinforcement it is possible to tailor the CTE of the composite to electronics substrates and components made from ceramics. The greatest interest was in aluminium matrix composites with particulate silicon carbide reinforcement. These MMCs are light, stiff and can be produced to near net shape at low cost. Conventional materials for packaging applications are not only more costly but are also invariably more dense thereby increasing the weight of the component.

This great potential raises the need for extensive study of the mechanical properties of these novel materials. This study becomes even more relevant when other applications of the composite are considered. Having a low thermal expansivity this material has potentially exceptional dimensional stability which, allied to a high specific stiffness, makes it an ideal candidate for structural aerospace applications as well as for lens and mirror supports, and many others where high specific stiffness and dimensional stability are primary design criteria. Although extensive research has been undertaken and results have been published on the mechanical properties of aluminium matrix composites with relatively low volume fractions of reinforcement, literature on the mechanical properties of these high volume fraction aluminium - silicon carbide composites is almost non-existent.

Of great importance to the understanding of the deformation behaviour and to the issue of dimensional stability is an understanding of the residual stress state in the composite and how it changes in service, under cyclic and static loading and through temperature cycles.
There are several potential sources of residual stresses in MMCs, but three main ones can be identified.
-Thermal gradients can induce residual stress gradients (macrostresses) in MMCs. When a composite is quenched, for example, and despite the good thermal conductivity of most MMCs, residual stresses are set up, which depend on the shape of the component as this controls the thermal gradient set up [2].
-As the composite cools from the fabrication temperature, the metal matrix, having a CTE significantly higher than the ceramic reinforcement (5 times higher in the case of aluminium/silicon carbide composites) is left in residual tension and the reinforcement in residual compression. Eqn. 1 is a simple expression put forward by Turner[3] which gives an approximate value for the isostatic differential thermal residual stress of a phase in a composite:

$$\sigma_i = K_i(\alpha_c - \alpha_i)\Delta T \qquad (1)$$

where σ_i is the isostatic stress in the ith phase, K_i its bulk modulus, α_i its volume coefficient of expansion, α_c the volume coefficient of expansion of the composite and ΔT the temperature drop from the stress free temperature. Some of this stress is relieved by plastic deformation [4-6] and therefore measured residual stresses often are lower than those predicted, for the same temperature drop.
-Mechanical cycling can also induce residual stresses. Plastic bending is an obvious example: yielding at the surfaces (where stress is highest) essentially elongates/shortens the material, which must be accommodated by residual stresses when the load is removed. In MMCs some regions of the metallic matrix experience higher stresses than other due to differences in local geometry, and will therefore yield first. This microyielding will induce residual stresses when the material is mechanically cycled, regardless of how the load is applied [7]. In essence heterogeneous yielding will always generate residual elastic stresses.
Different mechanisms also affect each other: dislocation motion due to mechanical loading can alter residual stresses caused by CTE mismatch and thermal cycling can alter mechanically induced internal stresses.

The present work is an attempt at characterising the residual stresses in a high volume fraction metal matrix composite, Hivol, and how these change as the composite undergoes thermal and mechanical cycling.

Characteristics of Hivol™

Hivol is a metal matrix composite with 70% of silicon carbide reinforcement in an aluminium cast alloy matrix. It is fabricated via a low pressure melt infiltration route by AEA Technology plc, Didcot, U.K. The reinforcement size ranges from 1 to 70 μm and is in the form of particulates with an aspect ratio higher than one (Fig. 1). Typical properties of this novel composite are presented in Table 1.

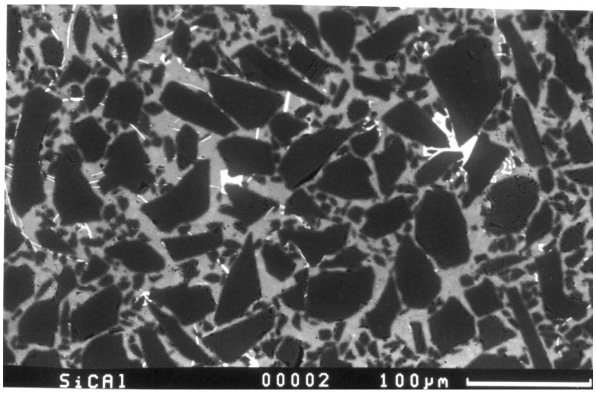

Fig. 1: Backscattered SEM micrograph of the silicon carbide reinforced composite.

Table 1: Some properties of Hivol™[8]

Young Modulus/GPa*	*Density /Mg* m^{-3}	*CTE* $/\mu\varepsilon\ K^{-1}$	*Thermal Conductivity* $/W\ m^{-1}\ K^{-1}$
250	3.0	5-6	210

*Measured by ultrasonic method.

RESIDUAL STRESS MEASUREMENTS

Samples

Hivol™ is currently produced in the form of rectangular plates 23 cm long, 15 cm wide and 2.5 mm thick. Rectangular samples of identical sizes were cut out from two plates from the same production batch to insure all had undergone the same production steps and had the same composition. The specimens, which were 6 cm in length and 1.5 cm in width, were then mechanically and thermally cycled. The samples used are summarised in Table 2. In addition to these, samples of SiC powder and of the alloy employed in the fabrication were used. The alloy was an Al-Si cast alloy, of commercial denomination LM6.

Table 2: Summary of samples used

Sample	*Thermal history*	*Mechanical history*
Silicon carbide powder	-	-
LM6 aluminium alloy	-	-
Hivol™	as received	as received
Hivol™	annealed at 250^{o}C for 2 hours furnace cooled (10^{o}C /min) to 20^{o}C	as received
Hivol™	annealed at 250^{o}C for 2 hours air cooled to 20^{o}C	as received
Hivol™	annealed at 250^{o}C for 2 hours quenched into water at 20^{o}C	as received
Hivol™	annealed at 250^{o}C for 2 hours quenched into liquid nitrogen	as received
Hivol™	annealed at 500^{o}C for 2 hours furnace cooled (10^{o}C /min) to 20^{o}C	as received
Hivol™	annealed at 500^{o}C for 2 hours air cooled to 20^{o}C	as received
Hivol™	annealed at 500^{o}C for 2 hours quenched into water at 20^{o}C	as received
Hivol™	annealed at 500^{o}C for 2 hours quenched into liquid nitrogen	as received
Hivol™	as received	stressed in uniaxial tension from 0 to 100 MPa
Hivol™	as received	stressed in uniaxial tension from 0 to 100 MPa -2 cycles
Hivol™	as received	stressed in uniaxial tension from 0 to 100 MPa -5 cycles
Hivol™	as received	stressed in uniaxial tension from 0 to 100 MPa - 10 cycles

Neutron diffraction measurements

The neutron diffraction measurements were performed at the ISIS facility of the Rutherford Appleton Laboratory, Didcot, U.K. ISIS uses a very powerful pulsed spallation source. The samples were placed in the diffractometer at 45 degrees to the incident neutron beam. Two detectors at ±90 degrees with respect to the incident neutron beam relayed diffraction data, which was electronically converted into time of flight diffraction patterns and recorded. In this way diffraction profiles for planes both parallel and perpendicular to the surface of the sample were obtained simultaneously.

Time of flight spectra were then converted into their interplanar spacing equivalent. This data was subsequently analysed through Rietveld curve fitting which yielded the lattice parameters for both the aluminium and the silicon carbide phases. The residual strains can then be calculated by comparing the lattice parameters of each sample and orientation to those obtained for the SiC powder and unreinforced alloy, using Eqn. 2,

$$\varepsilon = \frac{d\text{-}d_0}{d_0} \tag{2}$$

where d is the lattice spacing of any of the phases in the composite, d_0 the lattice spacing obtained for the corresponding stress free sample and ε the elastic strain of the phase in the composite.

RESULTS AND DISCUSSION

As received sample

The strains calculated from the diffraction data using Eqn. 1 for the as received sample are shown in Fig. 2.

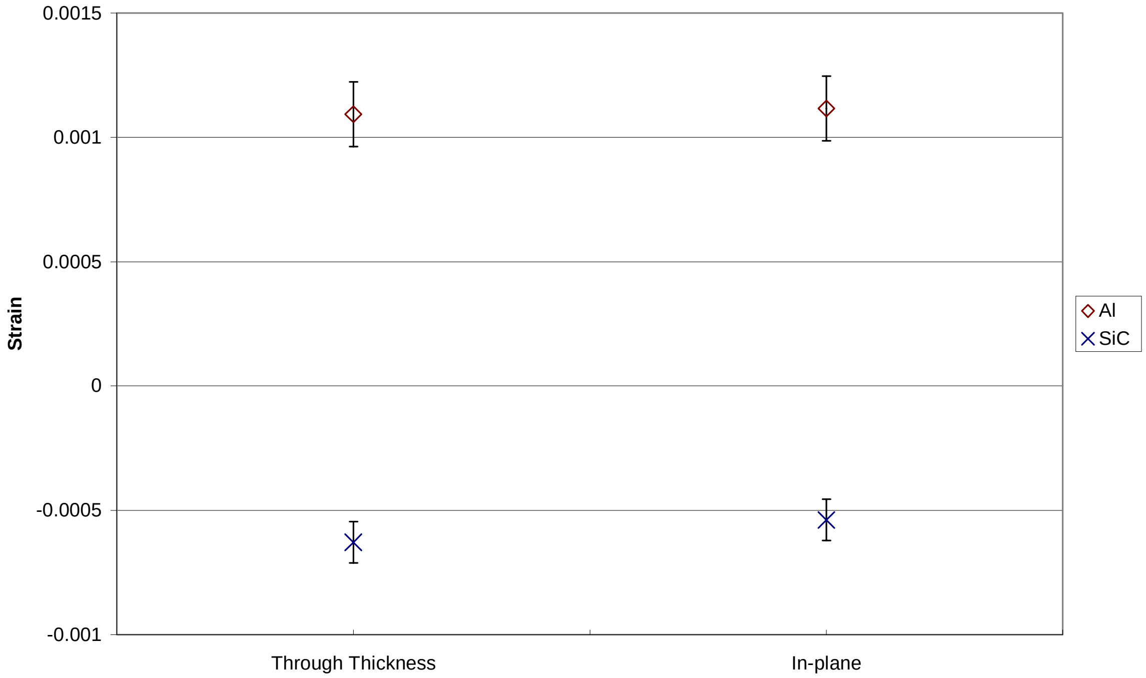

Fig. 2: Residual strains calculated for Hivol in the as received condition.

As expected, the residual strains are tensile in the aluminium phase and tensile in the silicon carbide phase. These arise from the difference in the coefficient of thermal expansion (CTE) between the matrix and reinforcement. The residual strains through the thickness of the plate and in-plane are essentially identical. That is, the residual stress state in the as received condition is isostatic. Assuming a stiffness of 70 GPa (Young modulus of aluminium) yields an approximate value of stress for the aluminium phase of 77 MPa. Using Eqn. 1 this value of stress corresponds to a very small temperature drop, which is evidence of significant stress relaxation.

Thermal cycled samples

The strains calculated for the samples held at 250^{o}C are shown in Fig. 3 as a function of cooling severity.

Heating Hivol to 250^{0}C and then slow cooling it to room temperature did not alter the residual strains significantly. Given the low stresses measured in the as received sample, the differential expansion/contraction is likely to be accommodated elastically during the heating and cooling. Furthermore the slow cooling rate insures no temperature gradients and hence macrostresses were set up due in the composite during cooling. In fact, even when cooled in air, a much higher cooling rate, the residual strains in the thermally cycled sample are essentially identical to those in its as received state.

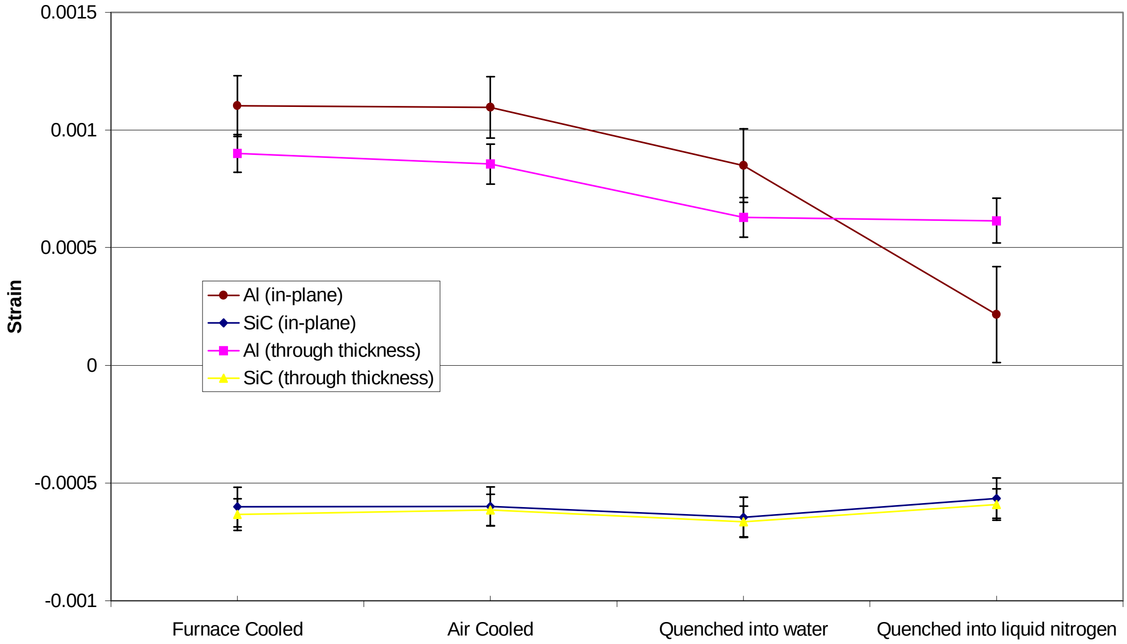

Fig. 3: Effect of cooling severity on the residual strains in Hivol samples held at 250^{o}C for 2 hours.

Quenching into water however appears to reduce the strains in the metallic phase considerably, while the strain in the carbide phase does not change appreciably. The lack of concurrent change of residual strains in both phases implies the macrostresses through and in the plane of the plate have changed. This is likely to be a result of non-uniform temperature profiles through the sample which arise during the rapid cooling.

The material quenched into liquid nitrogen showed the lowest value of residual strains in the matrix even though it underwent the most severe cooling. This is due to significant elastic strain relaxation that occurs as the composite warms up to room temperature as it is removed from the liquid nitrogen and the mismatch between the matrix and reinforcement is reduced. As a result, lower residual stresses are measured at room temperature.

Holding the composite at 500^{o}C for two hours allows extensive relaxation to take place in the matrix. At this temperature both dislocation motion and diffusion creep are available as relaxation processes. Furthermore dislocations present are annealed out making it easy for relaxation through dislocation slip to occur during cooling. Fig. 4 shows a summary of the results obtained for the samples held at 500^{o}C. As expected increasing the cooling severity leads to an increase in the in-plane residual strains in both the aluminium and the silicon carbide phases. As the cooling rate increases there is less time for stress relaxation to occur and hence the higher stresses.

The strains in the liquid nitrogen however are much lower because although the cooling is possibly more severe, any of the residual strains present at the end of the quenching, at -196^{o}C, are relieved elastically as the composite warms up to room temperature. Unlike in the sample held at 250°C the aluminium in this sample is essentially stress free which is evidence that some annealing does occur at 500°C, and the lack of dislocations allows relaxation to proceed further.

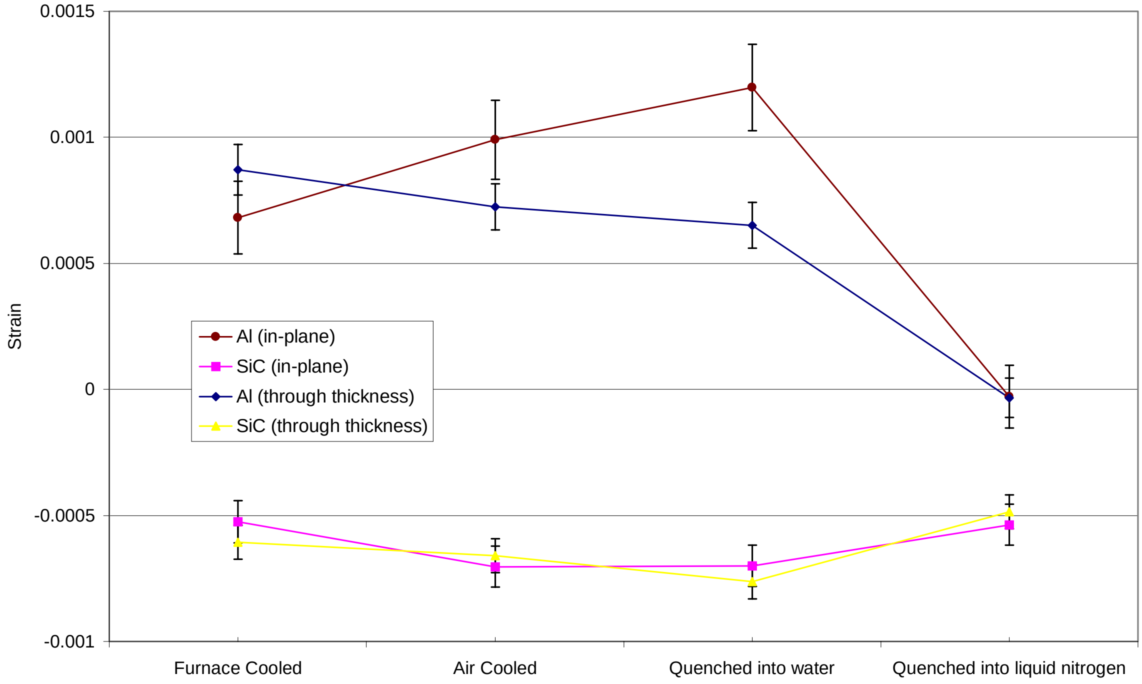

Fig. 4: Effect of cooling severity on the residual strains in Hivol samples held at 500°C for 2 hours.

Mechanical cycled samples

As mentioned previously residual stresses can also be set up and/or relaxed through mechanical cycling. This only occurs when the matrix deforms plastically. Hence measurements were made on samples which were strained to half its fracture strain to insure plastic yielding does occur. The residual strains measured can be seen in Fig. 5 as a function of number of loading cycles.

When the composite is strained to about half its failure strain and then unloaded, the residual stress state ceases to be isotropic. Whilst he through thickness stress state does not appear to change, the in-plane residual strains are lowered in the metallic phase and increased in the reinforcement.

The strains in the direction of loading almost halve in the metallic phase and double in the carbide phase. As this loading cycle is repeated, the residual strains in the matrix increase, peaking around the fifth cycle and then dropping to the value measured at the first cycle. The residual stresses in the carbide along this direction seem to increase with cycling. On the other hand repeated cycling appears to have limited effect on either the through thickness strains or the strains in-plane of the plate but perpendicular to the loading direction.

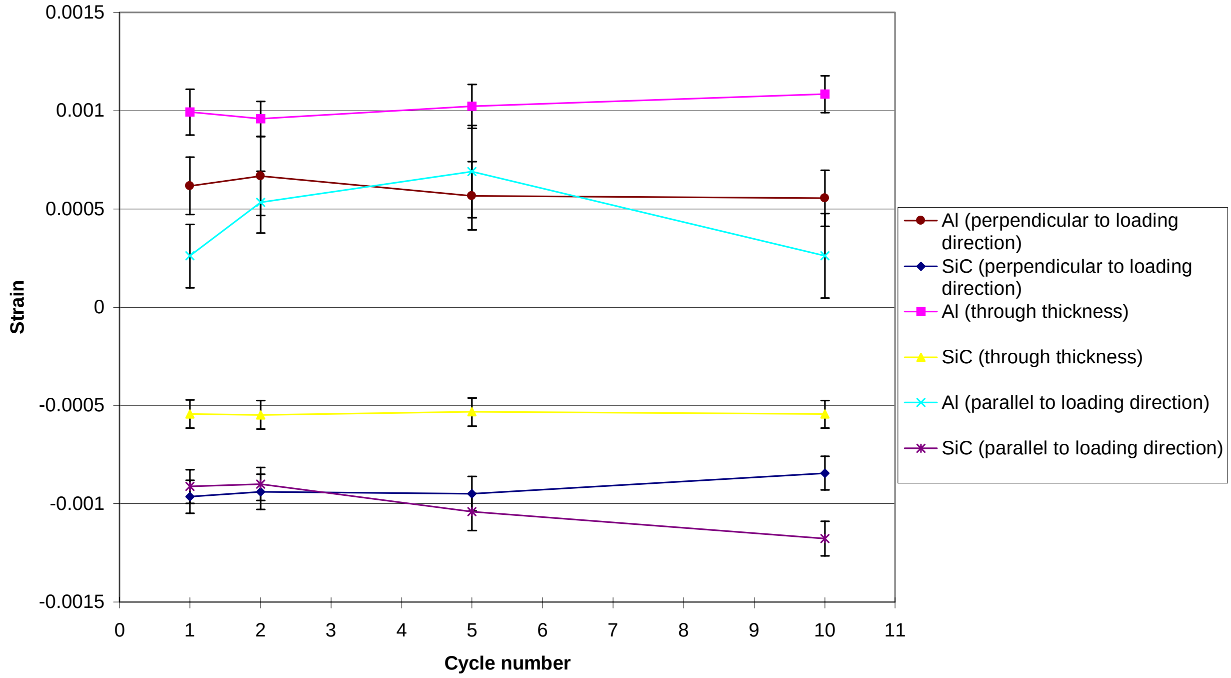

Fig. 5: Effect of cyclic straining on the residual strains in Hivol. The samples were stressed from 0 to 100 MPa in uniaxial tension for every cycle. A 100 MPa stress corresponds to half the typical fracture strain.

CONCLUSIONS

1. Residual stresses are present in Hivol in its as received state and in isostatic form. These are compressive in the metal matrix and tensile in the carbide reinforcement. From this it can be concluded these stresses are a result of differential thermal contraction in the two phases, caused by the CTE mismatch between them. However the magnitude of the stresses in the metallic phase is consistent with a small temperature drop only which is evidence of stress relaxation. This implies plastic deformation occurs readily in the aluminium, which is very relevant to the understanding of the deformation behaviour of the composite. Unlike in MMCs with low volume fractions of reinforcement, the deformation of the matrix in Hivol is potentially very constrained by the stiff carbide phase surrounding it. Thus it is not obvious that plastic deformation should occur readily, as these results imply.

2. It is possible to change the residual stresses in the matrix by cycling the composite thermally. However the stresses in the silicon carbide do not change considerably. From this it can be concluded that the stresses are altered by changing the macrostresses in the composite rather then affecting the microstresses. Future analysis of the experimental results will allow the deconvolution of the strains in to micro and macro components, which should elucidate this point further. Particularly efficient at lowering the residual stresses in the aluminium is annealing at 500^{o}C followed by a nitrogen quench.

3. The residual stress state is also modified through mechanical loading. On loading to 100 MPa, the residual strains in the metallic matrix along the loading direction are reduced significantly. The strains perpendicular to the loading direction (in-plane and through thickness) are very different. Whilst the through thickness residual strains remained

unchanged those in plane almost halved. This implies that the change in the residual stresses in the plane of the plate and normal to the direction of applied load, do not arise solely from Poisson effects but also from the effects of plastic deformation of the aluminium.

AKNOWLEDGEMENTS

The neutron diffraction measurements reported here were performed at the ISIS facility of the Rutherford Appleton Laboratory, U.K.

We wish to thank Robin Young of AEA Technologies plc for supplying the material used in this study and for his support. One of us[*] also wishes to acknowledge, for funding, the University of Leeds.

REFERENCES

1. C. Zweben, *Journal of Metals* , 1992, 15-23

2 M. E. Fitzpatrick, T. J. Downes, M. T.Hutchings, J. E. King, D. M. Knowles and P. J. Withers, *ICCM 9, Vol 1, Metal Matrix Composites,* A. Miravete, University of Saragoza, Madrid, 1993, 642-649

3 P.S. Turner, *J. Res. Natl. Bur. Stand.*, **37**, 1946, 239-240

4 M. Suery, C. Teodosiu and L. F. Menezes, “Thermal residual stresses in particle reinforced viscoplastic metal matrix composites”, *Mat. Sci. Eng*, **A167**, 1993, 97-105

5 D. C. Duncan and A.Mortensen, “On plastic relaxation of thermal stresses in reinforced metals”, *Acta Metall. Mater.,* **39**, 1991, 127-139

6 M. Taya, K. E. Lulay and D. J. Lloyd, “Strengthening of a particulate metal matrix composite by quenching”, *Acta Metal. Mater.*, **39**, 1991, 73-87

7 G.L. Povirk, M.G. Stout, M. Bourke, J.A. Goldstone, A.C. Lawson, M. Lovato, S.R. MacEwen, S.R. Nutt and A. Needleman, “Mechanically Induced Residual Stresses in Al/Sic Composites”, *Scipta Metallurgica et Materialia*, **25**, 1991, 1883-1888

8. R. Young, AEA Technologies plc., Harwell, U.K., 1997, Private communication

[*] J. Quinta da Fonseca