On the Work Hardening Behaviour of a Rheocast SiC Reinforced Aluminum Metal-Matrix Composite

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ABSTRACT

An understanding of the work hardening behaviour of particulate reinforced metal-matrix composites is crucial in optimising the parameters for deformation processing of these materials. In this study the SiC reinforced aluminum metal-matrix composite was produced by a rheocasting procedure. The microstructure of the composite was characterized and the mechanical properties were determined. The rheocast composite exhibited a significant improvement in tensile strength compared to the unreinforced alloy. A modified continuum model was applied to relate the work hardening behaviour of the composite to microstructural parameters and to predict the fracture strain of the composite. The model is shown to predict the fracture strain of the composite quite accurately.

INTRODUCTION

The development of metal-matrix composites has been catalyzed by the need for structural materials with high specific strength and stiffness. Reinforcements may be continuous in the form of fiber or discontinuous in the form of whiskers or particulates. While fiber reinforced composites offer the highest specific stiffness along the reinforcement direction, particulate reinforced composites are more isotropic in their properties and are also easier to process via powder metallurgy or casting routes.

Active research has led to considerable advances in theoretical and experimental understanding of MMCs. In particular, a lot of work has been concentrated on explaining the strengthening mechanisms in these materials. Models using continuum mechanics, like the shear lag model and the Eshelby type /1-7/ lead to a yield strength dependence on the shape and volume fraction of the reinforcement. In contrast, dislocation based models /8-10/ lead to a yield strength dependence on particle spacing which in turn leads to a dependence on particle size and volume fraction. Many models have concentrated on the behaviour of these materials at low strain levels.

An understanding of the flow behaviour of the material over the entire range of stresses and strains is essential to optimize the deformation processing of these materials. This would necessitate a model for the work hardening characteristics of these materials and the dependence of work hardening on the microstructural parameters such as the particulate volume fraction and size. A model has been proposed in an earlier paper /11/ for explaining the work hardening behaviour of 2024 Al alloy matrix composites. In this paper, this model is extended for a different composite system. In particular, an attempt is made to predict the fracture strain from a knowledge of the work hardening behaviour of the material.

MATERIALS AND EXPERIMENTAL PROCEDURES

The nominal composition of the matrix alloy used in the present study was Al-2.0%Cu. This alloy was reinforced with silicon carbide (α-SiC) particulates with an average size of 23 μm.

The rheocasting procedure was used in the present study to produce the metal-matrix composites. The cleaned metal ingots were superheated in a graphite crucible to 750°C, and then preheated SiC particulates were added in the metallic melt. The composite mixture was then stirred in the liquid phase regime and the two phase regime in order to achieve uniform distribution of SiC particulates in the metallic matrix. The composite material thus obtained was allowed to solidify in the crucible and was subsequently remelted in the same crucible. This was followed by casting of the composite into cylindrical steel moulds (25 mm diameter and 178 mm height). For comparison, the base alloy was also cast into cylindrical steel moulds using a similar superheat temperature.

Quantitative assessment of the SiC particulates in the composite was carried out using a chemical dissolution method /12/. This method involved measuring the mass of the composite samples followed by dissolution in hydrochloric acid and finally filtration to separate the ceramic particulates. Density measurements were carried out to ascertain the volume fraction of porosity in the Al-Cu matrix using a procedure detailed elsewhere /13/.

Aging studies were then carried out to determine the peak hardness time and temperature for the matrix alloy and the rheocast metal-matrix composite. The materials were solutionised at 490°C, quenched in cold water and aged isothermally at 160°C for various intervals of time. The hardness was evaluated on a Rockwell B scale.

The tensile properties of the materials were determined in accordance with ASTM E-8M91 /14/. The fracture surfaces of the tensile test samples were then examined using a JEOL scanning electron microscope.

RESULTS

The results of the acid dissolution experiments showed that the weight percentage of SiC particulates was approximately 10.9% for the rheocast composite specimens. The density measurements were used in combination with the acid dissolution tests to determine the volume fraction of porosity as 0.6% for the unreinforced alloy and 0.8% for the rheocast composite.

The results of the aging studies revealed a hardness peak at 9 hours for the unreinforced samples and at about 6 hours for the rheocast composite. The results also indicated substantial improvements in the hardness obtained in the rheocast composites in comparison with the unreinforced alloy.

The results of the tensile tests on the peak aged unreinforced alloy and the composite are summarized in Table 1 and a typical stress strain curve for the composite is plotted in Fig. 1. These results reveal the substantial improvements in the yield strength, ultimate tensile strength and fracture strain for the rheocast composites as compared to the unreinforced alloy.

DISCUSSION

Continuum models take into account the ability to transfer load from the matrix to the reinforcement and the accommodation of mismatch strains. In general, internal stresses develop in metal-matrix composites due to the differences in the elastic, plastic and thermal properties of the matrix and the reinforcement. One of the useful methods of modeling such property mismatches is to use a formulation originally developed by

Table 1
Summary of Mechanical Properties

Material	Processing	Condition	σ_y (MPa)	σ_u (MPa)	ε_f (%)
Al-Cu	Cast	Peak Aged	94 ± 12	140 ± 27	10 ± 1
Al-Cu +SiC	Rheocast	Peak Aged	126 ± 23	216 ± 8	8 ± 1

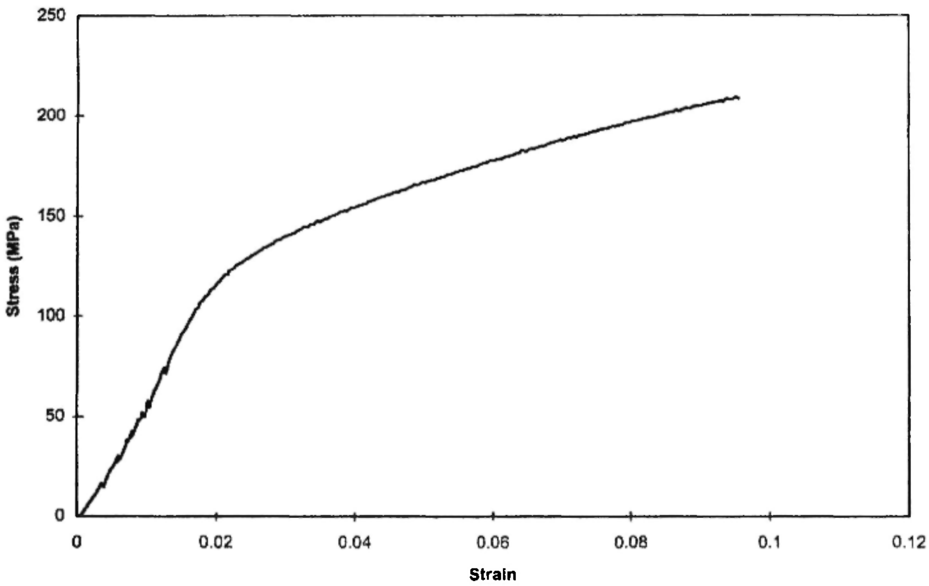

Fig. 1: True stress – true strain curve up to maximum load.

Eshelby. This classical problem, referred to as the "ball in a hole problem" relates to the fact that the inclusion does not fit perfectly into the hole in the matrix where it sits. The formulation essentially solves this problem by stressing the inclusion appropriately such that it fits the hole perfectly. The inclusion is then allowed to relax in the matrix in such a way that strains and corresponding stresses are set up both in the matrix and the inclusion. The misfit strain is of critical importance in the solution of this problem. This strain relates to the change in the shape and size of the inclusion, when it is stress free and before it is placed in its appropriate, but not fitting, hole in the matrix /6,7/. The mean internal stress is of importance since the dislocations experience this stress and the stress makes it more difficult to increase the plastic deformation, contributing to work hardening.

Lilholt /6,7/ has used such an analysis to predict the total strengthening, due to the presence of an inclusion in a metallic matrix. The total strength is taken to be a simple linear addition of the contribution from the matrix and the inclusions

$$\sigma_c = \sigma_m + \sigma_I \tag{1}$$

The inclusions contribute to the strengthening of the composite for two reasons. They act as barriers to dislocation motion resulting in an increase in strength. This increase is related to the stress needed to force a dislocation through a passage between two inclusions. The total passage stress /6/ is

$$\sigma_{pass} = \left(\frac{\mu b}{\lambda}\right) + \left(\frac{5}{2\pi}\right)\mu f \varepsilon \tag{2}$$

where μ is the shear modulus of the matrix, b is the Burgers vector, λ is the inclusion spacing, f is the volume fraction of the reinforcement and ε is the plastic strain.

The second contribution of the inclusions to the strengthening of the composite is that they result in a mean internal stress in the matrix, and since the plastic deformation normally takes place in the matrix, the dislocations see the mean internal stress which acts to make further plastic deformation more difficult. Using several simplifications, the mean internal stress can be estimated to be /7/

$$\langle\sigma\rangle_m = 4\mu f \varepsilon \tag{3}$$

Thus,

$$\sigma_I = \sigma_{pass} + \langle\sigma\rangle_m \tag{4}$$

$$\sigma_I = \frac{\mu b}{\lambda} + \frac{5}{2\pi}\mu f \varepsilon + 4\mu f \varepsilon \tag{5}$$

Hence, from Equation (1) the total strength of the composite can be estimated to be:

$$\sigma_c = \sigma_m + \frac{\mu b}{\lambda} + 4.8\mu f\varepsilon \qquad (6)$$

The above equation is based on the assumption that the reinforcement does not progressively crack or decohere during straining. However, cracking of reinforcements with strain has been observed for many systems during tensile and fracture tests as well as in *in-situ* deformation experiments in the SEM /15-18/. Decohering at the interface has also been observed in other cases /15/. In all these cases the load bearing ability of the reinforcements is reduced as only a fraction of the reinforcements can effectively carry the load. The exact dependence of the change in load bearing ability as a function of strain is complex. However, a linear dependence of particle cracking on the strain can be used as a first approximation Using this approximation, a model has been developed as outlined in detail elsewhere /11/.

In essence the model /11/ includes as a variable the fracture strain of the composite. The actual strength of the composite is predicted to be

$$\sigma_c = \sigma_m + \frac{\mu b}{\lambda} + 4.8\gamma\mu\left(1-\frac{\varepsilon}{2\varepsilon_f}\right)f\varepsilon \qquad (7)$$

Hence the work hardening rate of the composite can be calculated as:

$$\frac{d\sigma}{d\varepsilon} = 4.8\mu\gamma\left(1-\frac{\varepsilon}{\varepsilon_f}\right)f \qquad (8)$$

In the above equations, ε_f is the fracture strain and γ is a constant which is dependent on the aspect ratio of the particulate reinforcement.

One of the most interesting aspects of the above model is that if an equation can be curve fitted to the experimental stress strain curve, then the fracture strain can be predicted. Fig. 1 shows a typical stress strain curve up to maximum load for the composite under investigation. From this curve, the work hardening rate $d\sigma/d\varepsilon$ can be calculated for the plastic region of the stress strain curve. A plot of $d\sigma/d\varepsilon$ as a function of the plastic strain ε is shown in Fig. 2. Using a least squares procedure a straight line was fitted to the data points. The fitted straight line, as shown in the figure, has the form:

$$\left.\frac{d\sigma}{d\varepsilon}\right|_{\text{exptl}} (\text{MPa}) = 2014 - 21152\varepsilon \qquad (9)$$

This can be easily rewritten in a form which can be directly compared to the proposed model:

$$\left.\frac{d\sigma}{d\varepsilon}\right|_{\text{exptl}} (\text{MPa}) = 2014\left(1-\frac{\varepsilon}{0.09}\right) \qquad (10)$$

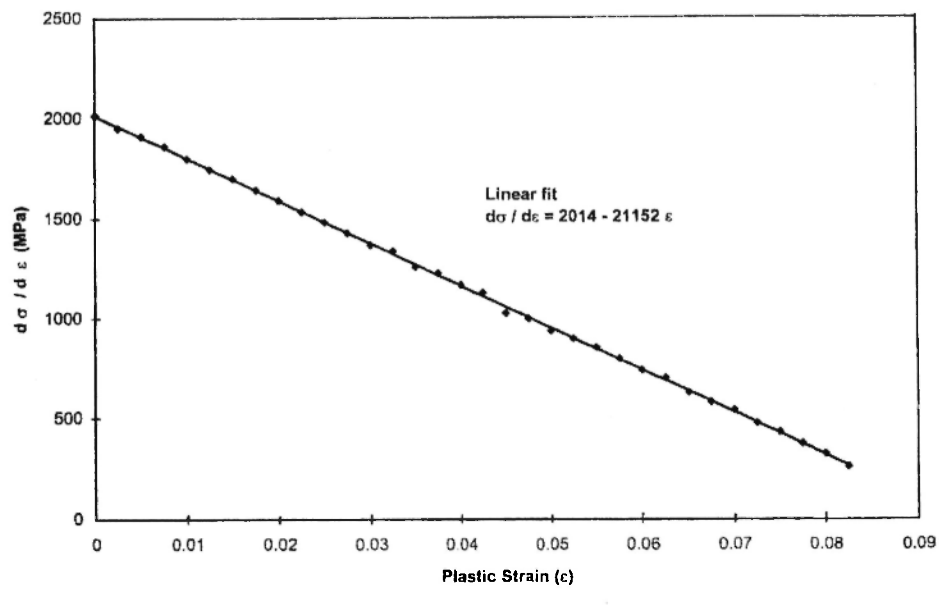

Fig. 2: Plot of work hardening rate vs. plastic strain.

The above equation predicts that the fracture strain is 0.09 which is in excellent agreement with the measured fracture strain. Thus, the modified continuum model proposed earlier /11/ and used in this paper predicts the fracture strain using a knowledge of the work hardening rate. The model also relates the work hardening rate and the fracture strain to microstructure parameters, thus linking the materials science and mechanics aspects of the problem. Further studies, on verifying and extending the model for a range of matrix materials, reinforcement shapes, sizes and volume fractions, are underway.

CONCLUSIONS

1. The rheocast Al – Cu / SiC composite exhibits a significant improvement in tensile strength compared to the unreinforced alloy.
2. The work hardening behaviour of the composite can be modelled using a modified continuum theory.
3. The observed experimental relationship between the work hardening rate and strain is compatible with the proposed model and hence the fracture strain derived from the model agrees very well with the experimentally measured value.

ACKNOWLEDGEMENTS

The authors would like to thank Mr. Ang Soon Ee, Mr. Thomas Tan and Mr. Tung Siew Kong (National University of Singapore, Singapore), Dr. S.V. Kamat (Defence Metallurgical Research Laboratory, Hyderabad, India), Professor O. Prabhakar (Indian Institute of Technology, Madras, India), and Professor John P. Hirth (Washington State University, Pullman, USA) for assistance and valuable discussions.

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