THERMOMECHANICAL STUDIES OF PRESTRAINED Al_2O_3/Al METAL MATRIX COMPOSITE

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ABSTRACT

The effect of prestraining on the elastic modulus (E) and damping capacity (tan ϕ) of 10 and 20 volume percent (v/o) Al_2O_3 particle reinforced composites has been investigated as function of temperature using Dynamic Mechanical Analysis. The present study described a strong influence of both particle mean size and plastic strain on elastic modulus and damping capacity of the aluminum oxide reinforced 6061 composite. This influence becomes considerable when a critical amount of broken particles exists in the composite. There is a synergetic effect of particle size and plastic strain in that the larger particles are more susceptible to fracture during straining. This effect could also be considered as a result of difference in thermal and plastic properties of the matrix and aluminum oxide particulate.

INTRODUCTION

Ceramic particulate reinforced aluminium alloy-based metal-matrix composites (MMCs) display substantial increases in strength, stiffness and wear resistance over conventional unreinforced aluminum alloys [1-3]. In addition, they exhibit a reduced coefficient of thermal expansion and in certain composites, increased thermal conductivity has been reported [1,2]. These excellent properties combined with practical pricing, availability and the economics of liquid processing have enabled the production of such diverse components as bicycle frames and tire stud jackets as well as stimulating interest in large volume automotive applications such as brake rotors, drive shafts, differential housings, etc.

The greater elastic modulus and reduced coefficient of thermal expansion (CTE) is due to the incorpration of ceramic particles with increased modulus and reduced CTE into the matrix. However, during cold deformation, the mechanical properties of the composite, particularly the modulus, can deteriorate. Recently, it has been demonstrated that the Young's modulus of Al_2O_3/6061 composites is reduced by plastic straining and that the reduction is related to particle damage during the deformation process [4,5]. As a result, the change in elastic modulus with strain can be used to monitor the extent of particle cracking. It is expected that particle cracking will also magnify the effect that the ceramic reinforcement has on damping capacity of the composite, and that changes in the damping with plastic prestrain will reflect the extent of particle damage.

The main objective of this study is to determine the effect of prestraining on the elastic modulus (E) and damping capacity (tan ϕ) of Al_2O_3/Al composites as a function of temperature using Dynamic Mechanical Analysis (DMA). In this investigation the testing was performed on composites containing 10 and 20 v/o aluminum oxide particles in 6061 Al. The variation in E and tan ϕ between 25 and 450°C for specimens having undergone prestrain ranging from 0 to 14% are presented. Scanning electron microscope analysis of metallographic sections of strained composite specimens are used to explain the physical and mechanical results obtained.

EXPERIMENTAL PROCEDURES

a) Composite materials

The 6061 Al composites reinforced with 10 and 20 v/o aluminum oxide particulate used in this study were produced by the Duralcan™ (San Diego, USA) molten metal mixing process [6]. The composites were D. C. cast into billet which were then hot rolled into sheet. The microstructure of the composite sheet was examined using both optical and scanning electron microscopy. Fig. 1 is a low magnification micrograph of the longitudinal section of 20 v/o Al_2O_3/6061 composite showing a uniform distribution of particles throughout the aluminum matrix. This uniformity of microstructure is believed to be responsible for the isotropic nature of mechanical properties reported in this study and elsewhere [1-3].

Figure 1. Typical microstructure of 20 v/o Al_2O_3/6061.

* DURALCAN™ - Owned by Alcan Aluminum Limited

Tensile samples were machined from the composite sheets, then heat treated to the T4 condition (solutionized at 550°C for 1 hr then quenched in water followed by room temperature aging for a minimum of 2 days). These specimens were then prestrained to a specific plastic strain (ε_p) at room temperature at a cross head speed of 2.5 mm/min. To establish the level of particle cracking with tensile prestrain, optical microscopy was used. 200 fields at 500x were examined, the broken particles counted and classified by size range using IBAS2 image analyzer.

b) DMA Analysis

Specimens for DMA testing, 50 x 8 x 1 mm in size, were cut from the prestrained composites using a diamond saw. Specimen surfaces were then polished using 1μm diamond paste. Four samples of each composite were tested under each condition to verify reproductibility of the data.

The DMA, model 983 from Dupont was used to measure the Young's modulus and damping capacity of the specimens as a function of temperature between 25-450°C. The rate of heating was about 5°C/min. The specimens were clamped between two parallel arms and then subjected to a uniform sinusoidal displacement of a constant maximum strain. The oscillation frequencies were fixed at 0.1 and 1 Hz to show frequency dependence. The specimen displacement is monitored by an LVDT and the measured lag between the drive signal and the LVDT is the phase angle. The phase angle and drive signal are used to calculate the elastic modulus and damping capacity (Tan ϕ) of the specimen. In addition, experiments were conducted at a fixed frequency of 1 Hz and spanning the strain amplitude range of 8×10^{-5} through 5×10^{-3}. These strain values correspond to the calculated maximum strain experienced by the specimens as they are deformed by the DMA in cantilever configuration.

RESULTS

a) Particle cracking

The microscopic observations combined with the results of the image analysis show that the particulates used in the composite containing 20 v/o Al_2O_3 are larger than those used at 10 v/o. A comparison of cumulative volume of the particles as a function of mean particle size of each of the particulates used is shown in Fig. 2. At 10 v/o the composite contains an aluminum oxide particulate having a mean particle size of 12 μm and 54% of the particles are below 12 μm in size (Fig. 2a); at 20 v/o the mean particle size is 20 μm and 56% of the particles are below 20 μm (Fig. 2b). Figs. 3 and 4 show the particle size distribution of fractured particles at different strains for each of the composite tested. The vertical axis is the ratio of the number of broken particles to the total number of particles having the same mean size. The results indicate that with plastic strain, the fraction of broken particles increases with mean particle size. For example, in 20 v/o Al_2O_3/6061 samples prestrained to 10%, 52% of the particles having a mean size of 36 μm (the largest sampled) were broken. These data suggest that at a given strain a large particle would have a greater tendency to fracture than a smaller one. The variation in the total fraction of broken particles with strain is shown in Fig. 5. It is apparent that the total fraction of broken particles increases with ε_p for both composites. The particle cracking increases more rapidly with strain at 20 v/o reinforcement, which also has the larger particle size.

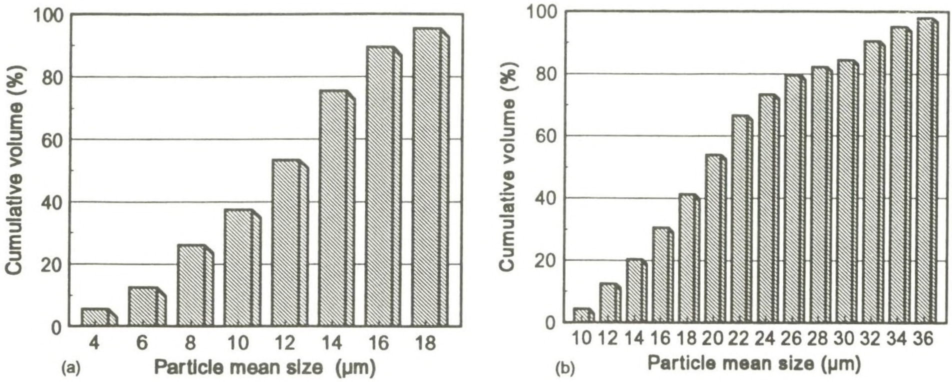

Figure 2 Cumulative volume fraction of particle prior to plastic straining: (a) 20 v/o Al_2O_3/6061, and (b) 20 v/o Al_2O_3/6061

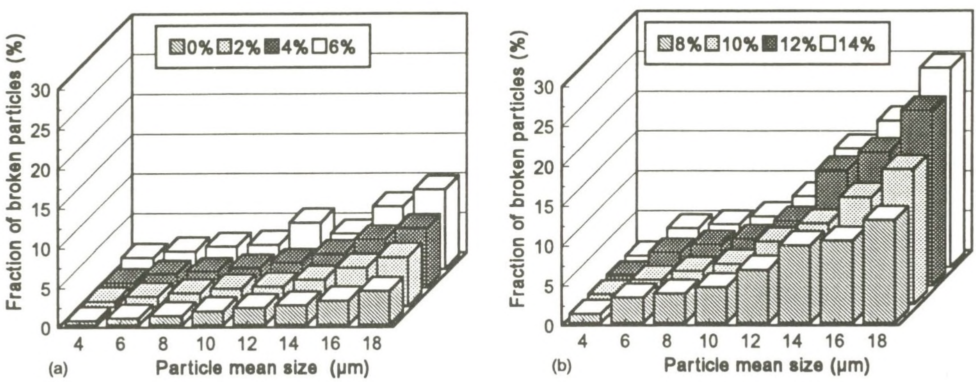

Figure 3 Fraction of broken particles as a function of particle size for various plastic strain of the 10 v/o Al_2O_3/6061 composite : (a) ε_p= 0-6%, and (b) ε_p= 8-14%.

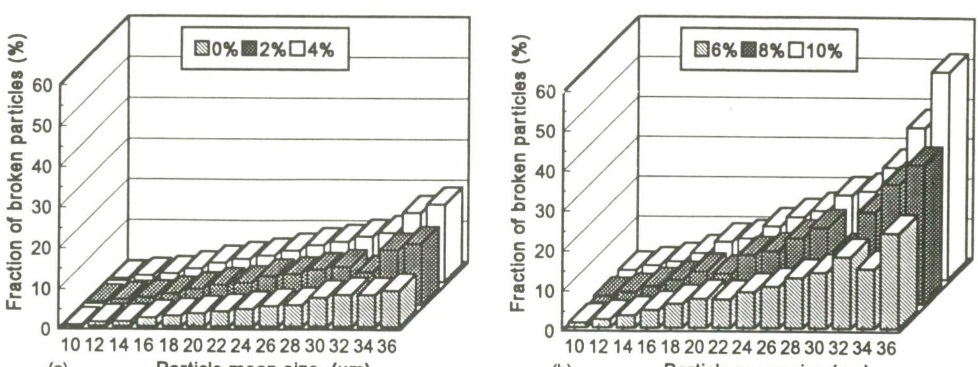

Figure 4 Fraction of broken particles as a function of particle size for various plastic strain of the 20 v/o Al_2O_3/6061 composite : (a) ε_p= 0-4%, and (b) ε_p= 6-10%.

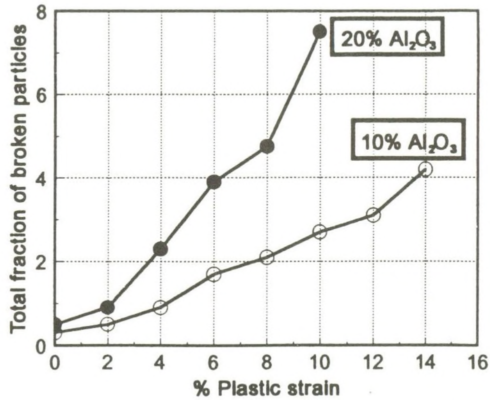

Figure 5 The plastic strain dependence of particle fracture.

b) Young's modulus and damping capacity of the composites

The elastic modulus and damping capacity (Tan ϕ), as measured by the DMA for 10 v/o Al_2O_3/6061 composite prestrained to 10%, are shown in Fig. 6. The results revealed a general trend of decreasing modulus with increasing temperature up to 150°C, followed by a rapid decrease at high temperatures. The damping capacity generally exhibited an increase with increasing temperature followed by an abrupt increase in the slope of the curve above 200°C. At temperatures below 150°C, the composite appeared to be frequency independent at 0.1 and 1 Hz. Above 150°C, however, the MMCs became temperature and frequency sensitive with the lowest frequency exhibiting the highest damping. The Young's modulus and damping capacity of the composites prestrained to different plastic strains (0 to 14%) are plotted at various temperatures in Figs. 7 and 8, respectively. The room temperature measurements of elastic modulus at 10 and 20 v/o were 81 and 94 GPa respectively. These values agreed with modulii measured on similar materials using standard tensile specimens and strain gages reported in the literature [1,3]. The agreement tends to support the validity of measurements of E generated through the use of DMA. The results indicate that the room temperature elastic modulus of the 20 v/o Al_2O_3 composite decreases as plastic strain increases ranging from approximately 94 GPa at 0% prestrain to 82 GPa at 10% deformation (Fig. 7a). Therefore, the prestrain has a negative influence on the elastic modulus of the 20 v/o Al_2O_3/6061 composite where approximately 8% of the reinforcing phase is fractured at 10% prestrain. In the same specimen damping capacity shows a significant increase. In contrast, the Young's modulus at low temperatures (25°C) of the composite containing 10 v/o alumina showed a much more gradual decrease with increasing plastic strain (Figs. 7a and b), within the bounds of experimental error (3%). Unexpectedly, at 450°C, the modulus of specimens containing 10 v/o Al_2O_3 appeared to actually be higher than the modulus measured at 20 v/o. It should be noted that each experimental point on Figs. 7 and 8 is the average of four DMA tests and consequently, it is believed that the observed response is a material characteristic and should not be dismissed as experimental scatter. As expected from Fig. 6, the modulii of the composites are relatively insensitive to frequency at room temperature. However, at 450°C, it is evident that the modulus increases with increasing frequency.

As shown in Fig. 8, the damping capacity increases with particulate content. With increasing plastic strain the tan ϕ of the 10 v/o Al_2O_3/6061 composite was found to not change significantly. On the other hand, the damping capacity of the composite containing 20 v/o reinforcement increases with

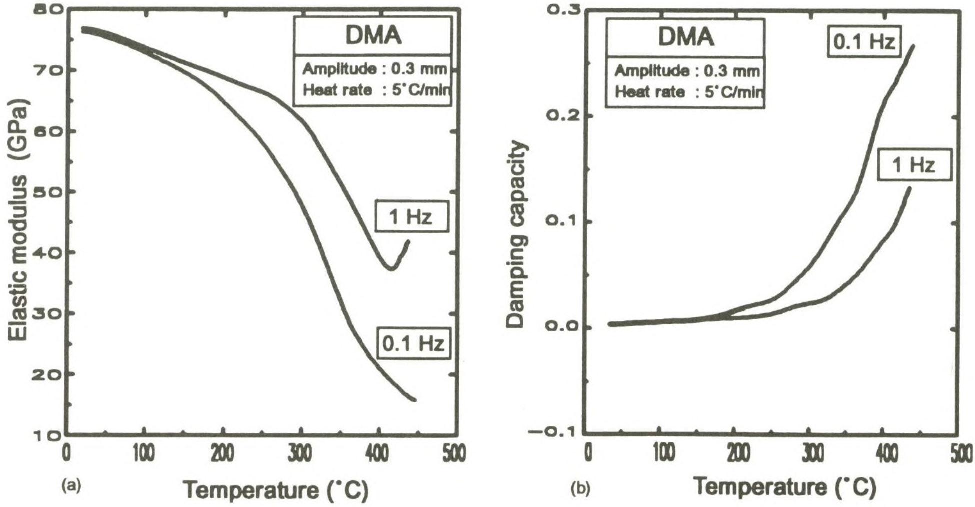

Figure 6 Typical DMA plots for 10 v/o Al_2O_3/6061 composite in prestrained condition (ε_P=10%): (a) elastic modulus, and (b) damping capacity.

plastic strain, ranging for example, from 0.15 at 0% prestrain to 0.42 at 10% prestrain (Fig. 8b). It is also observed that damping capacity is enhanced by decreasing oscillation frequency over the entire range of plastic prestrain investigated.

A further elucidation of the mechanism of damping in the specimens was performed by plotting damping capacity versus strain amplitude (Fig. 9). The results demonstrate essentially amplitude-independent behaviour. The strain amplitude dependence is observed only in the case of the 20 v/o Al_2O_3/6061 composite prestrained to 10%. It is apparent that the damping of the composite increases and passes through a maximum as the strain amplitude is further increased.

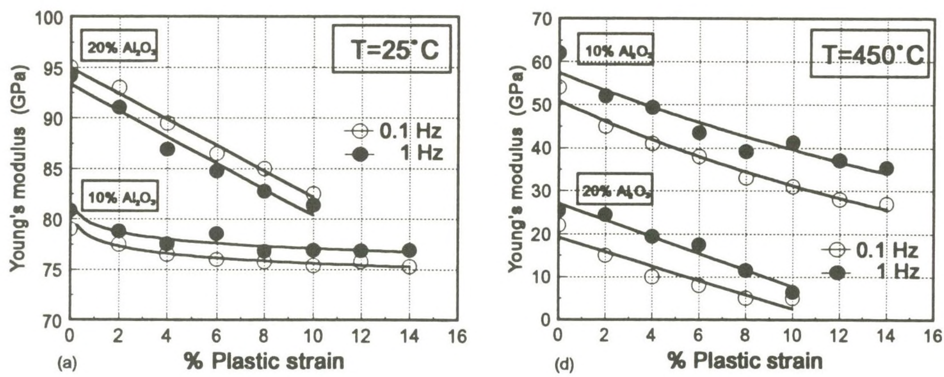

Figure 7 Young's modulus of the 10 and 20 v/o Al_2O_3/6061 composites as a function of plastic strain, at : (a) 25°C, and (b) 450°C.

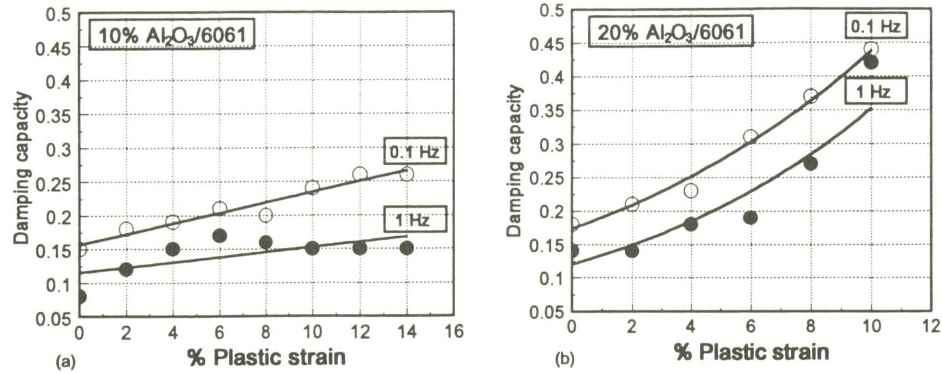

Figure 8 Damping capacity (Tan ϕ) of the composites as a function of plastic strain: (a) 10 v/o Al_2O_3/6061, and (b) 20 v/o Al_2O_3/6061.

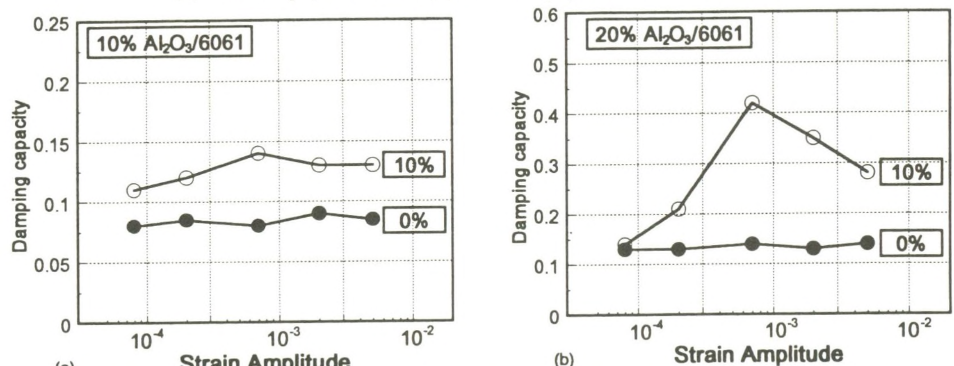

Figure 9 Damping capacity (Tan ϕ) of the composites as a function of strain amplitude: (a) 10 v/o Al_2O_3/6061, and (b) 20 v/o Al_2O_3/6061.

DISCUSSION

By combining the results of image analysis and DMA we can make three important points:

1) In the case of 20 v/o Al_2O_3/6061 composite, which contains larger particles (median size of 20µm), a significant number of broken particles is noted. As a consequence this composite displays a substantial decrease in elastic modulus with increasing prestrain. It is likely that the presence of voids at particle fracture sites not only reduces the capacity of the larger aluminum oxide particulate to reinforce the matrix, but also creates a structure of pores randomly distributed throughout the matrix. This defect structure has a deleterious effect on elastic modulus. Some previous studies of metal-matrix composites [3,7] have also indicated that the generation of thermal residual stresses during quenching from the processing temperature significantly decreases the initial stiffness during subsequent mechanical loading.

2) The 20 v/o Al_2O_3 composite also showed the highest levels of damping capacity (Tan ϕ = 0.42 at 10% prestrain). It appears that the presence of broken particles and the associated void like defects leads to an increase in damping capacity. The effect of these defects on damping is likely to be augmented by the high density of dislocations generated during MMC processing as a result of the thermal mismatch between matrix and ceramic particulate. This is believed [8] to have an important effect on the dissipation of elastic energy.

3) The plastic strain did not have a strong influence on the damping capacity of the 10 v/o Al_2O_3/6061 composite. The composite was reinforced with smaller particles (12μm mean size) and showed fewer broken particles with prestrain. Therefore, it appears likely that the particle size range and the amount of broken particles are critical values affecting the damping behaviour of these composites.

The modulus and damping response of the composites tested exhibits an increased frequency dependency with temperature. The tendency towards lower modulus and higher damping at the lower frequency is believed to be directly related to the increased capacity for time dependent plastic flow at the matrix. On the other hand, no dependency of damping on strain amplitude was observed except for the singular peak noted in the prestrained sample of 20 v/o Al_2O_3/6061 composite. This type of response is believed to be consistent with observations made on Al/Al_2O_3, Al/SiC and Al/W composites [8] where the behavior is explained by Granato and Luckes's theory of dislocation damping.

CONCLUSIONS :

1) As a result of the larger propensity for particle fracture with prestraining, the composite reinforced with 20 v/o Al_2O_3 showed the greatest decrease in modulus with increasing plastic strain. The modulus measured at ambient temperature dropped from 94 GPa at 0% plastic strain to 82 GPa at 10%.
2) The 20 v/o composite which showed the greatest particle damage with prestrain also had the highest damping capacity, tan ϕ = 0.42 at 10% prestrain. Therefore, the damping capacity measured with the DMA can be used as a sensitive indicator of microstructural damage in MMCs.
3) The plastic strain did not have a significant influence on the damping capacity of the 10 v/o Al_2O_3/6061 composite, which was reinforced with a smaller particulate (12μm).
4) At low temperatures, the composites appeared to be frequency independent over the range tested. Above 150°C, however, the MMCs became temperature and frequency sensitive with the lowest frequency exibiting the lowest modulus, but the highest damping.
5) The damping capacity of 10 v/o Al_2O_3/6061 was relatively insensitive to strain amplitude. In contrast, the prestrained composite containing 20 v/o Al_2O_3/6061 is amplitude dependent.

Acknowledgements

The authors are grateful to Duralcan (San Diego, USA) for providing specimens. The authors also extend their thanks to Dr. D. J. Lloyd from Alcan International, Kingston, Canada, for helpful suggestions.

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