ELASTIC MODULI OF SILICON CARBIDE PARTICULATE REINFORCED ALUMINUM METAL MATRIX COMPOSITES

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INTRODUCTION

The mechanical properties of metal matrix composites (MMCs) reinforced by discontinuous silicon carbides are governed by the properties of the reinforcing phase, as well as their morphology (whisker vs. particulate), orientation and volume fraction. The morphology of SiC particles and their orientation are major variables affecting the anisotropic properties of these composites. SiC whisker (SiCw) reinforced aluminum MMCs tend to have higher strengths and moduli in the extrusion direction due to the high degree of whisker alignment in that direction, and these values are higher than those for SiC particulate (SiCp) reinforced composites at a given reinforcement level [1]. SiCp reinforced MMCs are known to be more isotropic in the extrusion plane. In situations requiring multidirectional reinforcement, particulate reinforced composites can outperform whisker reinforced composites. Thus, it is important to characterize the mechanical properties of these composites in order to develop the criteria for selecting microstructural design variables.

In this paper, we investigated the effect of metal working (extrusion) on the microstructure and mechanical properties of 2124, 6061 and 7091 Al alloys reinforced by 10-30 v/o(volume percent) SiC particulates. Consequently, we examined the microstructure of these composites using scanning electron microscopy (SEM) [2] and image analysis. Image analysis was conducted on the 7091 Al/SiCp system to assess the SiCp orientation distribution in the three mutually perpendicular planes. Image analysis results showed that SiC particles with aspect ratios of 2 to 4 were slightly aligned in the extrusion direction, making these composites macroscopically orthotropic. By measuring ultrasonic wave velocities using the water immersion method [3], we then determined the nine complete elastic stiffness components from which Young's and shear moduli were obtained for each system of composites. The orientation dependence of the measured moduli agreed with the expectation based on particulate alignment. Elastic anisotropies exhibited a maximum difference of about 10% in Young's modulus for 30 v/o SiC samples. Ultrasoundically measured Young's moduli
were also compared with those obtained from tensile tests in which specimens were loaded both longitudinally and transversely with respect to the plate extrusion direction. Finally, ultrasonically measured Young's moduli were compared with a model due to Tandon and Weng [4] which is based on a generalization of the method developed by Mori and Tanaka [5].

MATERIALS

Three aluminum base alloys of 2124, 6061, and 7091 reinforced by 0-30 v/o SiC\textsubscript{p} were investigated. A total of 12 samples were studied. These metal matrix composites were fabricated by DWA Composites Specialities, Inc. using a powder metallurgy technique. The composite materials were received in an extruded-plate form with plate dimensions of approximately 1.27 cm in thickness, 12.7 cm in width, and 30 cm to 200 cm in length. Following extrusion, the 2124 Al/SiC\textsubscript{p} were T4 heat treated, while the 6061 Al/SiC\textsubscript{p} and 7091 Al/SiC\textsubscript{p} were T6 heat treated.

MICROSTRUCTURAL ANALYSIS

We examined the SiC\textsubscript{p} orientation distribution in three mutually perpendicular faces. The composite materials are assumed to be orthotropic, with three material symmetry axes. The three symmetry axes are: x\textsubscript{1} in-plane extrusion direction, x\textsubscript{2} perpendicular to the extrusion plane, and x\textsubscript{3} in-plane perpendicular to extrusion direction (Fig. 1). For metallographic examination, three pieces of specimens were cut from one 20 v/o and two 30 v/o 7091 Al/SiC\textsubscript{p} system with their faces parallel to the symmetry planes. These pieces were ground, and polished by an usual metallographic method. Optical micrographs were taken on each face and micrographs were then analyzed using an image analysis system. Attention was given to the aspect ratio and orientation distribution of SiC particles. Preliminary results showed that most of the SiC particles had elongated shapes with aspect ratios of about 2 to 4. On x\textsubscript{1}-x\textsubscript{2} plane and x\textsubscript{2}-x\textsubscript{3} plane, SiC particles had preferred orientation in x\textsubscript{1} and x\textsubscript{3} directions, respectively. On x\textsubscript{1}-x\textsubscript{3} face, most particles were randomly oriented, but they were slightly aligned in x\textsubscript{1} direction. Fig. 1 shows the typical micrographs and symmetry axes of the material.
ULTRASONIC IMMERSION MEASUREMENT

We followed the experimental procedure of ultrasonic immersion method [3] to determine the nine stiffness components for orthotropic composites. The stiffnesses $C_{11}$, $C_{22}$ and $C_{33}$ are determined from the longitudinal (L) wave velocity propagating along the $x_1$, $x_2$ and $x_3$ axes, respectively while $C_{12}$, $C_{13}$ and $C_{23}$ require measurements of quasilongitudinal (QL) or quasitransverse (QT) waves propagating at an angle to these axes. In principle, $C_{44}$, $C_{55}$ and $C_{66}$ may be determined from transverse (T) waves along the $x_1$, $x_2$ and $x_3$ axes, respectively using shear wave transducers. These stiffness components can also be measured using the immersion technique as described below.

Anticipating the energy beam deviation from the phase front normal for oblique incidence [6,7], we cut two parallelepipeds of about $4.0 \times 1.5 \times 1.2$ cm from each sample with faces parallel to the symmetry planes. Surfaces were prepared by grinding so that opposite faces are flat and parallel to within $5 \mu$m. Throughout the experiment, two $5$ MHz broadband transducers of $1/4$ inch diameter were used. The transmitting transducer was driven by a spike voltage pulse. Turntable with $0.1^\circ$ angle resolution was used to control the incidence angle.

Measurements of $C_{11}$, $C_{22}$ and $C_{33}$

In order to measure $C_{11}$, a pulse of L-wave is propagated along the $x_1$ axis in an immersion setup. By measuring the time delay $\Delta t$ of the L-wave with and without the sample in the path, the longitudinal velocity $V_L$ is calculated from $V_L = (1/\Delta t - d/V_W)^{-1}$ where $d$ is the sample thickness and $V_W$ is the sound velocity in water which is a function of temperature. The temperature of the water bath was measured with $0.1^\circ$ accuracy and the sound velocity equation given in [8] was used. $C_{11}$ is then calculated from $C_{11} = \rho V_L^2$ where $\rho$ is density of the material. $C_{22}$, and $C_{33}$ were measured in a similar manner.

Measurements at oblique incidence

In an oblique incidence through-transmission immersion test, the difference in delay time for the QL-wave with and without the sample in place at an incident angle $\theta_i$ is given by

$$\Delta t = \frac{d}{\cos \theta_r \cdot \cos \theta_i} \cdot \frac{\cos(\theta_r - \theta_i)}{V_W} - \frac{1}{V_L} \tag{1}$$

in which the refraction angle $\theta_r$ is given by

$$\theta_r = \tan^{-1}\left(\frac{\sin \theta_i}{\cos \theta_i - \Delta t V_W / d}\right) \tag{2}$$

The longitudinal phase velocity in the direction $\theta_r$ is then calculated from Snell's law by

$$V_L = V_W \frac{\sin \theta_r}{\sin \theta_i} \tag{3}$$

Similar expressions can be written down for the shear wave in which $V_s$ and $\theta_r$ are replaced by phase velocity $V_s$ and refraction angle $\theta'_r$ of QT-wave. Hence by measuring $\theta_i$ and $\Delta t$ for the QL and QT waves, one can calculate $\theta_r$ and $\theta'_r$ and then $V_L$ and $V_S$.

It should be noted that the time delay measured by this method is due to the group velocity while the equations for calculating stiffnesses use the phase velocity.
Since the refracted QL and QT waves will travel in non-symmetry directions when the incidence of the beam is oblique, the acoustic wave energy propagates at a deviation angle, $\psi$, as shown in Fig. 2. However, using the relation between the phase and group velocity [9], $V_p = V_g \cos \psi$, and Snell's law, it can be shown that the time delay taken by the group velocity is equal to the time delay taken by the phase velocity. Thus, the phase velocity can be correctly measured using the time delay experienced by the group velocity.

Measurements of $C_{66}$ and $C_{12}$

The sample is oriented with the $x_3$-axis vertical. The pulse is then propagated in the $x_1$-$x_2$ plane. Two refracted waves (QL and QT) can be generated as $\theta_1$ is increased from zero. $\Delta t$, and hence $\theta_r$ and $V$, can then be measured for QL and QT waves for different incident angles.

With the sample mounted as shown in Fig. 3a, refracted waves will propagate along the vector $(n_1, n_2, 0)$, where $n_1 = \sin \theta_r$, $n_2 = \cos \theta_r$, and the velocities of QL and QT waves will satisfy the relationship:

$$n_1^2 C_{66} + n_2^2 C_{22} - \rho V^2 (n_1^2 C_{11} - n_2^2 C_{66} - \rho V^2) - n_1^2 n_2^2 (C_{12} - C_{66})^2 = 0 \quad (4)$$

Equation (4) is quadratic in $V^2$, so that if two values of $(\theta_r, V^2)$ are known, it can be solved for $C_{12}$ and $C_{66}$ using the values of $C_{11}$ and $C_{22}$ measured earlier. We measured two sets of $(\theta_r, V^2)$ at $\theta_1 = 6^\circ$ and $8^\circ$, and found $C_{66}$ and $C_{12}$.

Measurements of $C_{55}$ and $C_{13}$

The sample is oriented with the $x_2$-axis vertical (Fig. 3b).
A pulse is then propagated in the $x_1$-$x_3$ plane. Refracted waves will propagate along the vector $(n_1,0,n_3)$, where $n_1 = \sin \theta_r$, $n_3 = \cos \theta_r$, and the velocities of QL and QT waves will satisfy the relationship:

$$\left(n_1^2C_{SS} + n_3^2C_{33} - \rho V^2\right)(n_1^2C_{11} + n_3^2C_{55} - \rho V^2) - n_3^2n_1^2(C_{13} + C_{55})^2 = 0 \quad (5)$$

Measurements of $C_{44}$ and $C_{23}$

The sample is oriented with the $x_1$-axis vertical (Fig. 3c). The pulse is then propagated in the $x_2$-$x_3$ plane. Refracted waves will propagate along the vector $(0,n_2,n_3)$, where $n_2 = \cos \theta_r$, $n_3 = \sin \theta_r$, and velocities of QL and QT waves will satisfy the relationship:

$$\left(n_2^2C_{44} + n_3^2C_{33} - \rho V^2\right)(n_2^2C_{22} + n_3^2C_{44} - \rho V^2) - n_2^2n_3^2(C_{23} + C_{44})^2 = 0 \quad (6)$$

RESULTS AND DISCUSSION

Young's moduli in $x_1$, $x_2$ and $x_3$ directions were computed from the relations:

$$E_{11} = 1/S_{11}, E_{22} = 1/S_{22}, E_{33} = 1/S_{33},$$

where $S_{ij}$ denote elastic compliances, which are related to the $6 \times 6$ elastic stiffness matrix according to $S_{ij} = C_{ij}^{-1}$. Shear moduli in the 2-3, 1-3 and 1-2 planes were obtained from the relations:

$$G_{23} = C_{44}, G_{13} = C_{55}, G_{12} = C_{66}.$$ 

Table 1 shows the experimental results of Young's modulus and shear modulus for the Al/SiC_p system.

In the SiC_p reinforced composite samples, the Young's modulus is the highest along the extrusion direction $x_1$, the next highest along the in-plane transverse direction $x_3$, and the lowest along the out-of-plane direction $x_2$. This ordering of the Young's modulus is consistent with the SiC particle orientation distribution observed in the image analysis. The difference between the extrusion direction ($x_1$) and the out-of-plane direction ($x_2$) is about 10% for 30 v/o SiC samples. Shear moduli have the highest values in the $x_1$-$x_3$ plane, and the difference between $G_{13}$ and $G_{23}$ is about 9% in 30 v/o SiC_p samples.

Shear moduli $G_{12}$, $G_{13}$ and $G_{23}$ can be measured by oblique incidence immersion tests described above or by direct shear velocity measurement using a contact transducer. Fig. 4 shows the comparison of shear moduli measured by the immersion method and the direct contact method. The excellent agreement between the two methods proved the validity of the immersion method.

Table 1. Ultrasonic measurement results for the Al/SiC_p composites

<table>
<thead>
<tr>
<th>Base Alloy</th>
<th>Billet No. (SiC %)</th>
<th>$E_{11}$</th>
<th>$E_{22}$</th>
<th>$E_{33}$</th>
<th>$G_{12}$</th>
<th>$G_{13}$</th>
<th>$G_{23}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2124 Al</td>
<td>PE-2600 (0)</td>
<td>74.7</td>
<td>73.3</td>
<td>75.9</td>
<td>28.0</td>
<td>27.2</td>
<td>27.0</td>
</tr>
<tr>
<td>2124 Al</td>
<td>PE-2404 (25)</td>
<td>122.4</td>
<td>108.0</td>
<td>118.9</td>
<td>42.3</td>
<td>47.1</td>
<td>41.8</td>
</tr>
<tr>
<td>2124 Al</td>
<td>PE-2229 (25)</td>
<td>122.0</td>
<td>108.6</td>
<td>118.2</td>
<td>42.8</td>
<td>46.6</td>
<td>42.2</td>
</tr>
<tr>
<td>2124 Al</td>
<td>PE-2488 (30)</td>
<td>129.3</td>
<td>116.0</td>
<td>125.6</td>
<td>45.8</td>
<td>50.1</td>
<td>45.6</td>
</tr>
<tr>
<td>6061 Al</td>
<td>PE-2045 (0)</td>
<td>74.0</td>
<td>71.7</td>
<td>73.7</td>
<td>26.9</td>
<td>25.9</td>
<td>26.7</td>
</tr>
<tr>
<td>6061 Al</td>
<td>PE-2047 (20)</td>
<td>122.1</td>
<td>110.0</td>
<td>118.2</td>
<td>43.0</td>
<td>46.3</td>
<td>42.1</td>
</tr>
<tr>
<td>6061 Al</td>
<td>PE-2731 (30)</td>
<td>125.5</td>
<td>113.0</td>
<td>122.4</td>
<td>45.4</td>
<td>48.5</td>
<td>44.8</td>
</tr>
<tr>
<td>7091 Al</td>
<td>PE-2730 (0)</td>
<td>74.9</td>
<td>73.6</td>
<td>75.5</td>
<td>27.3</td>
<td>26.5</td>
<td>27.0</td>
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<tr>
<td>7091 Al</td>
<td>PE-2711 (10)</td>
<td>90.6</td>
<td>84.4</td>
<td>87.8</td>
<td>31.8</td>
<td>32.4</td>
<td>31.0</td>
</tr>
<tr>
<td>7091 Al</td>
<td>PE-2712 (20)</td>
<td>111.3</td>
<td>99.8</td>
<td>108.2</td>
<td>39.4</td>
<td>44.1</td>
<td>38.0</td>
</tr>
<tr>
<td>7091 Al</td>
<td>PE-2713 (30)</td>
<td>124.0</td>
<td>112.3</td>
<td>120.4</td>
<td>44.6</td>
<td>47.6</td>
<td>45.3</td>
</tr>
<tr>
<td>7091 Al</td>
<td>PE-2665 (30)</td>
<td>127.0</td>
<td>116.3</td>
<td>125.6</td>
<td>46.7</td>
<td>49.7</td>
<td>45.4</td>
</tr>
</tbody>
</table>
The ultrasonically measured Young's moduli were also compared with those obtained in mechanical tensile tests. The comparison, shown in Fig. 5, showed that the agreement were usually good to within a few percent. The agreement between these two methods indicates that the ultrasonic immersion technique is a valid method for determining the anisotropic properties of Al/SiC<sub>p</sub> MMCs.
COMPARISON WITH A MODEL

Ultrasonically measured Young's moduli for 7091 Al/SiC<sub>p</sub> MMCs were compared with a two phase composite model developed by Tandon and Weng [4]. We considered two different distributions of SiC particle orientation: three dimensional random orientation and unidirectional alignment in the x<sub>1</sub> direction. While the 3-D random orientation results in a macroscopically isotropic solid, unidirectional alignment gives a transversely isotropic one.

Throughout the calculation we assumed the SiC particles to be prolate spheroids with an aspect ratio of 3, and two isotropic elastic constants, E=458 GPa, G=196 GPa [10]. For 7091-T6-Al, E=76 GPa and G=28 GPa were used. Nominal volume fraction of SiC<sub>p</sub> was used in the calculation.

![Graph showing comparison of Young's moduli](image)

Fig. 6. Comparison of Young's moduli for 7091 Al/SiC<sub>p</sub> MMCs with those computed from a model based on 3-D random orientation distribution of SiC particles with an aspect ratio of 3.

The calculated results based on a 3-D random orientation are compared to the measured moduli in Fig. 6. The model curve falls between E<sub>11</sub> and E<sub>22</sub> and is close to E<sub>33</sub> in value. Since this model predicts isotropic properties, it does not explain the anisotropic behavior. Fig. 7 shows the comparison with the transversely isotropic model. E<sub>11</sub> and E<sub>22</sub> calculated by this model agree well with the measured values. The model therefore may be used to predict the highest and lowest Young's modulus of the Al/SiC<sub>p</sub> MMCs. However, in order to interpret the complete anisotropic elastic behavior, one must consider the orthotropic distribution of the SiC particle orientation. This requires further analytic model development and quantitative measurement of the microstructure.
Fig. 7. Comparison of Young's moduli for 7091 Al/SiCp MMCs with those computed from a model based on SiC particles aligned in \( x_1 \) (extrusion) direction.

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