Mechanical Properties and Wear Resistance of 6061 Alloy Reinforced with a Hybrid of Al₂O₃ Fibers and SiC Whiskers*

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The mechanical properties and wear resistance of 6061 alloy reinforced with Al₂O₃ fibers and a hybrid of Al₂O₃ fibers and SiC whiskers were investigated. The elastic modulus of T6 tempered Al₂O₃/6061 and Al₂O₃-SiC/6061 composites can be expressed as 

\[ E_{c} = 140 V_{f_{Al_2O_3}} + 68 \]

and 

\[ E_{c} = 140 V_{f_{Al_2O_3}} + 180 V_{f_{SiC}} + 68, \]

respectively. The fiber arrangement coefficient \( \alpha \) is found to be 0.7 for Al₂O₃ and 0.45 for SiC whisker. The wear resistance of Al₂O₃/6061 composites is inferior to that of SiC/6061 composites. The addition of small volume fractions of SiC whisker to Al₂O₃/6061 composites gives rise to a remarkable improvement of the wear resistance which is, on the contrary, superior to that of SiC/6061 composites.

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I. Introduction

Aluminium alloys reinforced with high elastic modulus, high strength fibers\(^{(1)}\) showing an improvement of the mechanical properties\(^{(2)-(15)}\) are now evoking immense interest. In recent years significant advances have been made on development of applications of these composites\(^{(14)}\). The most generally used reinforcements are carbon fibers, alumina fibers and more recently SiC whiskers. The properties of SiC whisker reinforced aluminium alloys are quite attractive. However, the high cost of SiC whiskers precludes the use of these composites in engineering structural materials.

Most of the previous investigations have been conducted on the mechanical properties\(^{(2)-(15)}\), but very few studies on the wear resistance have been available in the literature.

Moreover, the reinforcement with one species of fiber has been the major subject of research and development, while the reinforcement with the hybrid of fibers is not widely investigated.

In our previous work\(^{(16)}\), the mechanical property and wear resistance of SiC whiskers reinforced 4032 composites have been investigated. The results of this study indicated that the effects of SiC whisker on wear resistance were found due to (1) the contribution of high wear resistance of SiC whisker itself, and (2) the formation of uniform dispersion of SiC whiskers at the boundary of the hot pressed aluminium powder was found to be a barrier against the slip of Si particle along the sliding direction subsequent to the exfoliation. The aluminium matrix was scratched with slipped Si particle to form wear grooves. The formation of wear grooves was known as the cause of the degradation of the wear resistance.

In the present investigation, the mechanical properties and wear resistance of 6061 alloy reinforced with a hybrid of Al₂O₃ fibers and SiC whiskers were investigated to take advantage of the effect of hybrid reinforcement.
II. Experimental Procedure

1. Materials preparation

Composite materials were prepared by a powder metallurgical technique.

The matrix 6061 alloy powder was produced by inert gas atomization. The powder was sieved and particles that passed through 44 μm sieve openings were used. Chemical compositions of 6061 alloy powder are shown in Table 1.

The alumina fiber used was δ-Al₂O₃, known as "Saffil" with a mean diameter of 3 μm and lengths up to 500 μm. The SiC whisker was β-SiC with diameter ranging from 0.05 to 1.50 and lengths up to 200 μm. Typical properties of Al₂O₃ fiber and SiC whisker are shown in Table 2. Compositions of the composites are shown in Table 3. The 6061 alloy powder, Al₂O₃ fibers and SiC whiskers of the prescribed compositions were blended and then hot pressed in a vacuum of 10⁻² Pa at the temperature of 800 K and the pressure of 60 MPa in a graphite die to produce specimens 80 mm in diameter and 15 mm thick.

2. Mechanical test

Tensile specimens 4 mm in width, 3 mm in thickness and 15 mm in gauge length were machined from the hot pressed specimens with their transverse directions parallel to the hot pressing direction. The tensile test was carried out with a strain rate of 8 × 10⁻³ s⁻¹. The strain was measured with a strain gauge sticking on the surface of the tensile specimen.

3. Wear test

The wear test was carried out on a pin-plate apparatus. Dimensions of the pin and the schematic drawing of the wear test method are shown in Fig. 1. A load of 49 N was applied to the pin specimen which was placed in contact with the sliding plate sliding back and forth in an ethanol bath at room temperature with a speed of 80 mm/s. The total sliding distance was 600 m. The sliding plate SKH-51 was tempered to a hardness of Hv=880. The pin specimen and the sliding plate were machined to a surface roughness of Rmax=1.5 μm. The weight loss was obtained with the aid of a microbalance giving readings up to 10⁻⁵ g.

Specimens using in the mechanical and wear tests were solutionized at 793 K for 14.4 ks, water quenched and aged at 443 K for 28.8 ks. The wear coefficient was defined as the volume loss from the surface per unit load applied and distance slid.
III. Results and Discussion

Scanning electron micrographs of hot pressed $\text{Al}_2\text{O}_3/6061$ and $\text{Al}_2\text{O}_3-\text{SiC}/6061$ composites are in Fig. 2. The specimens were examined after being etching in a NaOH solution. $\text{Al}_2\text{O}_3$ fibers and SiC whiskers were dispersed uniformly at the boundary of 6061 alloy powder forming a three dimensional network. The aluminium cell size measured over several parts was in the range of 20–30 µm.

1. Mechanical properties

(1) Elastic modulus

The relationship between the elastic modulus $E_c$ (GPa) of $\text{Al}_2\text{O}_3/6061$ composites and the volume fraction of $\text{Al}_2\text{O}_3$ fibers is shown in Fig. 3, in comparison with that of SiC/6061 composites obtained in our previous work. The elastic modulus of $\text{Al}_2\text{O}_3/6061$ composites exhibits a linear relationship with the volume fraction of $\text{Al}_2\text{O}_3$ fibers, giving

$$E_c = 140V_f + 68$$  \hspace{1cm} (1)

The elastic modulus of the composites can be analyzed by a simple Rule of Mixture (ROM) for uniaxial continuous fiber composite above a critical volume fraction of fiber:

$$E_c = E_f V_f + E_m (1 - V_f)$$  \hspace{1cm} (2)

where $E_c$ is the elastic modulus of composite, $E_f$ is the elastic modulus of the fiber and $V_f$ is the volume fraction of the fiber and $E_m$ is the elastic modulus of the matrix.

However, in the present work modification is required to account for the lack of reinforcing due to the discontinuous fibers and the pseudo-three dimensional random orientation of fibers. Thus, an additional term $\alpha$ relating to the inefficiency of reinforcement must be introduced:

$$E_c = \alpha E_f V_f + E_m (1 - V_f)$$  \hspace{1cm} (3)

Equation (3) also may be expressed mathematically in a form as:

$$E_c = (\alpha E_f - E_m)V_f + E_m$$  \hspace{1cm} (4)

Comparison of the ROM elastic modulus eq. (4) with the elastic modulus of the present

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![Fig. 2 Scanning electron micrographs of (a) 20 vol% $\text{Al}_2\text{O}_3/6061$ and (b) 20 vol% $\text{Al}_2\text{O}_3-10$ vol% SiC/6061 composites. (NaOH etched)](image1)

![Fig. 3 Elastic moduli of $\text{Al}_2\text{O}_3/6061$ composites in comparison with those of SiC/6061 composites.](image2)
results (1), the following relation is obtained:

\[(\alpha E_f - E_m) \div 140\]

Taking the elastic modulus of the Al₂O₃ fiber to be \(E_f = 300\) GPa and the elastic modulus of the 6061-T6 alloy to be \(E_m = 68\) GPa, we obtain \(\alpha \approx 0.7\).

In our previous work(16), the elastic modulus of the SiC whisker reinforced 6061 alloy was obtained as follows:

\[E_c \div 180 V_{\text{SiC}} + 68\]  

Taking the elastic modulus of the SiC whisker to be \(E_f = 550\) GPa, a value of \(\alpha \approx 0.45\) is obtained.

A number of values for \(\alpha\) have been suggested; \(\alpha \approx 0.5\) for the planar random orientation and for \(\alpha \approx 3/8\) the three-dimensional random orientation. The value of \(\alpha \approx 0.45\) for SiC/6061 composites lies approximately between 3/8 and 0.5, which can be explained by the pseudo-three-dimensional random of the composites in the present study. However, the value of \(\alpha \approx 0.7\) for Al₂O₃/6061 composites is quite different from these values. The reason for this discrepancy is not clear. However, it is probable that (1) the distribution of fiber orientation for SiC whisker and for Al₂O₃ fiber is different due to the dimensional effect. Fine SiC whiskers tend to disperse in three-dimensional randomness at the triple points of the aluminium powders while larger fibers of Al₂O₃ exhibit the difference, and (2) the value for elastic modulus of the Al₂O₃ fiber is underestimated.

The elastic modulus of a hybrid of the Al₂O₃ fiber and SiC whisker reinforced 6061 composites are shown in Fig. 4. Assuming that the elastic modulus of the hybrid of Al₂O₃ fibers and SiC whiskers is a superimposing of the contribution of \((\alpha E_f - E_m) V_{\text{Al}_2\text{O}_3}\) of Al₂O₃ fibers and the contribution of \((\alpha_w E_w - E_m) V_{\text{SiC}}\) of SiC whiskers on the elastic modulus of the 6061 alloy matrix, the elastic modulus of the composites can be expressed as follows:

\[E_c \div (\alpha E_f - E_m) V_{\text{Al}_2\text{O}_3} + (\alpha_w E_w - E_m) V_{\text{SiC}} + E_m\]  

where \(\alpha_c\) and \(\alpha_w\) are parameters characterizing the distribution functions for Al₂O₃ fibers and

\[
\begin{array}{|c|c|}
\hline
\text{Composition} & \text{Modulus (GPa)} \\
\hline
25Al₂O₃ & 102 \\
25SiC & 110 \\
20Al₂O₃ - 5SiC & 108 \\
30Al₂O₃ & 112 \\
30SiC & 116 \\
20Al₂O₃ - 10SiC & 115 \\
\hline
\end{array}
\]

Fig. 4 Effect of SiC whisker addition on elastic moduli of Al₂O₃/6061 composites.

For a limited volume fraction of Al₂O₃ fibers and whiskers, the elastic modulus calculated from eq. (6) are in good agreement with the experimental results:

\[E_c \div 140 V_{\text{Al}_2\text{O}_3} + 180 V_{\text{SiC}} + 68\]  

SiC whiskers, \(V_{\text{Al}_2\text{O}_3}\) and \(V_{\text{SiC}}\) are the volume fractions of Al₂O₃ fibers and SiC whiskers, respectively.

(2) Tensile properties

The tensile properties of T6 tempered composites are shown in Fig. 5. The reinforcement with a volume fraction of 0.15 resulted in an increase in the tensile strength and 0.2% tensile yield strength up to 20% compared with the corresponding values for the 6061 alloy matrix. However, there is little effect on the increase of the tensile properties with increasing volume fraction of Al₂O₃ fibers more than 0.15 in comparison with the corresponding values for the SiC/6061 composites. The SiC whisker additions were seen to be more effective in strengthening than Al₂O₃ fiber. The increase in volume fraction of Al₂O₃ fiber resulted in the reduction of ductility.

However, it is to be noted that the tensile strength of the composites reinforced with a hybrid of Al₂O₃ fibers and SiC whiskers, as shown in Fig. 6, was approximately equal to the value of that of the SiC/6061 composites reinforced with the same volume fraction.

Scanning electron micrographs of fracture
surfaces of tensile specimens are shown in Fig. 7. Most of the fracture surfaces consisted of fine and equiaxed dimples. It was observed that the Al$_2$O$_3$ fibers were fractured in the same plane of the matrix and that the pull-out was minimal. An example of the pull-out of Al$_2$O$_3$ fiber is shown in Fig. 7(b). The pull-out fiber, marked with the arrow, was covered entirely with a coating of the aluminium matrix. The present results indicated the high strength of the interfacial bonding of Al$_2$O$_3$ fiber and the aluminium matrix. A high magnification of the fracture surface containing SiC whiskers is shown in Fig. 7(c). The pull-out of SiC whiskers was not observed.
(3) Wear resistance

The relationship between the wear coefficient of Al₂O₃/6061 composites and the volume fraction of Al₂O₃ fibers is shown in Fig. 8, in comparison with that of SiC/6061 composites obtained in the previous study. The addition of Al₂O₃ fibers in a volume fraction of 0.15 resulted in a remarkable decrease of the wear coefficient to a value of 1/6 of that of the 6061 alloy matrix. The wear coefficient continuously decreased with increasing volume fraction of Al₂O₃ fibers. In comparison with the wear property of the SiC/6061 composite, it should be noted that the reinforcement with SiC whiskers was more effective in the improvement of the wear resistance than Al₂O₃ fibers.

However, it is interesting to note that the wear resistance of the composite reinforced with a hybrid of Al₂O₃ fibers and SiC whiskers was superior to that of the SiC/6061 composite reinforced with the same volume fraction, as shown in Fig. 9. For example, the wear coefficient of 0.16 × 10⁻⁸ mm³N⁻¹mm⁻¹ for the 20 vol% Al₂O₃-5 vol% SiC/6061 composite was lower than the corresponding value of 0.6 × 10⁻⁸ mm³N⁻¹mm⁻¹ for the 25 vol% SiC/6061 composite. Thus, the portion shown by the dotted line in Fig. 9, can be regarded as the contribution of 5 vol% SiC to the wear resistance of the 20 vol% Al₂O₃/6061 composite.

On comparing the contribution effect of SiC whisker to the wear resistance, the contribution of SiC whisker in the composites reinforced with a hybrid of Al₂O₃ fibers and SiC whiskers was more effective than that in the composites reinforced with a single species of SiC whiskers.

The outstanding wear resistance of composites reinforced with a hybrid of Al₂O₃ fibers and SiC whiskers was investigated by observation of the wear surfaces. The results are shown in Fig. 10.

The wear surface of the composites reinforced with Al₂O₃ fibers exhibited a number of deep wear grooves. The formation of these wear grooves is believed to be a result of the slip of Al₂O₃ fiber along the sliding direction. The aluminium matrix was scratched with slipped Al₂O₃ fibers, giving rise to an increase in the weight loss. The slip of Al₂O₃ fibers was clearly observed at the fibers lying on the wear surface with the fiber length orientation parallel to the sliding direction.

The slip of SiC whisker on the wear surface of SiC/6061 composites was also observed in our previous work. However, the extremely fine whiskers did not cause a considerable damage to the aluminium matrix compared with Al₂O₃ fibers.

However, the formation of wear grooves...
was not observed in the composites reinforced with a hybrid of Al₂O₃ fibers and SiC whiskers, as shown in Fig. 10(b). The present result was similar to that obtained in our previous work on SiC/4032 composites\(^{16}\). In most of the cases, the slip of Al₂O₃ fibers was found to be pinning with the dispersing SiC whiskers.

The present authors investigated previously the wear resistance of Al–Si alloys containing Si particles of various sizes\(^{17}\). It was found that the wear resistance of these alloys depended remarkably on the Si particle size and surface roughness of the counter material. For a given surface roughness, the slip of Si particles did not occur in the alloy containing Si particles whose sizes were above a critical value. The sizes of Al₂O₃ fibers and SiC whiskers were not large enough compared with the surface roughness of the counter material in the present study. Thus, the pinning effect resulted in a remarkable improvement of the wear resistance.

**IV. Conclusions**

(1) The elastic modulus \(E_c\) (GPa) of T6 tempered Al₂O₃/6061 composites exhibits a linear relationship with the volume fraction of Al₂O₃ fibers. For a limited volume fraction of Al₂O₃ fibers the elastic modulus of the composites can be calculated from the following relation:

\[
E_c \approx 140 V_{Al_2O_3} + 68
\]

The elastic modulus \(E_c\) (GPa) of the T6 tempered composites reinforced with a hybrid of Al₂O₃ fibers and SiC whiskers is found to be a superimposing of the contribution of Al₂O₃ fibers and SiC whiskers on the elastic modulus of the matrix, namely,

\[
E_c \approx 140 V_{Al_2O_3} + 180 V_{SiC} + 68
\]

(2) The tensile strength of the 6061–T6 alloy was increased by 20% by the reinforcement with 15 vol% of Al₂O₃ fibers. SiC whisker addition is more effective in strengthening than Al₂O₃ fibers.

(3) The reinforcement with SiC whiskers is more effective in increasing the wear resistance than Al₂O₃ fibers. However, the wear resistance of the composites reinforced with a hybrid of Al₂O₃ fibers and SiC whiskers is superior to that of the SiC/6061 composites. The effect of SiC whiskers in the hybrid of Al₂O₃ fibers and SiC whiskers can be interpreted as a barrier against the slip of Al₂O₃ fibers.

**REFERENCES**

(1) A. P. Levitt: *Whisker technology*, John Wiley and Sons, New York, (1970), p. 168.
(2) W. C. Harrigan, Jr. and W. W. French: *ICCM 1 Proc.*, The Met. Soc. AIME, (1975), p. 519.
(3) M. F. Amateau and W. D. Hanna: *ICCM 1 Proc.*, The Met. Soc. AIME, (1975), p. 586.
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(4) A. P. Divecha and S. G. Fishman: *ICCM 3 Proc.*, vol. 3, Cambridge, (1979), p. 351.
(5) R. J. Lederich and S. M. L. Sastry. Mat. Sci. Eng., 55 (1982), 143.
(6) D. Wester: Metal. Trans. A, 13 (1982), 1511.
(7) T. G. Nieh: Metal. Trans. A, 15 (1984), 139.
(8) D. F. Hasson, S. M. Hoover and C. R. Crowe: J. Mater. Sci., 20 (1985), 4147.
(9) C. R. Crowe, R. A. Gray and D. F. Hasson: *ECCM Proc.*, Bordeaux, (1985), p. 843.
(10) T. W. Clyne, M. G. Bader, G. R. Cappleman and A. P. Hubert: J. Mater. Sci., 20 (1985), 85
(11) J. Dunwoodie, E. Moore, C. A. G. Langman, W. R. Symes: *ICCM 5 Proc.*, The Met. Soc. AIME, Warrendale, (1985), p. 671.
(12) Data sheet on Saffil, ICI, Mond Division, (1984).
(13) M. W. Mahoney and A. K. Ghosh: Metal. Trans. A, 18 (1987), 2115.
(14) A. P. Divecha, S. G. Fishman and S. D. Karmarkar: J. Metals, 9 (1981), 12.
(15) C. M. Friend: J. Mater. Sci., 22 (1987), 3005.
(16) Than Trong Long, T. Assaka, M. Ose and M. Morita: J. Japan Inst. Metals. 51 (1987), 864.
(17) To be published.