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# Wear of ceramic particle-reinforced metal-matrix composites

## Part I *Wear mechanisms*

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Pin-on-disc dry sliding tests were carried out to study the wear mechanisms in a range of metal-matrix composites. 6061-aluminium alloys reinforced with 10 and 20 vol % SiC and $Al_2O_3$ particles were used as pin materials, and a mild steel disc was used as a counterface. A transition from mild wear to severe wear was found for the present composites; the wear rate increased by a factor of $10^2$. The effects of the ceramic particles on the transition load and wear with varying normal pressure were thoroughly investigated. Three wear mechanisms were identified: abrasion in the running-in period, oxidation during steady wear at low load levels, and adhesion at high loads. A higher particle volume fraction raised the transition load but increased the wear rate in the abrasion and adhesion regimes. Increase of particle size was more effective than increase of volume fraction to prolong the transition from mild wear to adhesive wear. The reasons for different wear mechanisms were determined by analyses of the worn surfaces and wear debris.

### 1. Introduction

It is well known that improvement in the wear resistance of aluminium alloys can be achieved by adding ceramic particles such as SiC and $Al_2O_3$ to the matrix alloy [1–10]. Particle-reinforced metal-matrix composites (MMCs) have been used in brake and piston components in automobiles and aircrafts over the last decade owing to their attractive friction and wear properties [2]. It has been found that the wear resistance of the aluminium matrix composites is influenced by numerous factors such as the morphology, size and volume fraction of reinforced particles, as well as the strength of the interface [1–5]. Earlier experimental studies [2, 3] have shown that the abrasive wear resistance of metal-matrix composites increased with increasing volume fraction of the particles. Hosking *et al.* [10] observed an increase in wear resistance of 2014 Al–$Al_2O_3$ with increasing weight per cent and size of ceramic particles. However, conflicting reports exist in the literature when metallic counterfaces are used as rubbing pairs. For example, Alpas and Embury [11] observed a decrease in the sliding wear resistance with increasing particle volume fraction in a 2014 Al–SiC/steel system. Saka and Karalekas [12] reported a decrease in sliding wear resistance with increasing particle concentration in a Cu–$Al_2O_3$ composite. Therefore, the selection of the rubbing pairs with metal-matrix composites seems important and different wear mechanisms may result in different wear behaviour. Because steel or steel alloy components as wear counterfaces are widely used in tribosystems, the study of MMCs/steel wear systems has become an important topic in recent years. For instance, Wang and Rack [5] indicated that the wear resistance of the MMCs may be offset by the accelerated wear of the steel. Smith [13] showed that the wear rate could be reduced if an oxide layer was present on the steel surface.

Both Wang and Rack [12] and Zhang and Alpas [6] have found a transition from mild wear to severe wear for the composites reinforced with ceramic particles. Zhang and Alpas [6] indicated that the transition behaviour was controlled by frictional heating to a critical temperature, which was higher for composites than unreinforced alloys. Wang and Rack [2], however, pointed out that the transition was caused by the fracture of the particles on the worn surface.

Although a number of studies has been carried out on the MMCs/steel systems [5–10], the wear mechanisms of different types of metal-matrix composites sliding against steel are far from fully understood. The objective of the present work was to examine the wear mechanisms of this system under dry sliding conditions and to study the role of ceramic particles on the wear behaviour.

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TABLE I Mean diameter of the particles and Vickers hardness of the composites

| Composites | 10% SiC–Al | 20% SiC–Al | 10% $Al_2O_3$–Al | 20% $Al_2O_3$–Al |
|---|---|---|---|---|
| Diameter (μm) | 1.8 | 1.8 | 4.5 | 8.8 |
| Hardness, Hv (kgf/mm$^{-2}$) | 130 | 150 | 130 | 145 |

## 2. Experimental procedure

Four 6061-Al matrix composites reinforced with either SiC or $Al_2O_3$ particles were studied; two contained 10 vol % and the other two contained 20 vol %. Samples were machined from 20 mm extruded round bar and subjected to the following heat treatment: solution treated at 530 °C for 1.5 h, water quenched, naturally aged at room temperature for 20 h and then artificially aged at 175 °C for 8 h. Cylindrical pin samples were then machined to a length of 12 mm and a diameter of 8 mm. The Vickers microhardness was measured under a load of 5 N and averaged from five readings. The mean diameter of the particles and Vickers microhardness of these composites are shown in Table I. The SiC particles are much finer than the alumina particles.

Dry sliding tests were carried out by using a Plint-Cameron pin-on-disc wear machine. Two composite pin specimens were held against a rotating mild steel disc with a hardness of Hv 190. The surface of both the pins and disc were polished to a 1 μm finish and cleaned with acetone prior to testing. A fixed track diameter of 80 mm was used in all tests, and each test was run on a fresh track by re-machining and re-polishing the disc. Samples were tested twice at each condition and the average friction and wear values were taken from four samples. The tests were carried out at a sliding velocity of 0.98 m/s$^{-1}$, and the normal stress was varied from 0.3–3 MPa. The tangential force was measured by a force transducer attached to the specimen holder, and continuously recorded on a chart recorder. In the adhesive wear regime, the volumetric wear of the composite pins was measured by a linear variable displacement transducer (LVDT) and recorded on a chart recorder simultaneously with the tangential force. While in the abrasive and oxidative wear regimes, the volumetric wear was measured by weight losses of the specimens to 0.1 mg using an analytical balance, and then converted to volumes using the densities of each specimen. The wear rate was defined as the ratio of the wear volume to sliding distance. The worn surfaces and wear debris were investigated by using scanning electron microscopy (SEM), optical microscopy, atomic force microscopy and energy dispersive X-ray analysis (EDAX).

## 3. Analysis of wear mechanisms

Three wear mechanisms, abrasion, oxidation and adhesion, were observed in the present MMCs/steel system depending on the applied load and the sliding distance. Detailed results and discussions are presented below.

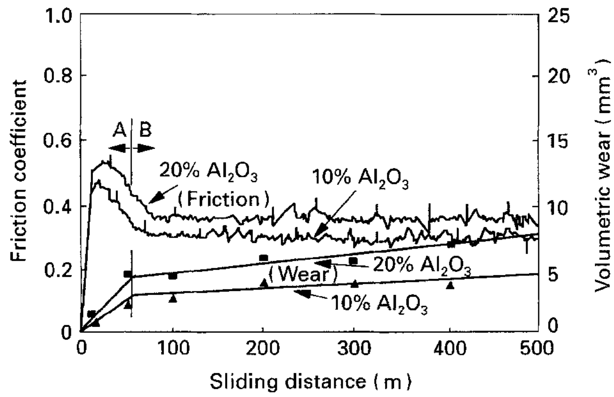


*Figure 1* Variation of friction coefficient and volumetric wear with sliding distance for 10% and 20% $Al_2O_3$ composites at a normal stress of 0.69 MPa.

### 3.1. Abrasive wear in the running-in period

At low load levels, the counterfaces were quickly abraded by the hard asperities on the polished surfaces until a steady state was reached. This process was called the running-in (regime A, Fig. 1). Such abrasive wear occurred in the first 50 m, with abrasion being the predominant wear mechanism. Typical variation in the friction coefficient and volumetric wear with sliding distance for $Al_2O_3$ composites, under a normal stress of 0.69 MPa, is shown in Fig. 1. The friction coefficient increased initially to a maximum value and then dropped to a steady level, which was independent of the sliding distance. Correspondingly, the volumetric wear of the composite pin increased steeply and then slowed down to a more steady rate. The reason for the rapid abrasion in regime A is that the reinforced ceramic particles protrude about 1 μm from the composite surfaces, as shown in Fig. 2, with an atomic microforce microscopic surface profile. These particles acted as cutting tools to scratch the steel surface and form rough grooves at the beginning of the wear process [4]. At the same time, the steel asperities abraded the matrix alloy to form grooves on the surface of the composites. In addition, particles were fractured or debonded or embedded on to the steel surface, resulting in extra scratching on the composites. The higher the volume fraction, the greater was the wear rate, see Fig. 1. On the other hand, the steel disc was severely scratched or machined by the composite in this regime. The heavier the load or the larger the particles, the larger the steel chips and the deeper grooves that were produced, which increased the roughness of the wearing surfaces and accelerated the wearing of both the composite pin and steel disc.

Tests by rough polished pin surfaces (down to 3 μm) were also carried out to compare the effects of initial

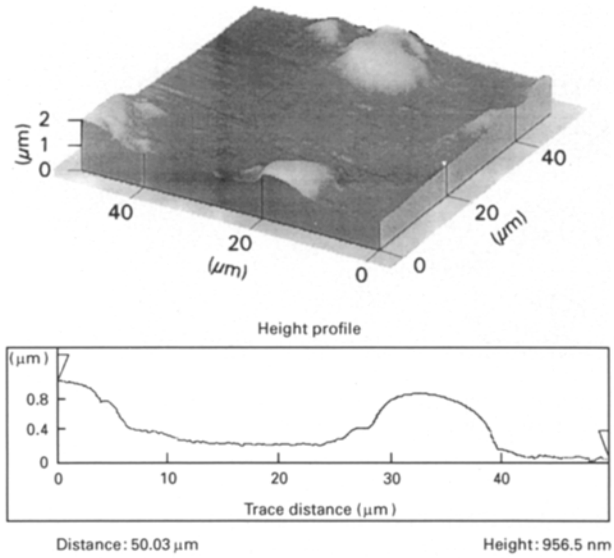


*Figure 2* Atomic force microscopic image showing large protruded $Al_2O_3$ particles after polishing to a 1 µm finish in a 20% $Al_2O_3$ composite.

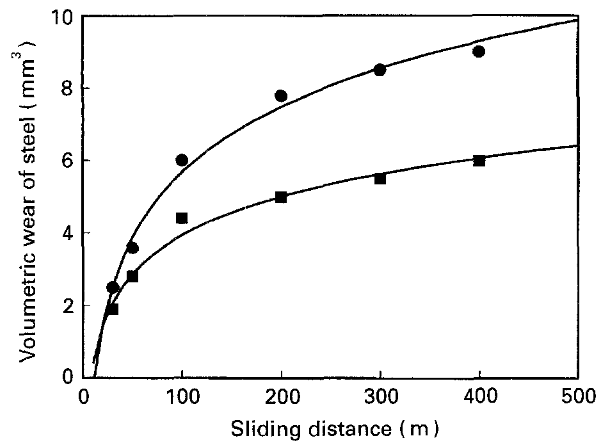


*Figure 3* Variation of abrasive wear of the steel disc with sliding distance at a normal stress of 0.69 MPa (●) against 20% $Al_2O_3$-Al; (■) against 10% $Al_2O_3$-Al.

surface roughness. An increased wear was observed in this case and the worn surface of both pins and disc were rougher than those tested by smooth surfaces. In the abrasive wear regime, the wear rate of composites with 20 vol % particles was slightly higher than that of composites with 10 vol % particles. One reason for this is that more ceramic particles may be embedded on to the disc surface and then accelerate the wear of the composite pins. Another reason is that the enhanced steel disc wear by higher particle volume fraction may aggravate the matrix wear of the composite. The volumetric wear of the steel disc increased with increasing particle size and particle volume fraction. The volumetric wear of the disc increases exponentially with the sliding distance as shown in Fig. 3.

A typical worn surface of a 20 vol % composite in the abrasive wear regime, at a normal stress of 1.06 MPa, is shown in Fig. 4. Parallel grooves can be seen and large cavities on the surface can also be found along the grooves. High magnification of the cavities is shown in Fig. 5. These cavities were produced by the fracture of large ceramic particles or clusters of the particles by repeated sliding. A number of small cracks

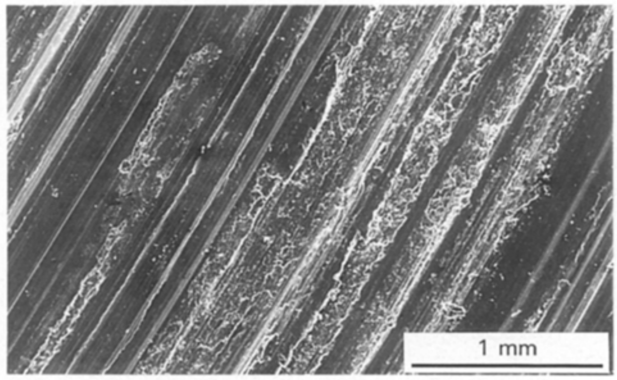


*Figure 4* Scanning electron micrograph showing a surface worn by abrasion on a 20% $Al_2O_3$ composite at a normal stress of 1.06 MPa.

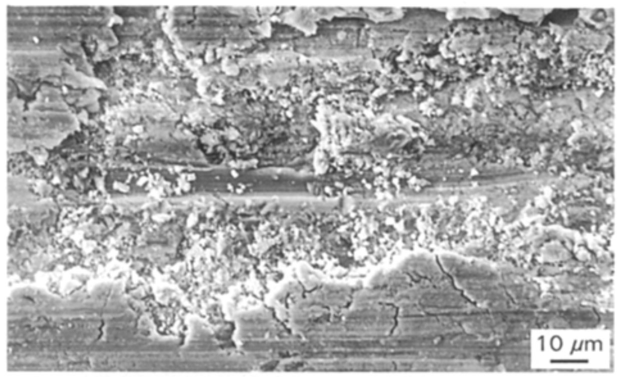


*Figure 5* High magnification of the cavities produced in the abrasive wear regime.


*Figure 6* Scanning electron micrograph of abrasive wear debris on a 20% $Al_2O_3$ composite.

at the edge of the cavity can also be seen. The fractured particles acted as load-bearing particles or as abrasives between the rubbing surface. Fig. 6 shows the irregular wear chips collected in the abrasive wear regime. EDAX revealed that they contained mainly aluminium, silicon and iron, as shown in Fig. 7, indicating that they came from both the composite pin and steel disc. These irregular chips were most likely produced by the interaction of the scratch grooves. The scratch interaction is illustrated in Fig. 8. Investigation of the chips and worn surfaces suggests that deformation of the composite is less important than chip formation for increasing wear rate in this regime.

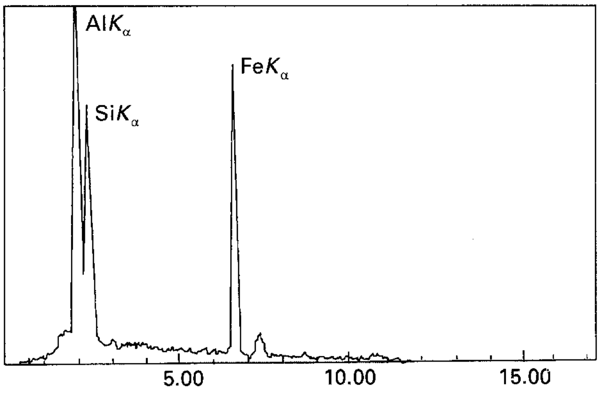


*Figure 7* Energy dispersive X-ray analysis of the irregular shape wear debris in abrasion.

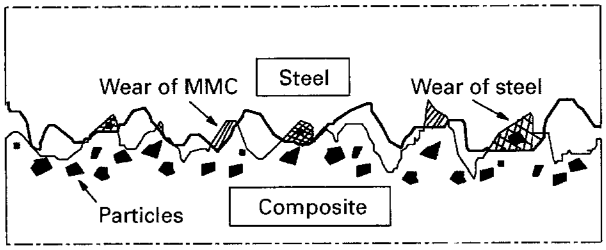


*Figure 8* Illustration of scratch interactions.


*Figure 9* An example of a steel chip resulting from abrasive wear on a 20% $Al_2O_3$ composite.

Apart from the irregular chips, continuous steel chips were occasionally produced. This cutting behaviour became more obvious in the system of $Al_2O_3$-reinforced composites and steel. A typical continuous chip cut from the steel disc is shown in Fig. 9, corresponding to a sharp rise in the friction coefficient, see Fig. 1. Observations of the continuous steel chips show that their width is several times larger than the average particle, indicating it is not due to a single ceramic particle but rather an accumulation of hard asperities. This phenomenon may be found when a negative attack angle of the abrasive particle is formed.

The above abrasion mechanism presided only for a very short duration. The whole wear process in this regime is somewhat similar to grinding. Variation of both the friction coefficient and volumetric wear indicated that a wear mechanism transition took place when the tests entered regime B.

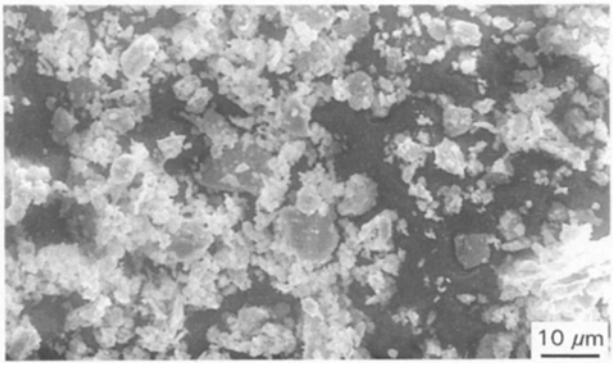


*Figure 10* Scanning electron micrograph showing powder-like oxidative wear debris and some particles.

## 3.2. Oxidation in steady wear

At low load levels, after a short period of abrasion, the volumetric wear reached a steady state, represented by regime B in Fig. 1. Oxidative wear was found to be the main wear mechanism. Evidence for this is given by the low wear rate, supported by examination of the powder-like wear debris and the worn surfaces. At this stage, the wear rates for both the pin and disc were small and the wear debris produced in this regime was powder-like and grey in colour. The friction coefficient in this regime is the lowest and the worn surfaces were dull and grey. The oxidative wear debris is shown in Fig. 10. Powder-like debris and small fractured ceramic particles can be seen. Because most of the surface track of the steel disc is exposed to air, and with increasing sliding distance, the temperature goes up quickly, oxidation easily occurs. Thus oxidative particles or films lubricate the surface and reduce wear. The worn surfaces of pin and disc were smoother than those in the abrasive wear regime. Cutting of the steel also occurred occasionally in this regime, but few irregular chips were produced.

Although oxide formation degrades the metal surface by removing metal atoms, the resulting film may produce a lubricating effect and, in many cases, may reduce friction and wear rate. This is also consistent with the observations of Smith [13]. If the groove was rough in the abrasive wear regime, the transition to oxidation emerged earlier. Oxidative wear is good for decreasing wear of the composites.

## 3.3. Adhesion in the severe wear regime

For a given MMC, the severe wear regime C, as shown in Fig. 11, would be encountered if the applied load reached a critical value. The wear rate in this regime is about two orders of magnitude greater than that in regimes A. The friction coefficient reached a maximum value quickly and then remained constant. The volumetric wear of the pin increased steeply with sliding distance, as shown in Fig. 12. On the contrary, the steel disc was covered by the composite materials, suggesting that no wear occurred.

The worn surfaces of the composite pins were white and shiny and appeared to be smoother than those in regimes A and B. Fig. 13 shows the worn surface of a 20 vol % SiC composite at a normal stress of

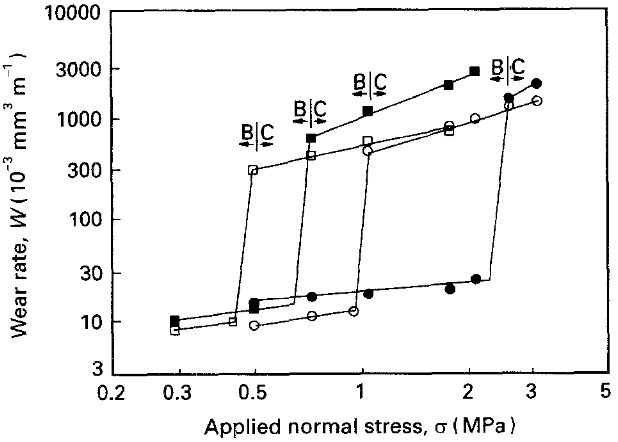


*Figure 11* Variation of wear rate with normal stress for SiC and $Al_2O_3$ composites. (□) 10% SiC, (■) 20% SiC; (○) 10% $Al_2O_3$, (●) 20% $Al_2O_3$.

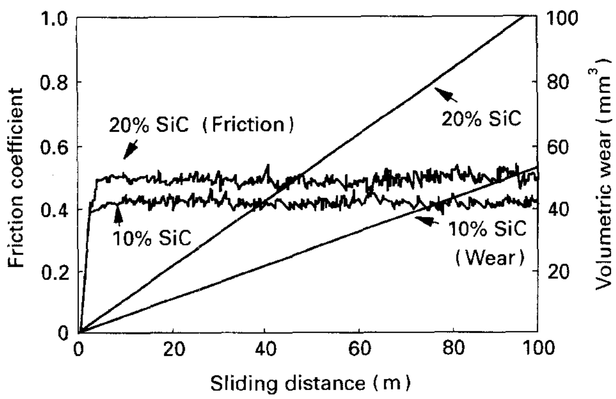


*Figure 12* Variation of friction coefficient and volumetric wear with sliding distance for 10% and 20% SiC composites at a normal stress of 0.69 MPa.

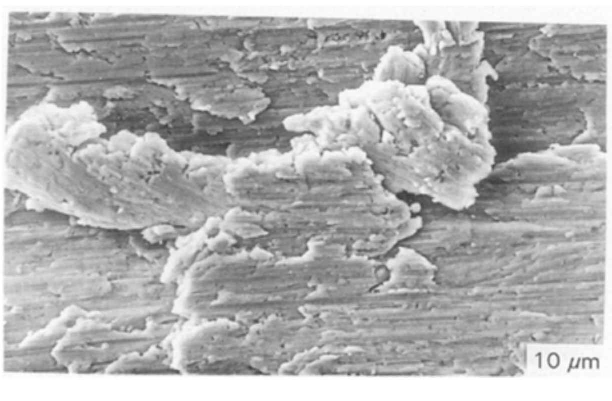


*Figure 13* Scanning electron micrograph showing worn surface of a 20% SiC composite at a normal stress of 1.06 MPa, in the adhesive wear regime.

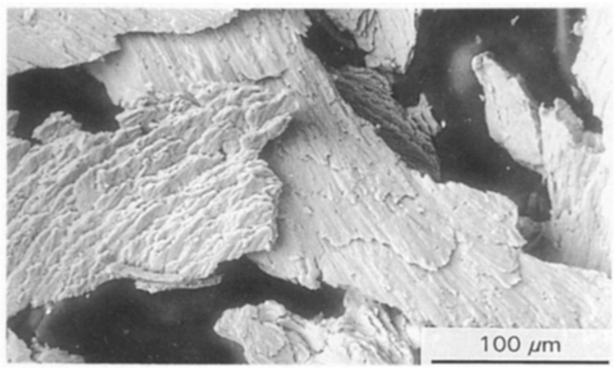


*Figure 14* Examples of large flaky debris on a 20% SiC composite produced in the adhesive wear regime.

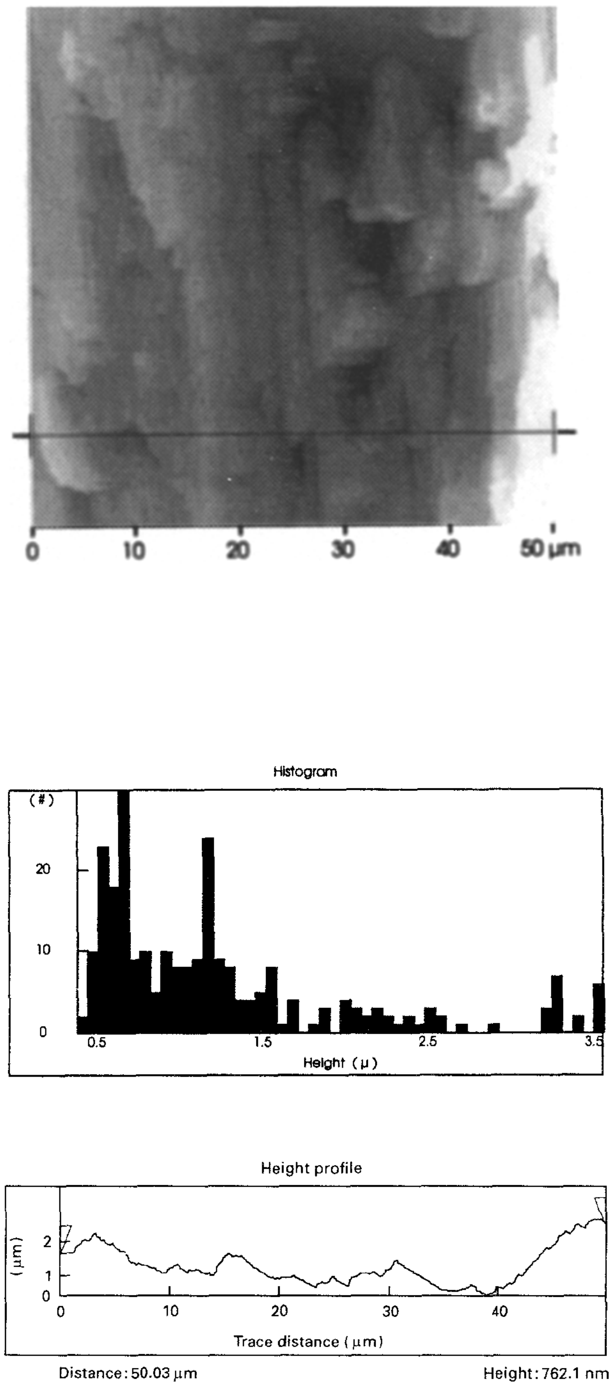


*Figure 15* Atomic force microscopic analysis showing a worn surface topograph of a 20% SiC–Al composite by adhesive wear at a stress of 1.06 MPa.

1.06 MPa. Large flaky wear debris was found on the worn surface. Examples of this thin flaky debris are shown in Fig. 14. EDAX analysis indicated that the debris was from the composite pin. The profile of the worn surface and the distribution of the height are illustrated in Fig. 15. Though the scan width is only 50 μm, it gives a general information of the worn surface. For example, the maximum height of the groove is about 3 μm, and most of the heights of the asperities are around 1 μm. Surface topography and wear debris analyses indicated that adhesion was a dominant wear mechanism in this regime.

Three material parameters which affect the critical load are the particle size, particle volume fraction and the type of reinforcement. Higher particle volume fractions raise the transition load by raising the shear strength of the composite and decreasing the load on each particle. On the other hand, severe wear due to adhesion has been proposed as delamination wear and is influenced by the initiation of subsurface cracking [14]. Larger particle sizes require higher loads to develop these cracks, and greater shear stresses to delaminate a substrate layer. The thickness of the wear sheets was measured by using optical microscopy and image analysis. Coarse $Al_2O_3$ particle-reinforced composites resulted in thicker wear sheets. This is another reason for the increase of the transition load by large particles. In addition, the composites reinforced with $Al_2O_3$ particles show better wear resistance owing to the better bond strength in $Al_2O_3$-reinforced composites as indicated by Bhansali and Mehrabian [3], which is also a reason why the transition loads of coarse $Al_2O_3$ particle composites are larger than those of fine SiC particle composites. A model of adhesive wear is given in Part II of this study [15].

Although a higher reinforcement volume can lower the fracture toughness of the composite [16], our results indicate that it does not reduce the transition load, but increases the wear rate in adhesive wear regime. This implies that increased shear strength by higher volume fraction is effective in delaying the transition load, but a higher possibility of crack initiation in higher volume-reinforced composites lead to more adhesive wear. Moreover, the transition from abrasion to oxidation is sliding-distance dependent and the transition to adhesive wear is controlled by the applied load. The reinforced particles play an important role in the wear resistance and the transition load of the composite materials. It is possible to extend the oxidative wear regime to a higher load by increasing the particle size and volume fraction. However, an increased wear rate may also be expected if the particle volume fraction is too high.

## 4. Conclusion

Three wear mechanisms were observed in the present MMCs/steel system: when the applied normal load is below a critical transition load, abrasion is dominant in the running-in period, and then oxidation wear occurs with increasing sliding distance. Above the critical transition load, severe wear caused by adhesion takes place. The abrasive wear rate of pins and disc increases with increasing particle volume fraction, and larger particle sizes lead to higher wear rate of the steel disc. Adhesive wear of pins also increases with increasing particle volume fraction. Higher particle volume fraction and larger particle size both increase the transition load.


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