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Wear behaviour of aluminium matrix composite materials

C. S. LEE, Y. H. KIM, K. S. HAN
Department of Mechanical Engineering, Pohang Institute of Science and Technology, PO Box 125, Pohang, Korea, 790-600

T. LIM
Department of Mechanical and Aeronautical Engineering, State University of New York at Buffalo, Amherst, NY 14260, USA

Wear behaviour of aluminium matrix composites is characterized by the dry spindle wear test under various conditions (volume fractions of reinforcements, sliding distances and speeds). Wear resistance of composites is improved due to the presence of reinforcements, but no noticeable improvements are observed in the wear resistance with more than 20% addition of reinforcements. To analyse wear mechanisms, wear surfaces are examined by scanning electron microscopy (SEM). The major wear mechanisms of discontinuous metal matrix composites (MMC)s are strongly dependent on sliding speeds. Dominant mechanism is the adhesive–abrasive wear at low and intermediate sliding speeds, and melt wear at high sliding speeds. Weight loss is linearly increased with the sliding distance. The effect of reinforcements' orientations on wear behaviours is also discussed.

1. Introduction

In many applications which demand light weight and energy efficient materials, such as machine parts in automobiles, aluminium alloys are desirable due to their low density. However, their applications have been often restricted because of their extremely poor wear resistance . The development of improved wear resistant aluminium based matrix composites is receiving considerable attention. Although many investigations have been conducted on the processing and mechanical properties, very few studies on wear behaviour have been available in the literature.

In previous investigations, it was shown that the incorporation of both hard ceramic reinforcements [1–10] and soft lubricants [11–13] into an aluminium alloy improved the wear resistance. Effect of particle size on wear behaviour was considered [2, 3]. According to them, the wear resistance increased with volume fractions and size of reinforcements. It was found that a major wear mechanism was the abrasion wear in Al/SiC and Al/Al_2O_3 particulate composites. Up to now, effect of reinforcements' hardness or type of reinforcements on wear behaviour have not been understood clearly. The wear resistance of Al/Al_2O_3 composites was found to be superior to that of Al/SiC composites because of the brittle interface between the SiC particle and the aluminium alloy matrix [4]. But, there is another study which suggested Al/SiC particulate composites had slightly superior wear resistance due to greater hardness of SiC.

The wear mechanism was studied by scratch tests of Al/zircon particle composites [5]. When the volume fraction of zircons is 0.35, the wear rate of composite was comparable with that of AISI 1045 steel. Under low stress conditions, worn surfaces showed good particle–matrix interface and protrusions of particles. Worn surfaces under high stress conditions showed gross fracture of particles, and wear under low stress was progressive whereas under high stress catastrophic. Abrasive wear tests of Al/bauxite composites were performed [7]. Under low and moderate loads (250, 600 g), the wear resistance of the composite with 20 wt % bauxite was equivalent to that of carbon steel (14.5 H_{RC}). However, under high loads (1000 g), carbon steel was superior. Under any condition, the wear resistance of composites was better than that of the unreinforced aluminium alloy. Particle clustering had little influence on the wear resistance.

The effects of SiC whiskers on the wear resistance of Al/SiC whisker composites were found due to: (1) high wear resistance of SiC whisker itself, i.e., superior hardness, and (2) uniform distributions of SiC whiskers which were found to be a barrier against the slip of Si particles [9]. The wear resistance of Al/SiC whisker, Al/Al_2O_3 fibre, and $Al/SiC–Al_2O_3$ hybrid composites was considered in a later investigation [10]. From this result, SiC whiskers were more effective in improving the wear resistance than Al_2O_3 fibres. However, the wear resistance of hybrid composites is superior to that of Al/SiC composites, the effect of SiC whiskers in the hybrid composite was regarded as a barrier against the slip of Al_2O_3 fibres.

Up to now, most investigations have considered particulate composites which are less effective for

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improving mechanical properties. Wear mechanisms of fibre reinforced MMCs are considered to be different from those of particle reinforced MMCs. For applications which require both high mechanical properties and good wear resistance, the wear mechanism of fibre reinforced MMCs should be identified. In this study, to identify wear behaviours of fibre reinforced MMCs clearly, abrasive wear tests were carried out with various test conditions. Wear behaviour of Al/SiC and Al/Al_2O_3 composites are discussed. Wear mechanisms of discontinuous MMCs are suggested by the examinations of worn surfaces.

2. Experimental procedure

2.1. Materials preparation

Discontinuous MMCs used in this study were prepared by the direct squeeze infiltration method. Matrix was a 6061 aluminium alloy, and SiC whiskers and alumina fibres were used as reinforcements. SiC whiskers, Tokawhisker, was from Textron Specialty Materials Co. and alumina fibres, "Saffil" RF Grade, from ICI Co. Their specifications are listed in Table I. A schematic illustration of experimental set-ups for the infiltration process is shown in Fig. 1. The 50 ton hydraulic press and the cylindrical mould were used. Aluminium melts and the preform were overheated to $770 \pm 10\,°C$ and 700 °C. Applied pressure was 25 MPa and the ram speed was $0.85\,m\,s^{-1}$.

Microstructure of discontinuous MMCs was observed through the optical microscope to examine distribution of reinforcements. Surfaces normal to, and parallel with, the pressure direction were looked into with the view of identifying effects of applied pressure on the orientation of reinforcements. To examine variations of local volume fractions in a single casting, specimens were observed along the height. Specimens were polished with emery papers (from 600 to 1200) and up to 0.05 μm alumina particles.

TABLE I Specifications of SiC whisker and Al_2O_3 fibre [14, 15]

Material	Composition (wt %)	Density ($g\,cm^{-3}$)	Diameter (μm)	Length (μm)	Aspect ratio (l/d)	Tensile strength (GPa)	Young's modulus (GPa)	Use temp. stability to (°C)
Al_2O_3 (Saffil RF Grade)	Al_2O_3:96–97 SiO_2:3–4	3.3	1.5–6.6[a] Av. = 3.5	3–110[a] Av. = 70	4–38[a] Av. = 20	2.0	310	1600
SiC (Tokawhisker)	SiC:100	3.2	0.3–0.6[a] Av. = 0.45	5–15[a] Av. = 8.4	10–25[a] Av. = 13.5	3–14	400–700	1600 (in air)

[a] Measured values from microstructures.

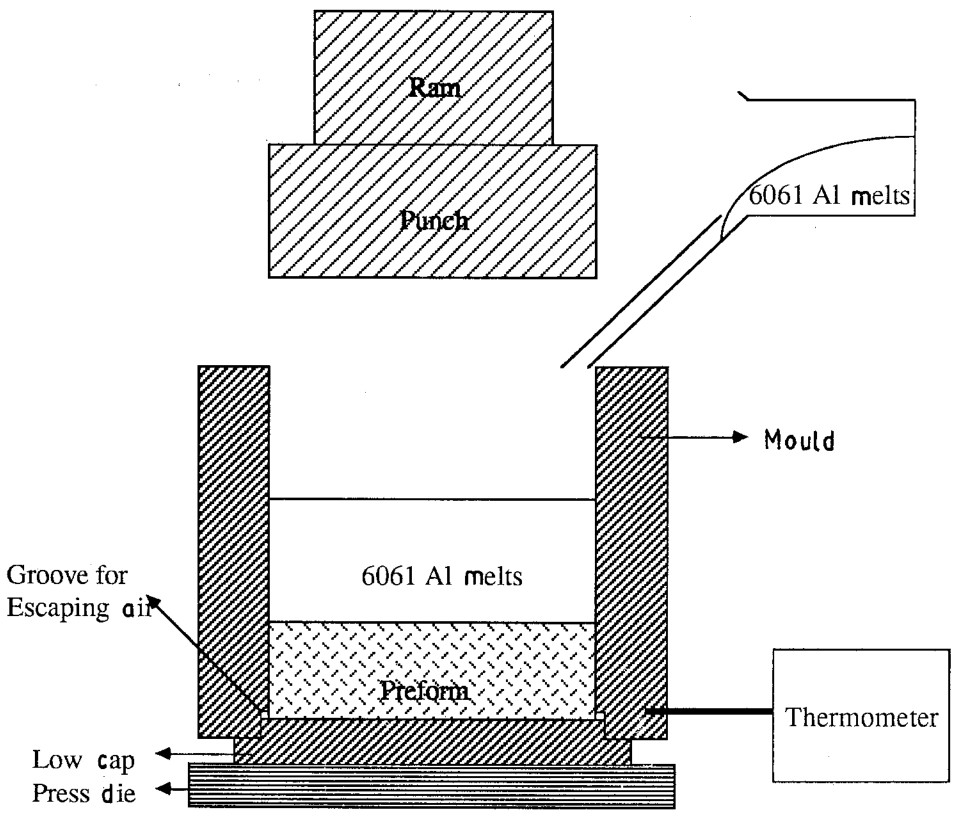

Figure 1 Schematic illustration of experimental set-ups for the direct squeeze infiltration process.

2.2. Abrasive wear test

Dry abrasive wear tests were carried out with the spindle type wear tester, Universal Wear Tester from Riken-Ogoshi Co., at room temperature. A simple schematic illustration for the spindle type wear tester is shown in Fig. 2. The electronic balance which is able to weigh up to 10^{-5} g was used to measure weight loss of composites. Specimens with dimensions of 50 mm × 20 mm × 6 mm were machined not only perpendicular but also parallel to the direction of the applied pressure. Their surfaces were polished by emery paper (#600) to achieve the same surface condition. Oil quenched SCM 4 (550 Hv) and 304 stainless steel (160 Hv) were used as counter material discs. Here, SCM 4 is equivalent to AISI 4140.

Abrasive wear tests were performed under the following conditions:

1. The final load, 3.2 kgf; sliding distance, 100 m; sliding speed, 0.94 and 1.98 m s^{-1}, and various volume fractions of reinforcements; 0.13, 0.15, 0.18, 0.20.
2. The final load, 3.2 kgf; sliding distance, 100 m; and various sliding speeds; 0.06–1.98 m s^{-1}.
3. The final load, 3.2 kgf; sliding speed; 0.94 m s^{-1}, and various sliding distances; 100, 200, 400 m.

After abrasive wear tests, weight loss was measured and worn surfaces were examined to investigate the state of surfaces and suggest the dominant wear mechanism.

3. Results and discussion

3.1. Microstructure

Typical microstructures of Al/SiC and Al/Al_2O_3 composites are represented in Fig. 3. It is demonstrated that uniform distribution of reinforcements and good bonding between reinforcements and the matrix alloy are achieved. And specially, SiC whiskers and Al_2O_3 fibres are uniformly distributed along the height of the cast, i.e., negligible variations of local volume fractions. Insignificant variations of local volume fractions are due to the homogeneity of the preform which can be obtained by the adequate pressure and the sufficient mixing of reinforcements. On the plane normal to the pressure direction, two-dimensional random distributions of MMCs is obtained due to the applied pressure.

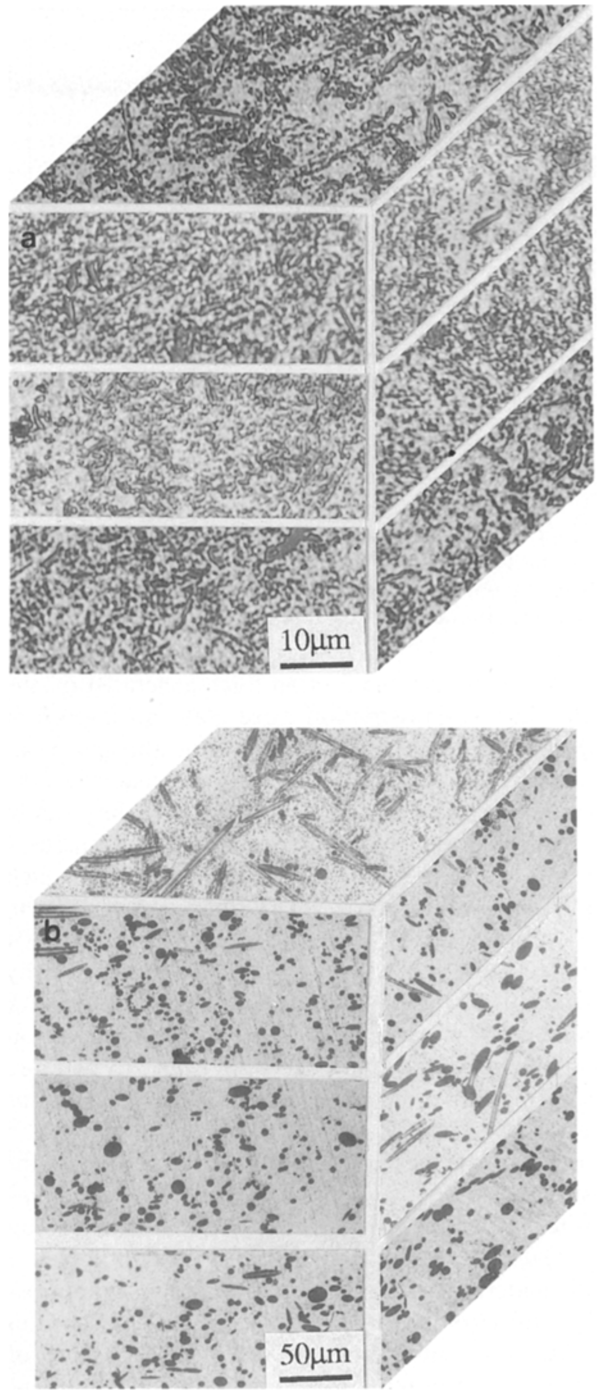

Figure 3 Microstructure of (a) Al/15 vol % SiC and (b) Al/15 vol % Al_2O_3 composite fabricated by the squeeze infiltration method.

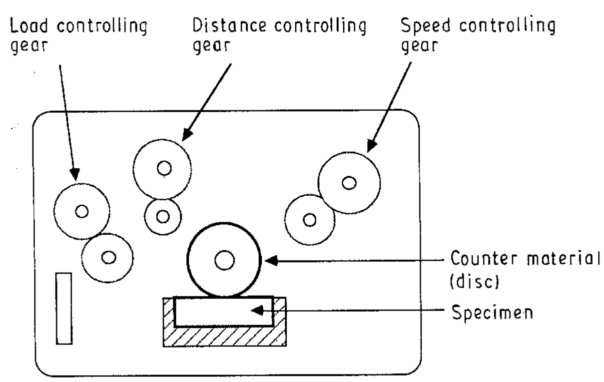

Figure 2 Schematic illustration of the abrasive wear tester.

3.2. Wear behaviours

Because the wear resistance of aluminium alloys is extremely poor, their applications as structural materials and machine parts are often limited. Fortunately, it is demonstrated from abrasive wear tests under diverse conditions that the wear resistance of discontinuous MMCs is improved remarkably by the incorporation of reinforcements.

Effect of the volume fraction of reinforcements on wear behaviour under the final load, 3.2 kgf, the sliding distance, 100 m, and the sliding speed, 0.94 m s^{-1}, is represented in Fig. 4. At sliding speed, 0.94 m s^{-1}, when counter material is SCM 4, wear resistances of discontinuous MMCs are improved up to 580 and 1120%, respectively. This is due to reinforcements

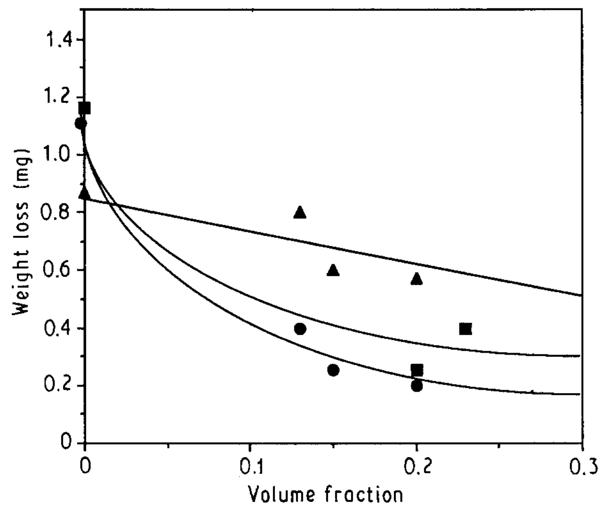

Figure 4 Effect of volume fraction of reinforcements on wear behaviour: final load, 3.2 kgf; sliding distance, 100 m; sliding speed, 0.94 m s^{-1}; counter materials, SCM 4 and 304 stainless steel*. (●) Al/SiC (T6); (■) Al/Al_2O_3 (T6); (▲) Al/SiC (T6)*.

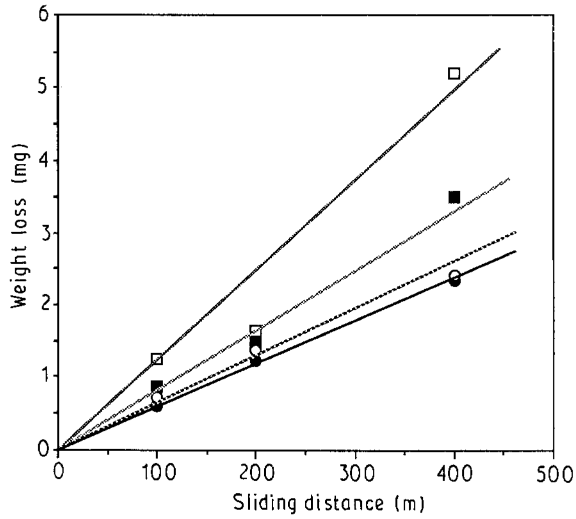

Figure 5 Effect of sliding distance on wear behaviour of 6061 Al alloy and Al/SiC composites: final load, 3.2 kgf; sliding speed, 0.94 m s^{-1}; counter materials, 304 stainless steel. (□) 6061 Al(F); (■) 6061 Al(T6); (○) Al/15 vol % SiC (T6); (●) Al/15 vol % SiC (F).

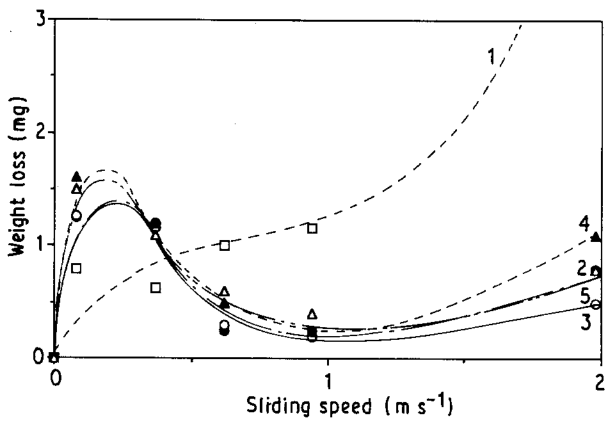

Figure 6 Effect of sliding speeds on wear behaviour of Al alloy and discontinious MMCs: final load, 3.2 kgf; sliding distance, 100 m; counter material, SCM 4. (□) 6061 Al alloy (T6); (●) Al/15 vol % SiC (T6); (○) Al/20 vol % SiC (T6); (▲) Al/20 vol % Al_2O_3 (T6); (△) Al/25 vol % Al_2O_3 (T6).

which can endure the friction force generated on the wear surface. This friction force plays an important role in wear behaviour, specially in the abrasive wear. Generally, the higher the friction force generated, the worse the wear resistance. It is found that the effect of the reinforcements incorporation on wear resistance is getting less notable at high volume fraction, which agrees with results of others [6]. But, improvements in the wear resistance are less distinguished when 304 stainless steel is used as a counter material. It is by virtue of the mutual abrasion between the counter material and the specimen, and it will be discussed in detail later. Also, SiC whiskers are found to be more effective for the improvement of the wear resistance than Al_2O_3 fibres.

Fig. 5 shows the effect of sliding distances on weight losses of 6061 Al alloy and Al/15 vol % SiC composites under the final load, 3.2 kgf, and the sliding speed, 0.94 m s^{-1}. As shown in Fig. 5, weight losses of both materials increase linearly with the sliding distance. Effect of heat treatments is less distinguished in Al/SiC composite than in 6061 Al alloy because of superior effect of reinforcements on the improvement in the wear resistance.

Fig. 6 illustrates the effect of sliding speeds on wear behaviour of 6061 Al alloy and Al/SiC composites under the final load, 3.2 kgf and the sliding distance, 100 m, when counter material is SCM 4. In Fig. 6, wear behaviour is changed with sliding speed. It means that wear mechanisms are strongly dependent upon the sliding speed. Major wear mechanisms of an Al alloy are adhesive and abrasive wear at sliding speeds up to 1 m s^{-1}, therefore, a 6061 Al alloy is worn by the friction force generated on the wear surface. Above the sliding speed, 1 m s^{-1}, the major wear mechanism is shifted to the melt wear because of the ascent of the temperature on the localized wear surface. Consequently, a 6061 Al alloy starts to be worn out abruptly.

In discontinuous MMCs, weight loss is greater than that of the unreinforced matrix alloy at low sliding speed, up to about 0.37 m s^{-1}, because reinforcements abrade the matrix by the high friction force and this abrasion deteriorates the wear resistance of discontinuous MMCs. At low sliding speeds, the friction force generated on the wear surface is large enough to abrade the surface of the composites. As the sliding speed increases, the friction force becomes weakened due to the reduction of the friction coefficient, and reinforcements can put up with the weak friction force. In consequence, weight loss decreases until the melt wear becomes the major mechanism for wear. At high sliding speeds (> 1.98 m s^{-1}), the wear resistance gets worse, weight loss starts to increase due to the melt wear and seizure of the matrix alloy. But the high thermal stability and superior mechanical properties of reinforcements make the deterioration of the wear resistance feeble. Also, it is found that the effect of the amount of reinforcements can be ignored until the sliding speed is 1 m s^{-1}. But beyond this speed, weight loss decreases with the addition of reinforcements. Wear behaviour of Al/SiC and Al/Al_2O_3 composites under various sliding speeds is illustrated in Fig. 7. On the whole, the wear resistance of Al/SiC composites is

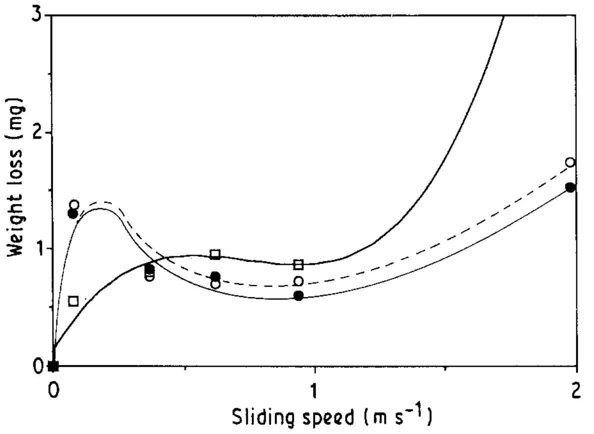

Figure 7 Effect of sliding speeds on wear behaviour of Al/SiC composites: final load, 3.2 kgf; sliding distance, 100 m; counter material, 304 stainless steel. (□) 6061 Al (T6); (○) Al/15 vol % SiC (F); (●) Al/15 vol % SiC (T6).

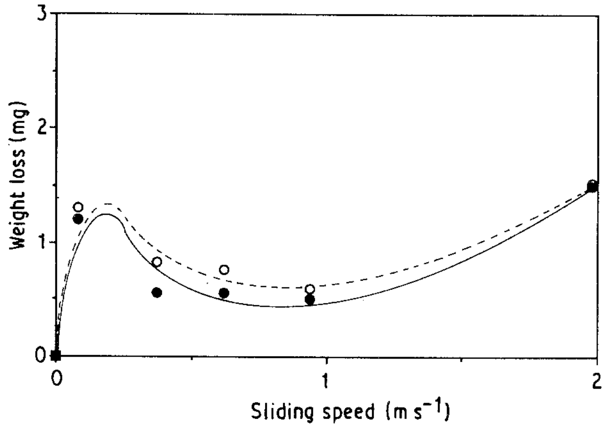

Figure 8 Effect of the direction of reinforcements of discontinuous MMCs under various sliding speeds: final load, 3.2 kgf; sliding distance, 100 m; counter material, 304 stainless steel. (○) Al/15 vol % SiC (T6); (●) Al/15 vol % SiC (T6). Wear surface is parallel to the direction of the applied pressure.

better than that of Al/Al_2O_3 composites on account of better mechanical properties, thermal stability, and smaller size of SiC whiskers.

Effects of sliding speeds on wear behaviour of Al/SiC composites are shown in Fig. 7. Their testing conditions are the final load, 3.2 kgf, the sliding distance, 100 m, and counter material, 304 stainless steel. Fig. 7 shows the same trend of the wear in Al/SiC composites as that shown in Fig. 6. Therefore, it is found that wear mechanisms are independent of counter material types. As shown in Fig. 8, effect of heat treatments on wear behaviour in Al/SiC composites is negligible under various sliding speeds because reinforcements play the major role in wear behaviour.

The orientation of reinforcements affects the wear resistance of discontinuous MMCs. The effect in Al/SiC composites is shown in Fig. 8. From microstructures of both materials (Fig. 3), most reinforcements are likely to have the two dimensionally random orientation on the surface normal to the direction of the applied pressure, and on the surface parallel to the pressure direction, most reinforcements have preferred orientations which are normal to the surface. In both composite systems, the surface with reinforcements normal to the wear surface has better wear resistance than the surface with the two dimensionally random orientation of reinforcements. Improving rate in the wear resistance between two different fibre orientations are decreasing as the sliding speed increases. This is because a higher friction force would be necessary for the abrasion of the surface of composite whose orientation of reinforcements are normal to the wear surface. And, at last, negligible improvements are found at high sliding speed, $1.98\ m\,s^{-1}$, since the major wear mechanism is the melt wear, and the orientation of reinforcements cannot affect much wear behaviour in the melt wear mechanism.

Fig. 9 represents effect of counter materials, 304 stainless steel and SCM 4, on wear behaviour of Al/15 vol % SiC composites under various sliding speeds. When a 304 stainless steel is used as a counter material, weight loss is greater than those when a SCM 4 is used. These phenomena are by virtue of the

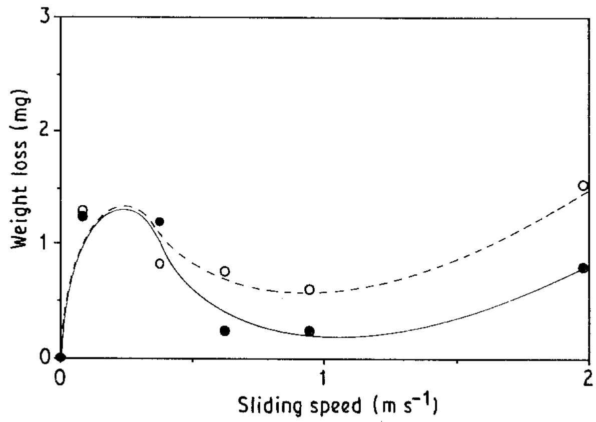

Figure 9 Effect of counter materials on wear behaviour of Al/15 vol % SiC composites under various sliding speeds; final load, 3.2 kgf; sliding distance, 100 m; counter materials, 304 stainless steel* and SCM 4**. (○) Al/15 vol % SiC (T6)*; (●) Al/15 vol % SiC (T6)**.

mutual abrasion between counter materials and specimens. Generally, SiC whiskers and Al_2O_3 fibres have very high hardnesses, 2800 and 1600 H_v, respectively. In consequence, a 304 stainless steel (180 H_v) is more apt to be abraded by reinforcements than SCM 4 (550 H_v). It is considered that the damaged surface of counter materials and particles from abrasions of counter materials accelerates to form grooves on the wear surface.

3.3. Wear surface analysis

Wear surfaces of both Al/SiC and Al/Al_2O_3 composites are examined by SEM. Fig. 10 represents overall wear surfaces of Al/20 vol % SiC and Al/20 vol % Al_2O_3 composites at various sliding speeds, 0.08, 0.94 and $1.98\ m\,s^{-1}$. Also wear surfaces of Al/20 vol % Al_2O_3 composites at high magnification are shown in Fig. 11. Generally, both composites show almost the same behaviour. At low sliding speed, $0.08\ m\,s^{-1}$, severe damage of wear surface in both composites are found. The removal of the material seems to be progressed by the fracture of reinforcements and the matrix which might be due to the high

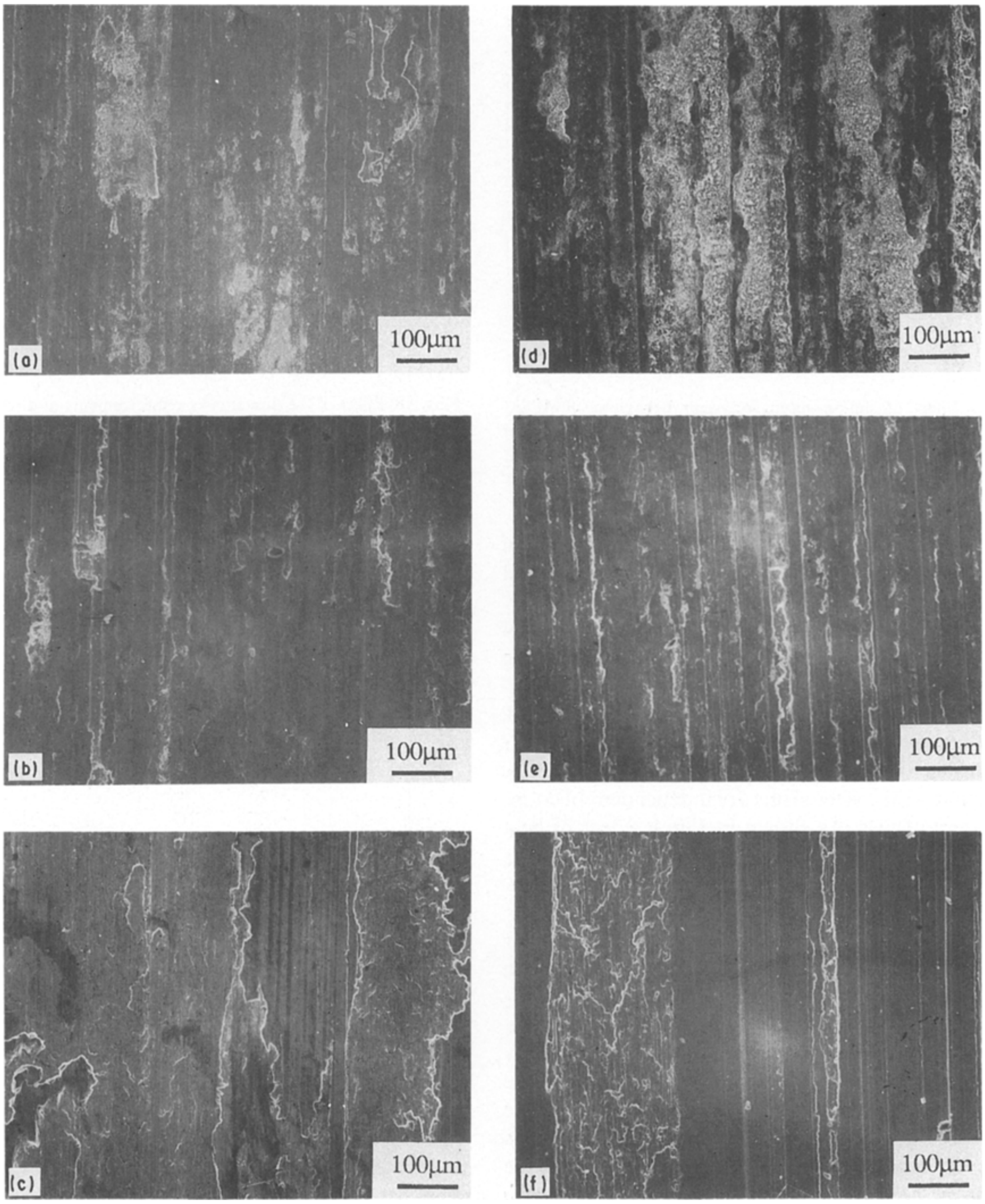

Figure 10 Overall wear surface of Al/20 vol % SiC (a, b, c) and Al/20 vol % Al_2O_3 (d, e, f) composites with various sliding speeds: sliding distance, 100 m; counter material, SCM 4, sliding speed (a), (d) 0.08 m s^{-1}, (b), (e) 0.94 m s^{-1}, (c), (f) 1.98 m s^{-1}.

friction force applied on the wear surface (Fig. 10a and d). Surface damages in Al/Al_2O_3 are much more severe than those in Al/SiC. It can be considered that delamination caused by the excessive fracture of reinforcements and the matrix deteriorate the wear resistance of metal matrix composites at the low sliding speed (Fig. 11a).

At the intermediate sliding speed, 0.94 m s^{-1}, the damaged section on the wear surface is reduced as shown in Fig. 10b and e. Grooves are also observed in these . Grooves in Al/20 vol % Al_2O_3 are more distinguished than Al/SiC. This is due to inferior mechanical properties of Al_2O_3 fibres to SiC whiskers. From the wear surface, it can be regarded that groove plays an important role in wear behaviour, i.e., wear is progressed by its formation and growth. The groove formation and growth are illustrated in Fig. 11b and c. The groove is formed at the locally fractured area of reinforcements and the matrix. Although less friction forces apply on the wear surface, this localized fracture is taken place by high localized friction forces which come from the nonuniform surface of the counter material and defective areas of the wear surface. The groove growth is advanced by the fracture of the wear surface at the end of the groove and along the groove (Fig. 11c). Wear surfaces indicate that the adhesive–abrasive wear is the dominant wear mechanism at low and intermediate sliding speeds.

Wear surfaces at the sliding speed, 1.98 m s^{-1}, are shown in Fig. 10c and f. Localized melted areas are observed owing to the high sliding speed in both composites. As shown in Fig. 11d, wear seems to be

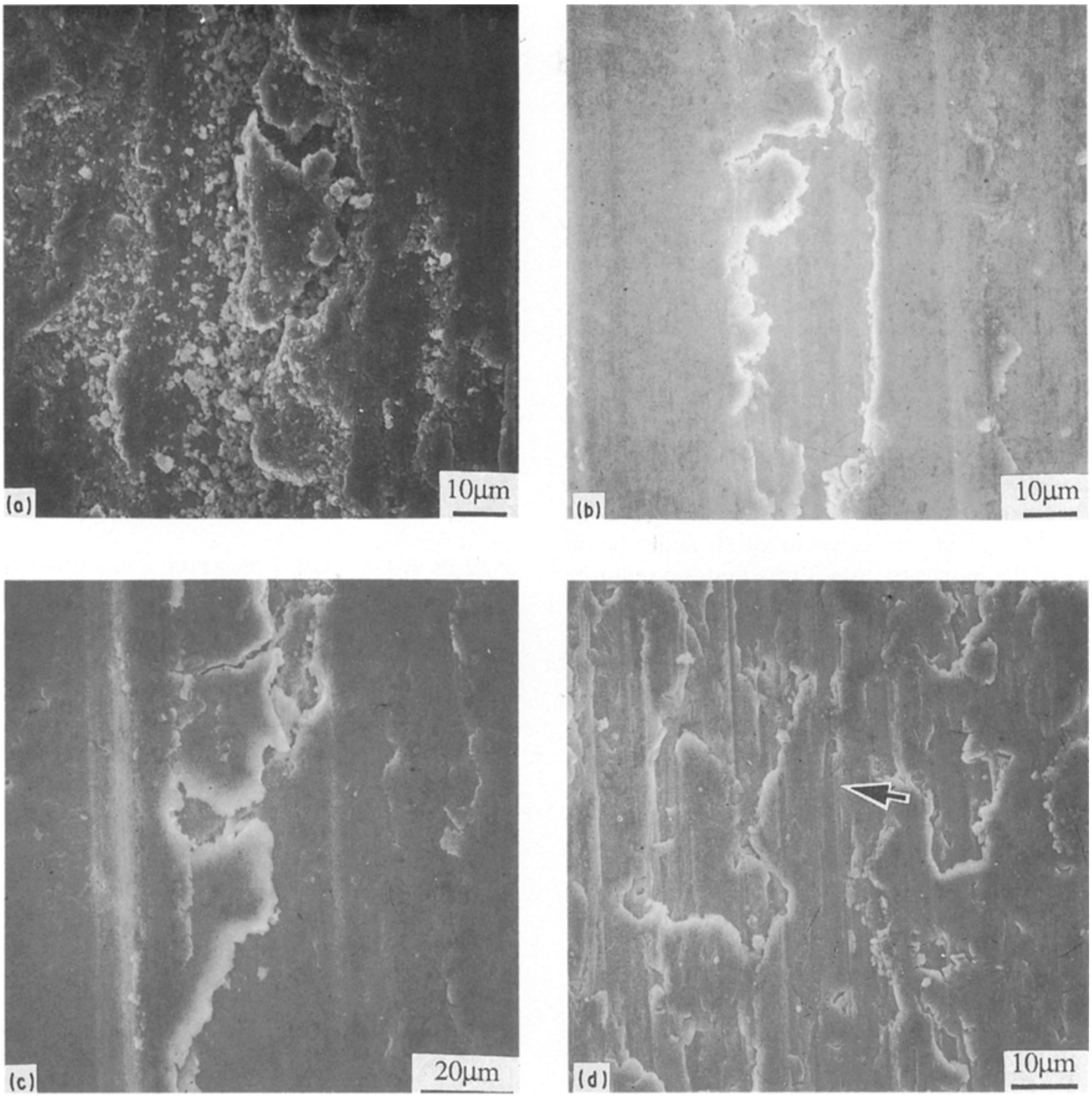

Figure 11 Wear surface of Al/20 vol % Al_2O_3 composites with various sliding speeds: sliding distance, 100 m, counter material, SCM 4: (a) adhesive–abrasive wear at 0.08 m s^{-1}, (b), (c) groove formation and growth at 0.94 m s^{-1}, and (d) melt wear at 1.98 m s^{-1}.

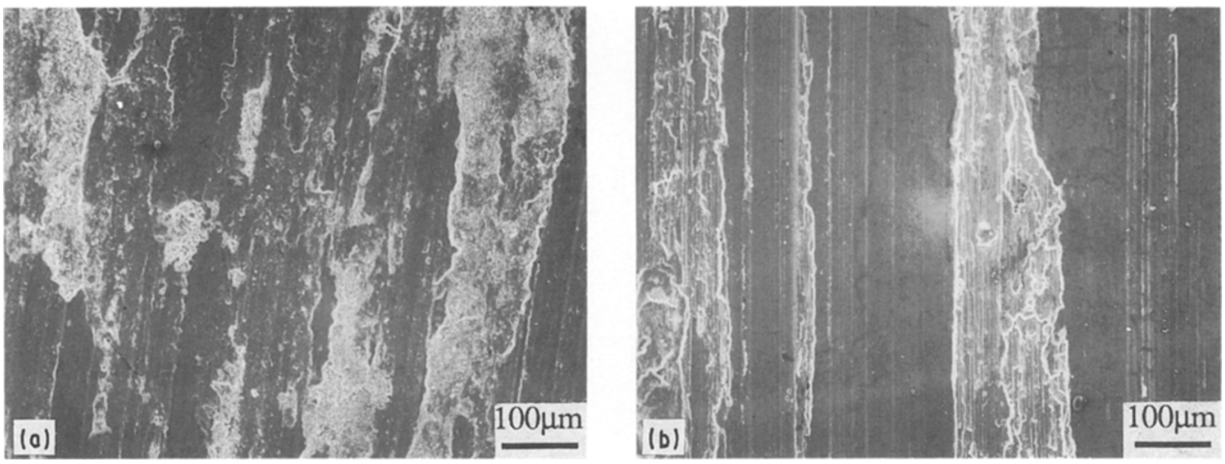

Figure 12 Wear surface of Al/20 vol % Al_2O_3 composites: sliding distance, 100 m; counter material, SCM 4; (a) 0.08 m s^{-1} and (b) 1.98 m s^{-1}. Wear surfaces are parallel to the direction of the applied pressure.

started by localized melting of the surface and proceed by delaminations from seizure or the large plastic deformation of the matrix. Also, fracture of reinforcements and the matrix is seldom observed due to the remarkable reduction of friction forces applied on the wear surface. Small grooves which might be related to precipitates, indicated by an arrow, are often shown (Fig. 11d). These show that major wear mechanisms at high sliding speeds are the melt wear and the seizure of the matrix.

Up to now, wear surface which is normal to the applied pressure direction – most reinforcement are distributed on the wear surface two dimensionally randomly – have been analysed to identify wear behaviours of Al/SiC and Al/Al_2O_3 composites. Wear surface parallel to the applied pressure direction – most directions of reinforcements are coming out of the wear surface – are studied to examine the effect of reinforcement orientations on wear behaviour of discontinuous MMCs. Fig. 12a and b represents the overall wear behaviour on the wear surface parallel to the applied pressure direction. It can be found by comparing these two to Fig. 10d and f that no significant differences in wear behaviour, at high sliding speed, between two directionalities of reinforcements are observed. On the other hand, at low sliding speed, more severe damage on the wear surface normal to the direction of applied pressure is found. It might be on account of the higher friction forces that are required for the abrasion of the wear surface parallel to the pressure direction.

From wear surface analyses, wear behaviour of discontinuous MMCs can be summarized as follows: 1. at low speeds, wear is progressed by fractures of reinforcements and the matrix which are due to high friction forces; 2. at intermediate speeds, the groove formation and growth are major mechanisms for wear; 3. at high speeds, localized melting and large plastic deformations due to the high frictional heat are dominant factors for the removal of discontinuous MMCs. In other words, the major wear mechanism is the adhesive – abrasive wear at low and intermediate sliding speeds and the melt wear at high speeds.

4. Conclusions

1. The wear resistance of discontinuous MMCs is remarkably improved by the addition of reinforcements. Weight loss increases linearly with the sliding distance.

2. Fibre orientations affect wear behaviour of discontinuous MMCs. The surface with reinforcements which are mostly normal to the wear surface has better wear resistance than the surface with the two dimensionally random orientation of reinforcements. Wear resistance is strongly dependent upon hardness of counter materials. A counter material with lower hardness deteriorates the wear resistance due to the mutual abrasion between the counter material and the wear surface.

3. Dominant wear mechanisms are suggested from wear surface analyses, the major wear mechanism is the adhesive–abrasive wear at low and intermediate sliding speed, and the melt wear at high sliding speeds.

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