Wear, *135* (1989) 53 - 65

WEAR OF BAUXITE-PARTICLE-REINFORCED ALUMINUM ALLOYS

JINGYU YANG* and D. D. L. CHUNG
Composite Materials Research Laboratory, Furnas Hall, State University of New York, Buffalo, NY 14260 (U.S.A.)

(Received June 7, 1988; revised March 8, 1989; accepted June 29, 1989)

Summary

Amounts of 1 - 20 wt.% bauxite particles were incorporated into Al–12Si–1.4Cu–1.3Mg alloy by the rheocasting method. Bauxite is a starting raw material of alumina with excellent chemical and thermal stability at high temperatures, a low coefficient of thermal expansion and high hardness. The abrasive wear resistance increased with increasing amounts of particulate addition. Under low and moderate loads, the wear resistance of the composite containing 20 wt.% bauxite was comparable with that of carbon steel. However, under high loads, carbon steel was superior to the composites in wear resistance. Particle clustering was observed in the composites owing to the small size of the bauxite particles (−300 mesh); it had little influence on the wear resistance and the mechanical strength of the composites. The sliding wear of the composite containing both bauxite and graphite particles, the matrix alloy and a hypereutectic Al–18Si alloy were also tested.

1. Introduction

In many tribological applications, aluminum alloys are desirable because of their low densities, but they are not used because of their extremely poor wear resistance. Therefore the development of aluminum–matrix composites is receiving considerable emphasis in meeting the requirements of various industries. In previous work, it was shown that the incorporation of both hard ceramic particles (*e.g.* alumina [1, 2], silicon carbide [3 - 6], silica [7] or zircon [8, 9]) and a soft solid lubricant (*e.g.* graphite [10 - 12] or mica [13]) into an aluminum alloy increased the wear resistance.

Considerable progress has been made in the application of particle-reinforced metals, most notably for engine components. The alumina-particle-reinforced aluminum alloy pistons performed well. Power output

---

*Permanent address: Department of Materials Science and Engineering, Nanjing Institute of Technology, Nanjing, China.

0043-1648/89/$3.50

increased with a remarkably low wear rate of the composite pistons [14]. Alumina particles also were used to reinforce magnesium alloy automobile parts, and after testing for long periods of time, there was no visible wear on the surfaces of the parts [15]. The use of an Al–Si–graphite particle composite piston resulted in a 9% reduction in the frictional horsepower losses of the engine and up to 3% reduction in the specific fuel consumption [10]. An Al–Si–graphite piston cylinder used in a Ferrari Formula One world championship winning engine provided increased and consistent outputs and reduced the fuel consumption [16, 17]. Particle-reinforced metals are so promising that metal–matrix composites may be gradually replacing most unreinforced metals [18].

Before the exciting potential market for composite engine components can be realized, some problems must be resolved. It is still costly [6, 19, 20] and difficult to manufacture the metal–matrix composites because of the poor wetting between matrix alloys and some reinforcements.

Composites containing SiC particles offered virtually no improvement or moderate improvement in wear resistance at different loads [21]. This was because the brittle interface formed between SiC particles and the aluminum matrix alloy was very weak in shear and was unable to resist the action of wear under high loads. It was demonstrated [20] that composites containing alumina particles exhibited excellent wear resistance compared with the matrix alloys, and the particle size played an important role. The wear resistance of a composite containing large (142 μm) alumina particles was better than that of composites containing smaller particles [21]. However, the size of hard ceramic particles also plays an important role in the ease of machining. If the hard particles are larger than 50 μm, the composites tend to be very difficult to machine, even though diamond or nitride edge tools can be used. Ceramic particle reinforced metals have always presented machining problems. Much research is devoted to eliminating this step by perfecting near-net-shape production techniques [20, 22]. Obviously, the problem can be solved only partially. Surappa *et al.* [23] reported that the dispersion of 5 wt.% Al_2O_3 particles (of size 100 μm) in a cast Al–Si eutectic alloy did not result in a significant improvement of the abrasion resistance. The presence of graphite particles in aluminum alloys helps to reduce the sliding wear and friction [10 - 12]. Nevertheless, Al–graphite composites will be limited to the wear conditions at moderate loads owing to the significant decrease in the mechanical strength with the increasing addition of graphite particles.

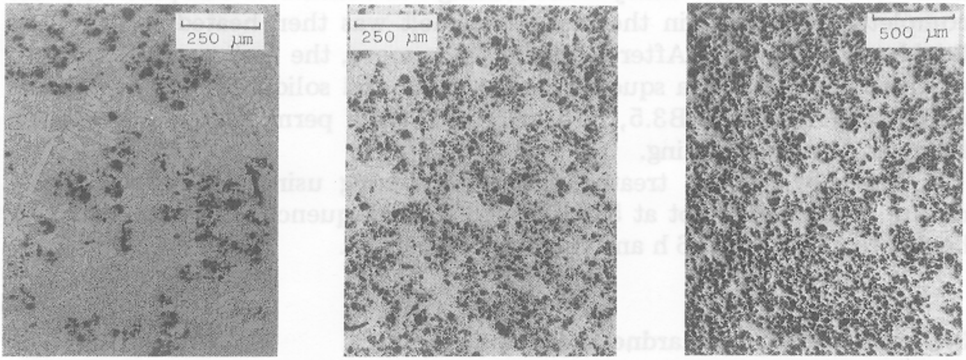
In this paper, the reinforcement used is bauxite powder which is the starting raw material of alumina. The mineral product has a composition comprising Al_2O_3, SiO_2, TiO_2, Fe_3O_4 etc. The Al_2O_3 content in bauxite used as reinforcement is typically more than 85% by weight. The baking process used to prepare bauxite at high temperatures results in a complicated structure consisting of mullite, alumina and a glassy phase. Bauxite is an excellent refractory with a low coefficient of thermal expansion and high hardness. We propose that bauxite particles may be used as a substitute for Al_2O_3 particles dispersed in aluminum for abrasion-resistant applications. Furthermore, the small amount of SiO_2 in bauxite may promote the chemical reaction and improve the wettability between the particles and the matrix alloy. In fact, it is easier to prepare bauxite-particle-reinforced aluminum alloys in comparison with Al_2O_3-particle-reinforced aluminum alloys. The explanation probably lies in the small amount of silica in bauxite, as silica at the particle surface could react with the matrix melt and promote wetting. The porous structure of bauxite particles decreases the density of the composites and strengthens the interface bonding between the particles and the matrix alloy. In addition, bauxite is abundant and inexpensive.

In this paper, the wear behavior of a bauxite-particle-reinforced aluminum alloy is presented.

2. Material preparation

Al–12Si–1.4Cu–1.3Mg was used as the matrix material. Engine pistons usually are made from such an aluminum alloy. The bauxite powder used here is a calcined refractory grade material. The chemical composition of this bauxite is as follows: Al_2O_3, 87.9%; SiO_2, 5.43%; Fe_2O_3, 1.18%; TiO_2, 3.78%; $K_2O + Na_2O$, $<0.2\%$; $MgO + CaO$, $<0.3\%$. The particle size is -300 mesh (less than about 50 μm).

Two different groups of composites were tested. The first group was composites containing 1 - 20 wt.% bauxite particles for mechanical strength testing. Composites containing 3.5, 15 and 20 wt.% bauxite particles, respectively labeled B3.5, B15 and B20, were prepared for abrasive wear tests. Optical micrographs of their polished and etched sections (etched with 5% HF aqueous solution) are shown in Fig. 1. The second group was a composite containing 8 wt.% bauxite particles, together with 3 wt.% uncoated graphite particles with a particle size of $-170 + 230$ mesh (about 63 - 90 μm), and was labeled B8G; an optical micrograph of its polished and etched



(a) (b) (c)

Fig. 1. Optical micrographs of polished and etched sections: (a) composite B3.5, (b) composite B15, (c) composite B20.

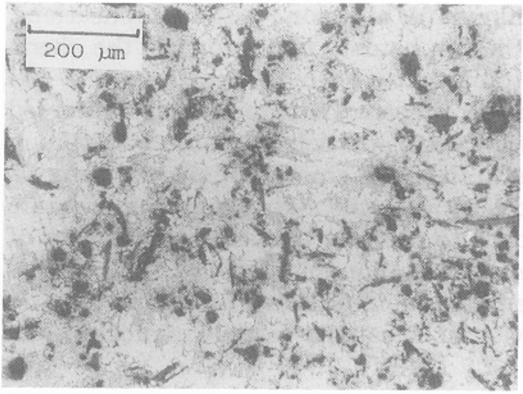


Fig. 2. Optical micrograph of a polished and etched section of a composite containing 8 wt.% bauxite particles and 3 wt.% graphite particles.

section (etched with 5% HF aqueous solution) is shown in Fig. 2. All these composite samples were machined easily from the ingots using conventional machining tools because of the small size of the bauxite particles. However, when particle additions are in the approximate 1 μm range, particles tend to aggregate [21]. Consequently, particle clustering was observed in the composites of this work.

The wear behavior of the matrix alloy, as well as an Al–18Si hypereutectic alloy, annealed 1040 steel and heat-treated 1040 steel, was also investigated.

The composites were prepared using the rheocasting method. The matrix alloy was first melted in a resistance furnace. After degassing with nitrogen, it was transferred into a cast iron crucible in a vessel with a stirrer. The temperature of the melt was kept between its liquidus and solidus curves. The stirrer blade was positioned below the surface of the melt. The melt was subjected to vigorous agitation. The dry bauxite particles were added to the semisolid slurry while stirring was continued. The particles were completely dispersed in the melt. The melt was then heated to above its liquidus temperature. After degassing once more, the melt was poured into a permanent mold or a squeeze casting mold and solidified. The cast ingots of the matrix alloys, B3.5, B15 and B8G, were permanent mold castings; B20 was a squeeze casting.

Ingots were heat treated before machining using the following procedure. They were kept at 515 ℃ for 8 h, then quenched in water at 20 ℃, heated to 175 ℃ for 16 h and finally cooled in air.

3. Tensile testing and hardness testing

Tensile tests were conducted on the matrix alloy and the composites. The results from some of these tests at room temperature are given in Fig. 3.

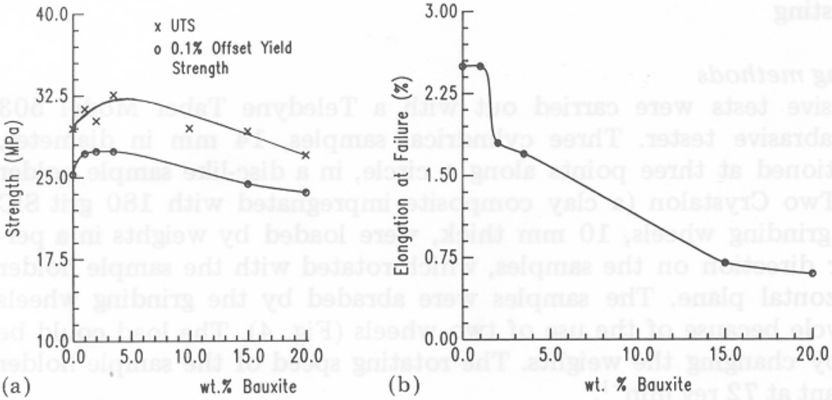


Fig. 3. Tensile test results on permanent castings as functions of the bauxite content: (a) ultimate tensile strength and 0.1% offset yield strength; (b) per cent elongation at failure. Each data point is the average of three test results. Wear testing was performed on a part of the samples used for tensile testing.

TABLE 1

Density and hardness values of the materials tested

Sample	*Material composition*	*Density* ($g\ cm^{-3}$)	*Hardness*
Matrix	Al–12Si–1.4Cu–1.3Mg	2.69	92 HB
B3.5	Matrix–3.5 wt.% bauxite particles	2.74	110 HB
B15	Matrix–15 wt.% bauxite particles	2.85	89 HB
B20	Matrix–20 wt.% bauxite particles	2.89	87 HB
1040 (H)	Steel 1040 heat treated[a]	7.85	37 HRC
1040 (A)	Steel 1040 annealed[b]	7.85	14.5 HRC

[a] Quenched in oil.

[b] Quenched in oil and then heated at 400 °C for 30 min.

The tensile strength and yield strength (Fig. 3(a)) increased by up to 8% for B3.5, and decreased with further addition of bauxite. The ductility (Fig. 3(b)) decreased with increasing bauxite content.

Table 1 shows the hardness data of the composites and matrix. The authors noticed that the hardness values of the composites were similar to that of the matrix. It appears that the hardness values are mainly related to the strengths of the materials and the fine reinforcements had little effect on the hardness. More experiments are needed for a clearer understanding of this effect.

4. Wear testing

4.1. Testing methods

Abrasive tests were carried out with a Teledyne Taber Model 503 standard abrasive tester. Three cylindrical samples, 14 mm in diameter, were positioned at three points along a circle, in a disc-like sample holder (Fig. 4). Two Crystalon (a clay composite impregnated with 180 grit SiC particles) grinding wheels, 10 mm thick, were loaded by weights in a perpendicular direction on the samples, which rotated with the sample holder in a horizontal plane. The samples were abraded by the grinding wheels twice a cycle because of the use of two wheels (Fig. 4). The load could be adjusted by changing the weights. The rotating speed of the sample holder was constant at 72 rev min^{-1}.

Sliding wear tests were conducted using a pin-on-disc-type tester under a dry condition. A sample, 6 mm in diameter and 12 mm in length, was allowed to slide under an applied load on a steel disc (hardness of 50 HRC).

Before starting a new wear test a run-in period was needed to make sure that the sample surface was completely in contact with the counter surface. The surface of the steel disc in a sliding wear test was cleaned by polishing with emery paper, so that the starting condition for every wear test was the same.

The weight loss due to wear was measured. From the weight loss, the volume loss and the wear rate of the samples were obtained. The wear surface texture was also examined using a scanning electron microscope.

The abrasive wear characteristics of the matrix alloy, B3.5, B15 and B20 were studied under both dry and oil-lubricated conditions. After 1000 abrasion cycles, the samples were cleaned with anhydrous alcohol or methyl alcohol and then dried. The samples were weighed before and after testing. The number of cycles used for each test ranged from 5000 to 10 000.

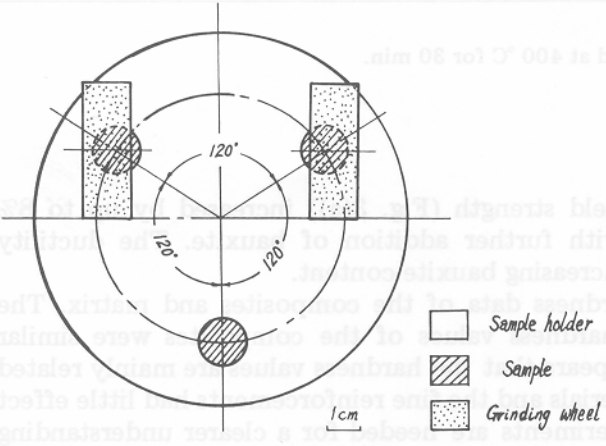


Fig. 4. Abrasive wear testing geometry.

4.2. Effect of bauxite content

The abrasive wear resistance of the matrix alloy was improved by the addition of hard bauxite particles. The effect of the bauxite content on the wear rate of the composites is shown in Fig. 5. Increasing the amount of particulate addition resulted in increased wear resistance when all other variables were kept constant. The wear rate dropped abruptly after the incorporation of 3.5 wt.% bauxite into the matrix alloy. With further addition of bauxite the wear rate decreased slightly, especially under low loads.

4.3. Effect of load

The loads used in the wear tests were 0.25, 0.60 and 1.00 kgf. Under loads up to 0.60 kgf, the wear rates of the matrix alloy and the composites increased gradually. Under the large load of 1.00 kgf, all the samples wore severely (Fig. 6). Comparison of the slopes of the curves in Fig. 6 indicates that the presence of even a small quantity of bauxite particles helps the matrix alloy sustain different wear loads. The capability of B15 and B20 in bearing loads is almost the same and is better than that of B3.5. Wear resistance of all these composites is improved relative to the matrix, especially under large loads.

Because the contact area between the grinding wheels and the sample was very small, the pressure that the samples experienced was high.

4.4. Comparison with carbon steel

Bhansali and Mehrabian [21] suggested that the abrasive wear resistance of composites should be at least comparable with that of plain carbon steel in applications where the wear by abrasive particles is of concern, *e.g.* for earthmoving vehicles.

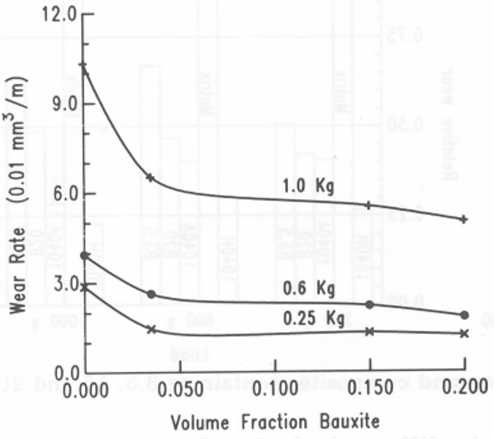


Fig. 5. Effect of the bauxite content on the wear rate of composites at three different loads during wear testing.

For convenience, a term "relative wear" is defined as the wear rate of a material divided by the wear rate of a standard material. The matrix alloy was chosen as the standard material. This term is almost the same as that adopted by Surappa *et al.* [23].

The relative wear of heat-treated steel is the least among all the materials tested under any condition. However, at low loads the abrasive wear resistance of B20 is comparable with that of steel with a moderate hardness (14.5 HRC) (Fig. 7).

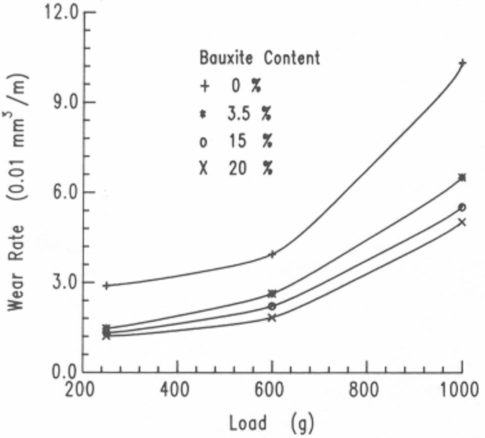
4.5. *Abrasive wear under an oil lubricating condition*

To simulate the wear conditions, like track shoes moving in mud, an abrasive wear test under an oil lubricating condition was conducted. Lubricating oil was added directly to the surface of the sample holder manually at a speed of 120 - 140 drops per min.

The results (Fig. 8) indicate that the relative wear of the composites is less than that of the matrix alloy but more than that of steel. It is noticeable that the relative wear of B3.5 (with less bauxite content) is less than that of B15 or B20 (with more bauxite content). It is suggested that the yield strength of the material plays an important role in its wear behavior.

4.6. *Sliding wear test of B8G composite*

The hardness of ceramic particles such as bauxite, alumina, silica etc. is much higher than that of carbon steel. In the pin-on-disc type of wear test for ceramic-particle-reinforced metals, the steel disc is the first to be scratched by the hard particles in the composites. Then the rough surface of the steel disc scratches the composite surface. Severe surface damage at the steel disc surface was observed when the composite specimen contained a high content of bauxite particles. The experimental results depend not



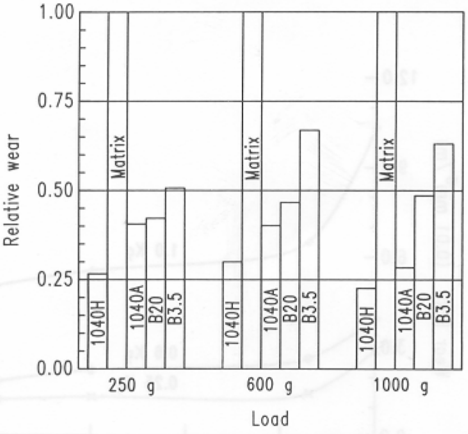
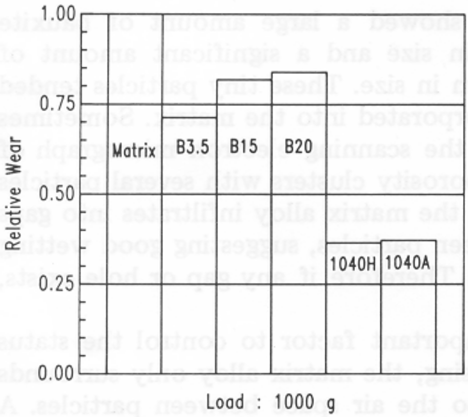


Fig. 6. Wear rate *vs.* load in the matrix alloy and composites containing 3.5, 15 and 20 wt.% bauxite particles.

Fig. 7. Relative wear of materials tested under different loads. Sample labels are defined in Table 1.



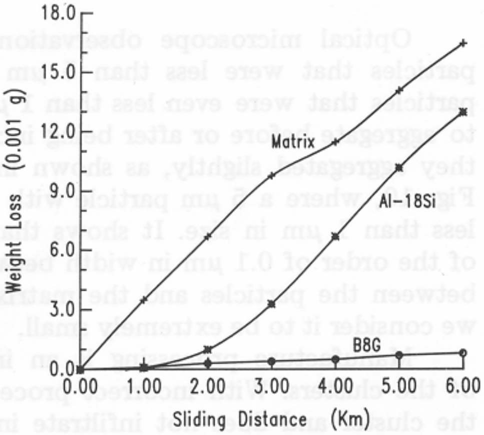


Fig. 8. Relative wear of the materials tested under an oil lubricating condition and a load of 1000 gf. Sample labels are defined in Table 1.

Fig. 9. Wear weight loss *vs.* sliding distance of the matrix, Al–18Si alloy and B8G composite.

only on the wear characteristics of the test material itself, but also on the roughness of the counterpart surface.

To solve such a problem, B8G contained both bauxite particles and graphite particles. The presence of graphite particles in B8G alleviated the surface scratch of the counterpart. The result in sliding wear test indicates that the weight loss of B8G is much less than that of two conventional alloys — the matrix alloy and the hypereutectic Al–Si alloy (Fig. 9).

5. Discussion

This paper focuses on the room temperature mechanical properties; the high temperature tensile strength data at 300 ℃ had been previously reported [24], as reproduced here in Table 2. Significant improvement in strength and ductility is noted. Necking was observed in the composite tensile specimens at 300 ℃, even though particle-reinforced metals have usually been considered to be brittle [25].

TABLE 2

Tensile test results of the matrix alloy and the composites containing 1 wt.% and 2 wt.% bauxite particles at 300 ℃ [25]

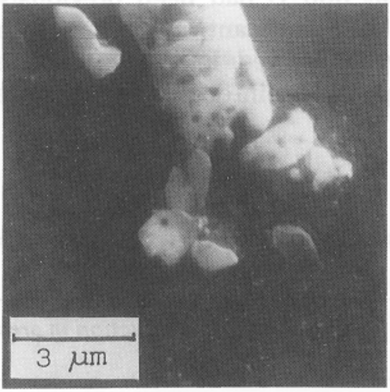
	UTS (MPa)	*Elongation* (%)	*Reduction in area* (%)
Matrix	82.3	5	8
Matrix–1 wt.% bauxite particles	110.7	17.5	22.5
Matrix–2 wt.% bauxite particles	95.6	9.8	19

Optical microscope observation showed a large amount of bauxite particles that were less than 5 μm in size and a significant amount of particles that were even less than 1 μm in size. These tiny particles tended to aggregate before or after being incorporated into the matrix. Sometimes they aggregated slightly, as shown in the scanning electron micrograph of Fig. 10, where a 5 μm particle with porosity clusters with several particles less than 1 μm in size. It shows that the matrix alloy infiltrates into gaps of the order of 0.1 μm in width between particles, suggesting good wetting between the particles and the matrix. Therefore if any gap or hole exists, we consider it to be extremely small.

Manufacture processing is an important factor to control the status of the clusters. With incorrect processing, the matrix alloy only surrounds the cluster and does not infiltrate into the air space between particles. A scanning electron micrograph (Fig. 11) shows a fracture surface with such a cluster 100 μm in size. Most of the particles in the cluster dropped out after the specimen broke in tensile testing. Only a part of them remained stuck to the matrix alloy. In fact such clusters lead to holes within the matrix. They decrease both the wear resistance and the mechanical strength.

No significant reaction zone was observed in microscopic studies of the interface between the particles and the matrix. The explanation probably lies in the small amount of silica in the bauxite particles. Any silica at the particle surface will react with the aluminum alloy melt. The chemical reaction ensures the wetting and infiltration. However, there is not sufficient silica in the particles to form a significant interface layer. We have noticed that bauxite can wet liquid aluminum more easily than alumina can in composite preparation. The wear resistance of bauxite-particle-reinforced metals is comparable with that of alumina-particle-reinforced metals.

Figure 12 is a scanning electron micrograph of the wear surface of B3.5. Wear scars can be seen clearly after scratching by grinding wheels. A lot of bauxite particles were embedded on the wear surface. The scar



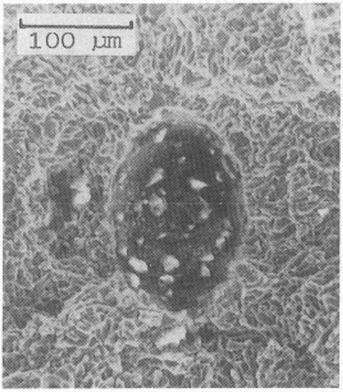
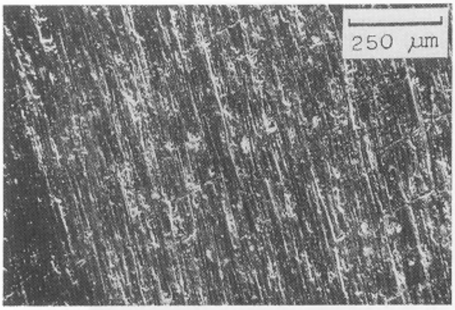


Fig. 10. Scanning electron micrograph of a cluster of bauxite particles in a composite.

Fig. 11. Scanning electron micrograph of the fracture surface of a composite showing a cluster of bauxite particles.



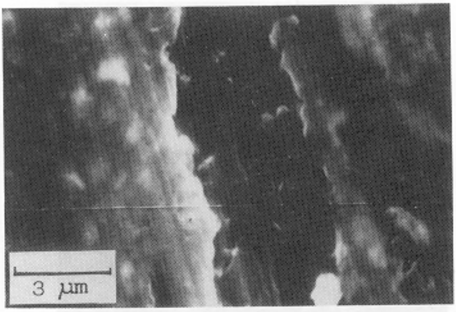


Fig. 12. Scanning electron micrograph of the abrasive wear surface of composite B3.5. The surface is embedded with bauxite particles.

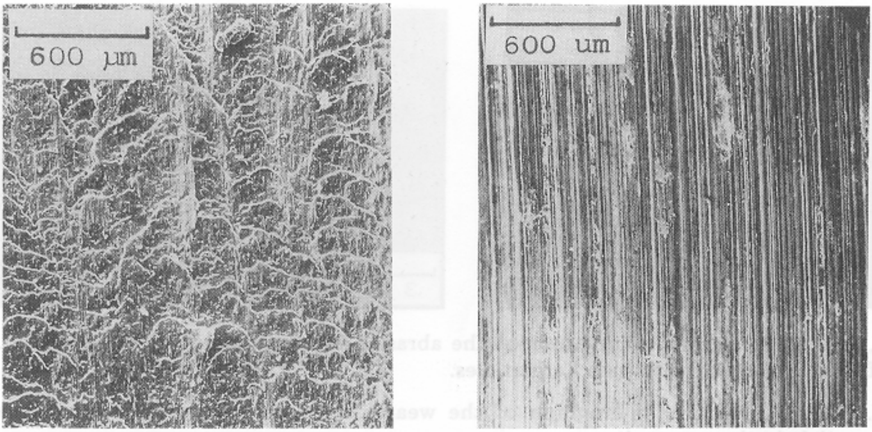
Fig. 13. Scanning electron micrograph of the wear scar of composite B15, showing a bauxite particle in the composite.

depth depended predominantly upon the grit of the grinding wheels. All the experiments were carried out with the same grinding wheels. Figure 13 shows a scanning electron micrograph of a bauxite particle (dark middle region of Fig. 13) in the wear surface. No crack existed in the interface between the particle and the matrix nor within the particle. The direction of the wear scars on the particle surface was almost parallel to that at the matrix surface (bright region of Fig. 13). It indicates that the bauxite particles, towering above the wear surface, supported by the soft matrix, resisted scratching by grits owing to their higher hardness. The bulk wear resistance was thus increased. At high loads, the grits ploughed more deeply into the composite surface. In this way, the fine particles might be moved away together with the matrix. Therefore the large particles would have an advantage over the small ones in abrasive wear at high loads.

The influence of large clusters of composites on the wear resistance is complicated. The wear resistance will decrease because of the reduction in bulk mechanical strength when other variables are kept constant. However, if the large clusters are strong enough to sustain the loads, the particles in the clusters are effective against the scratching action by the grits. In general, large clusters should be eliminated by improving the processing.

Under the oil lubricating condition, the wear rate of B3.5 is less than the composites containing more bauxite particles. We have noticed that the grinding wheels were slipping on the composite surface during the experiments. In this case, the mechanical strength of the composites rather than the hard particles dispersed in the composites plays an important role in the wear resistance.

In the sliding wear test, the steel disc was scratched by hard particle-reinforced aluminum alloys. The bauxite-particle-reinforced aluminum alloy pistons equipped in a small model engine scuffed the chromium-plated cylinder under poor lubricating conditions. Improvement has been made by incorporating graphite particles into the bauxite-particle-reinforced metals.



(a) (b)

Fig. 14. The wear surface of (a) the matrix alloy and (b) composite containing graphite particles; (a) shows much more plastic deformation than (b).

Graphite is a good solid lubricant. Under pressure, a continuous solid lubricant film will develop on the wear surface to protect the surface from scuffing. Generally, composites containing hard particles have higher friction coefficients [1]. The presence of graphite reduces the friction coefficient and the temperature rise (due to friction) in composites [26]. Figure 14 shows the wear surfaces of the matrix alloy and the composite containing graphite after sliding wear under the same condition. Surface plastic deformation occurs in the matrix alloy, while the wear surface of the composite remains relatively smooth because of the protection by the graphite. The use of B8G composite pistons resulted in an 8% increase in the rotating speed, from 4800 to 5200 rev min^{-1} and the reduction in the cylinder wall temperature rise from 150 to 120 ℃. The piston wore less compared with conventional aluminum alloy pistons [24].

6. Conclusions

(1) The abrasive wear rates of Al–12Si–1.4Cu–1.3Mg alloy castings decrease with the addition of bauxite particles. Increasing the amount of particulate material results in increased wear resistance.

(2) The use of fine particles (−300 mesh) results in a decrease in the abrasive wear rate. (Moreover, it leads to an increase in the mechanical strength and ductility at 300 ℃ and an improvement in the machinability of the composites [24].)

(3) The weight loss in sliding wear is decreased by adding a small amount of graphite particles into the bauxite-particle-reinforced aluminum alloy.

Acknowledgements

The authors are grateful to Mrs. M. Wang, Mr. M. G. Zhu and Mr. J. Yan of Nanjing Institute of Technology, and to Mr. M. A. Lukowski and Mr. Jeng-Maw Chiou of SUNY/Buffalo for technical assistance.

References

1 A. Sato and R. Mehrabian, *Metall. Trans.*, *7B* (1976) 443.
2 F. M. Hosking, F. F. Portillo, W. Wunderlin and R. Mehrabian, *J. Mater. Sci.*, *17* (1982) 477.
3 M. K. Surappa and P. K. Rohatgi, *J. Mater. Sci.*, *16* (1981) 983.
4 D. M. Schuster, M. Skibo and F. Yep, *J. Met.*, (November 1987) 60.
5 R. Mehrabian, R. G. Riek and M. C. Flemings, *Metall. Trans.*, *5* (1974) 1899.
6 *Light Met. Age*, *44 (5 - 6)* (1986) 7.
7 P. K. Rohatgi, B. C. Pai and S. C. Panda, *J. Mater. Sci.*, *14* (1979) 2277.
8 A. Banerji, M. K. Surappa and P. K. Rohatgi, *Metall. Trans.*, *14B* (1983) 273.
9 A. Banerji, S. V. Prasad, M. K. Surappa and P. K. Rohatgi, *Wear*, *82* (1982) 141.
10 B. P. Krishnan, N. Raman, K. Narayanaswamy and P. K. Rohatgi, *Wear*, *80* (1980) 205.
11 P. K. Rohatgi and B. C. Pai, *Wear*, *59* (1980) 323 - 332.
12 P. R. Gibson, A. J. Clegg and A. A. Das, *Wear*, *95* (1984) 193.
13 Deonath, R. T. Bhat and P. K. Rohatgi, *J. Mater. Sci.*, *15* (1980) 1241.
14 *Automob. Ind.*, *5* (1984) 33, (in Russian).
15 S. O. Shook, *Met. Prog.*, (September 1985) 11.
16 L. Bruni and P. Ignera, *Automot. Eng.*, *3* (1978) 29.
17 R. C. Cornell, *10th SDCE Int. Die Casting Exposition and Congress, St. Louis, MO, 1979*, Paper G-179-071, p. 1.
18 C. F. Lewis, *Mater. Eng.*, (May 1986) 33.
19 Fact Sheets, Technical Marketing Department, Dural Aluminum Composites Corporation, 1987.
20 J. F. Schontens, *J. Met.*, (June 1985) 43.
21 K. J. Bhansali and R. Mehrabian, *J. Met.*, (September 1982) 30.
22 J. C. Bittence, *Met. Prog.* (July 1987) 45.
23 M. K. Surappa, S. V. Prasad and P. K. Rohatgi, *Wear*, *77* (1982) 295.
24 Jingyu Yang, Mingguang Zhu, Ming Wang, Jun Yang and Guangji Shu, *Proc. 4th Nat. Conf. on Composite Materials, Guangzhou*, December 15 - 21, 1986, p. 515 - 519 (in Chinese).
25 M. Wang, J. Yan and J. Yang, The influence of graphite and ceramic particle size on the mechanical strength and wear behavior of composites, *Proc. Conf. on Metallurgical Materials, Nanjing, July 3, 1987* (in Chinese).
26 J. Yang, M. Zhu, Y. Wang and Z. Shi, Friction and wear behavior of Al–graphite particle composites at high sliding speed and high temperature, *Acta Materiale Compositae Sinica*, *4 (3)* (1987) 51 (in Chinese).