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Role of Al_2O_3 fiber in eutectic Al-Si alloy composites①

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[Abstract] The effects of Al_2O_3 fiber on wear characteristics of eutectic Al-Si alloy composites were studied using a pin-on-disk tester under dry sliding condition. The results show that the Al_2O_3 fiber can make matrix grain be fine, specially the eutectic Si be finer and prevent the plastic flow of matrix and prohibit the crack propagation in the wear layer, thereby it can remarkably improve the mechanical property and the wear resistance of the MMCs. Since Al_2O_3 fiber plays a role of certain framework in protecting the matrix against crash, it can eliminate the severe wear of MMCs with higher φ_f of fiber from the beginning of test. At mild stage, when φ_f is in the range of 8% ~ 10%, the wear rates are the lowest. With increasing φ_f of Al_2O_3 fiber, the wear mechanism of MMCs can be transformed from adhesive delamination to brittle breakaway.

[Key words] Al_2O_3 fiber; eutectic Al-Si alloy; composite; wear mechanism

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1 INTRODUCTION

Metal matrix composites (MMCs) have many important applications in aircraft and automobile industry, for they have many advantages such as mass-lighting and wear-resisting over the matrix materials. Many studies on the wear behavior of Al_2O_3 fiber reinforced Al-matrix composites have been reported. The main objectives of these studies focus on: 1) the wear rate of MMC under different test conditions such as sliding speed and contact load, etc[1~11]; 2) the investigation on the worn surface and subsurface in order to clarify the wear mechanism of MMC[2]. The materials of metal matrix are Al-Zn alloy[7] and Al-Si alloy[9], etc. Their conclusions are as follows: 1) Al_2O_3 fiber can remarkably improve the wear resistance and decrease the wear rate of MMC; 2) a lower wear loss can be obtained by arranging the fiber perpendicular to the sliding surface; 3) the wear rate increases with an increase of contact load; 4) Al_2O_3 fiber can reduce the wear-induced microstructural changes and the subsurface plastic deformation, etc. Recently, Jiang et al[12] have reported that the wear resistance of Al-Si alloys were remarkably improved when reinforced with 5% ~ 16 % Al_2O_3 (volume fraction) fibers and the presence of Al_2O_3 fiber suppressed the transition to the severe wear regime. Sahin[13] studied the wear behavior of planar-random fiber-reinforced Zn-Al-Cu alloy composites with 0~ 26% Al_2O_3 volume fraction fibers. The results have shown that the wear rate decreases with increasing φ_f (volume fraction of fiber) and SEM examination of worn surfaces shows that large scale micro-fracture of fiber and delamination is the principal mechanism for the planar-random orientation of fibers in composite. The wear mechanism was different from the one of fibers pull out proposed by Saka et al[4]. This review shows that although many studies have been made for Al_2O_3 fiber reinforced Al-matrix composites, wear property of Al_2O_3 fiber reinforced eutectic Al-Si alloy composites with a large range from 0~ 26% fiber (volume fraction) have not been reported. The purpose of present study intends to investigate the wear characteristics of Al_2O_3 reinforced eutectic Al-Si alloy composites, in particular, to delineate the effect of Al_2O_3 fiber content on wear resistance and wear-induced microstructure changes of the matrix of MMCs under dry sliding condition. Furthermore, SEM observations and metallography studies of worn surfaces will contribute to reveal the operative wear mechanisms.

2 EXPERIMENTAL

2.1 Materials

The eutectic Al-Si alloy composites with 0 to 26% of Al_2O_3 fiber were fabricated by a high pressure and low speed die casting. The Al_2O_3 fibers were 4 μm in diameter and 40 μm to 200 μm in length. The composition of the Al-Si alloy (ADC12) was: 10.8% Si; 2.5% Cu and balance Al. The fibers were aligned parallel to the wear surface and presented in a random distribution in the MMCs. The counter face of the SUS440B steel pin was nitrided whose depth of nitridation was 70 μm and Vickers was HV 1 200.

2.2 Wear tests

The wear tests were conducted under a contact load of 10 N and at a sliding velocity of 0.1 m/s using a pin-on-disk wear tester. The disk was made from

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MMCs and was 30 mm in diameter and 5 mm in thickness, whereas the pin was made from nitrided steel with a cylinder of 4 mm in diameter. The diameter of the wear track was 23 mm. The surface of both the disk and the pin were polished to 0.1 μm by using 1 200 grit emery paper. As the test environment had a remarkable effect on the wear resistance of aluminum alloys[14], the tests were carried out at 30 ℃ and 70% relative humidity. The mass loss was measured using a precision balance of 0.01 mg sensibility after ultrasonic cleaning of the specimen in acetone. The measured mass losses were converted into volume losses by dividing via their corresponding densities.

2.3 Examination of SEM and metallography

The worn surfaces of matrix and composites were examined using a scanning electron microscope, and the examination of the cross fractures of worn sample were also made in the same way. Moreover, using a highly sensitive digital microscope, the subsurface was observed on cross sections of worn sample mounted in polyester resin and polished using standard metallography techniques.

3 RESULTS AND ANALYSES

3.1 Effects of Al_2O_3 fiber on mechanical properties and microstructure of eutectic Al-Si alloy composites

The variations of yield strength and elongation and Brinell hardness of MMCs with φ_f of fibers are shown in Figs. 1 and 2. It seems that though both the yield strength and the elongation of MMCs are lower than those of the matrix, beside of elongation decreasing with increasing φ_f of Al_2O_3 fiber, the change of yield strength with increasing φ_f of fiber has no remarkable regularities, whereas the Brinell hardness increases along with increasing in φ_f of fiber. These concern with Al_2O_3 fibers, it affects the structure of the matrix of MMC and thus changes the wear properties. Fig. 3 shows the structure of ADC12 and MMCs with different φ_f on cross section. There are strong morphology of flaky eutectic Si and many polygonized shape primary Si in the matrix (Fig. 3(a)). For the structure of 5% fiber(volume fraction), the amount of primary Si is small as compared with Al-matrix and the eutectic Si near Al_2O_3 fiber becomes fine (Fig. 3(b)). For the structure of 9% fiber(volume fraction), the primary Si and eutectic Si become finer and distribute uniformly because they nucleate and grow under the influence of the fiber (Fig. 3(c)). The grain of matrix also

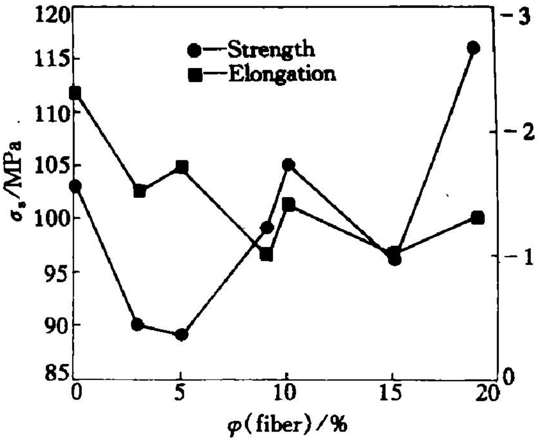

Fig. 1 Variations of mechanical properties of MMCs with φ_f of Al_2O_3

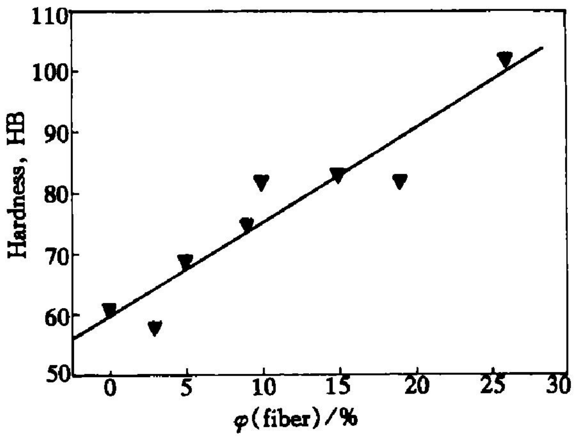

Fig. 2 Variation of Brinell hardness of MMCs with φ_f of Al_2O_3

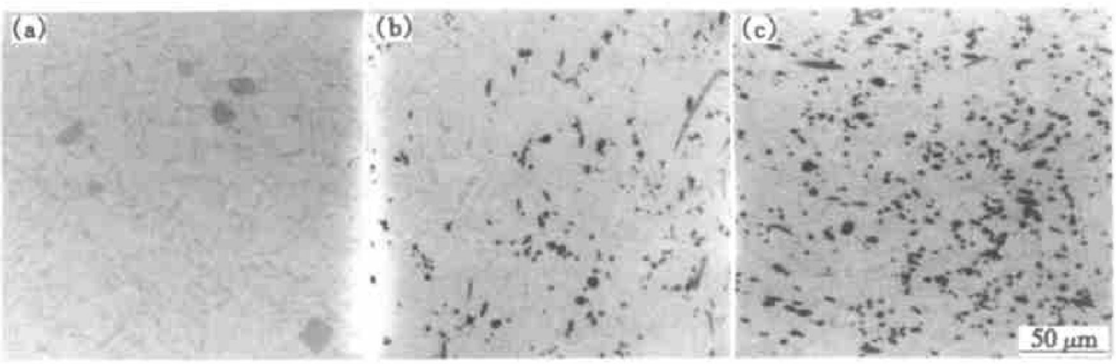

Fig. 3 Microstructures of ADC12 and MMCs
(a) —φ_f= 0%; (a) —φ_f= 5%; (c) —φ_f= 9%;

becomes fine with increasing content of fiber. This may result from the two reasons, on one hand, the Al_2O_3 fibers bring about the increasing of solidification undercooling in Al-Si alloy melt, which results in an increase of nucleation rate. On the other hand, Al_2O_3 fibers itself can promote the nucleation of Si crystal. From the view of crystallization, Si is of FCC crystalline structure, its lattice constant is 5.428 Ù while α - Al_2O_3 is of HCP crystalline structure, its lattice constant is 5.118 Ù, the mismatch degree of both lattices δ is given by

$$\delta = (a_{Si} - a_{\alpha\text{-}Al_2O_3}) / a_{Si} \qquad (1)$$

where δ is no more than 6%, that is, the Si atoms in liquid can nucleate on the surface of Al_2O_3 fiber and hence make the Si crystal finer greatly. It can be confirmed by the metallography observation as shown in Fig. 4 by arrowhead. Since Si crystal is a brittle material and frequently presents in the form of polygonized shape structure, it causes stress concentration and initiates cracks. Therefore, although fibers deteriorate the continuity of the matrix, it can improve the mechanical properties of MMC by making matrix grain, particularly eutectic Si, finer. After all, the fiber is in hardening phase, and it can improve the hardness of MMCs effectively.

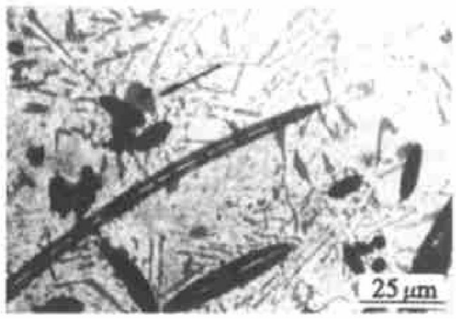

Fig. 4 Si crystal nuclei on surface of Al_2O_3 fiber

3.2 Effects of Al_2O_3 fiber on wear characteristic of eutectic Al-Si alloy composites

The relation between wear loss and content of the fiber is shown in Fig. 5. There were two stages: an initial severe stage and a mild wear stage. At the initial severe stage, the average severe wear rate ($k'r$) can be obtained by dividing initial wear loss via the sliding distance. As for the mild stage, because the wear losses of both unreinforced ADC12 and composites were linear with sliding distance, the wear rate can be shown simply with the slope (kr) of wear curve (as shown in Fig. 5 on wear curve of matrix). It is clear that the unreinforced ADC12 and composites with low content of fiber have a high value of $k'r$ which corresponds to severe wear. While the initial $k'r$ values of composites with high content of fiber were almost zero, the composites whose volume fraction was more than 9% had no severe wear stage from very beginning of test. Furthermore, at the mild wear stage, the wear rates (kr) decrease remarkably with increasing content of fiber when volume fraction of the fiber is low and increases slightly with increasing content of fiber after the volume fraction is more than 9%.

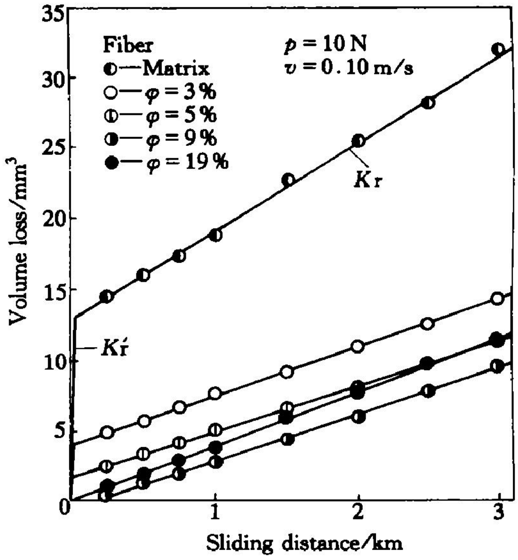

Fig. 5 Relations between wear loss and φ_f of Al_2O_3

3.2.1 Severe wear

From Fig. 5, it is found that the wear characteristic of MMCs is mainly dominated by volume fraction of Al_2O_3 fiber. The observation shows that the matrix plastic flow of irreinforced ADC12 and lower content of fiber MMC occurs at the beginning of the wear test which results in adhesive severe wear. Since the plastic flow of matrix can lead to a deformation of eutectic Si as shown in Fig. 6, the extent of plastic flow of subsurface has been shown with the depth of the deformation zone of eutectic Si measured immediately using VH-6300 highly sensitive digital microscope on un-etched cross sections of sample parallel to sliding direction.

Fig. 7 shows the depths of the plastic flow layer (DPFL) of the MMC with different φ_f. The depth of the plastic flow layer decreases with increasing content of fiber. While volume fraction of fiber is more than 9% and the depth of the plastic flow layer of the MMC approaches zero, the severe rate almost tends to become zero. Al_2O_3 fibers that are uniformly distributed in Al matrix can prevent the matrix plastic flow of worn surface due to friction, thereby it increases the wear resistance of MMCs effectively. Moreover, Al_2O_3 fiber can prevent the crack propagation in the worn surface. Fig. 8(a) shows the wear cracks observed on the cross section. The crack propagates initially in a direction parallel to the sliding in the subsurface and then propagates towards the worn surface due to the existing of Al_2O_3 fiber. As a result, the removal of particles is restrained. For these reasons, the severe wear rate decreases remarkably with increasing content of fiber as

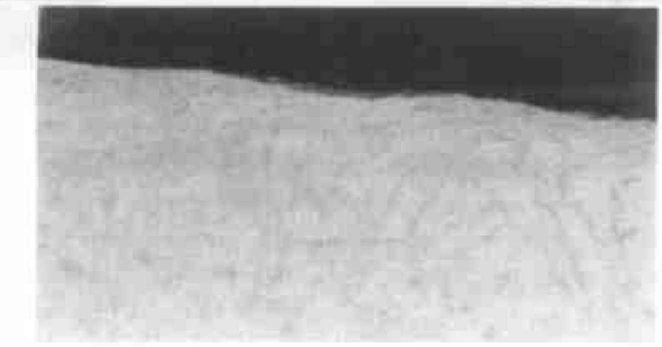

Fig. 6 Deformation microstructure of matrix in subsurface

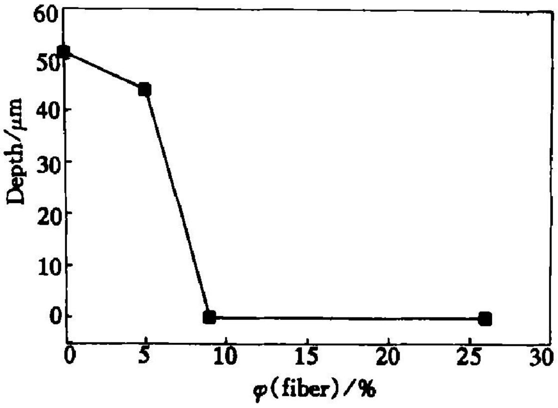

Fig. 7 Depths of plastic flow layer of wear subsurface

shown in Fig. 5.

3.2.2 Mild wear

At the mild wear stage, with increasing content of the Al_2O_3 fiber, since the reinforcing action of Al_2O_3 fiber on the matrix becomes gradually stronger and stronger, the wear rates decrease remarkably and become stable as shown in Fig. 5. In addition, the work hardening and oxidization of the worn surface may have some effects on decreasing wear rate. But when the volume fraction of fiber is more than 9%, the wear rate tends to have a slight increase. This may be related to the facts that Al_2O_3 fibers make fine eutectic Si achieve size limit and worsen the continuity of matrix, particularly when a large quantity of Al_2O_3 fibers are crushed into small pieces due to rubbing, which causes an increase in microcrack density between the fiber and the matrix, so that the loose combination layer is formed with the sliding distance. These results lead to the whole combination strength of wear layer become worse, which can be a disadvantage to the improvement of the wear resistance.

Further observation in the mild wear stage shows that Al_2O_3 fiber has a remarkable effect upon wear mechanism. Fig. 8(b) shows the microstructure of wear layer in matrix. With increasing the sliding distance, the eutectic Si is broken into small pieces and appears in the change from a curve streamline arrange

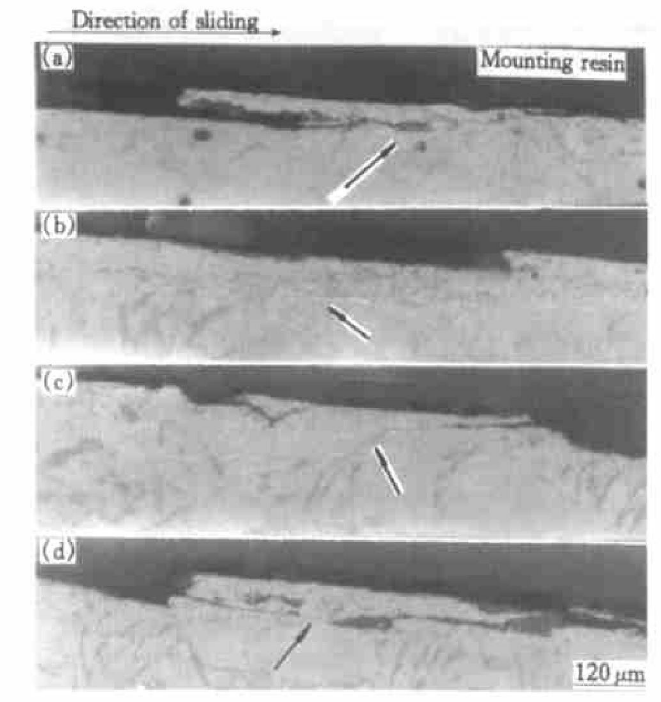

Fig. 8 Microstructures of worn subsurface on cross section

(shown as arrowhead) in the subsurface to a straight-line parallel to the worn surface due to the plastic flow of metal matrix. Increasing the density of crushed Si in worn layer, the microcracks between the crushed Si and metal matrix gradually link up (shown in Fig. 8(c) as arrowhead) and form a longer crack (shown in Fig. 8(d) as arrowhead) and thus the layer will be removed. This phenomenon is very similar to the delamination mechanism proposed by Sahin[13]. But for the composites with lower content of fiber the difference is that the flaky eutectic Si intensifies the large area delaminating of MMCs due to friction. Fig. 9 shows a SEM image of adhesive features of worn surface. Afterwards, the pieces of adhesive delamination are re-adhered with others or partly broken into smaller pieces. Finally the relatively large wear particles with the size of 2~10 μm are formed.

At high content of fiber, although the fine eutectic Si is crushed into very small pieces in a very thin subsurface, the curved streamline of crushed Si is not clear. On the other hand, large quantity of the Al_2O_3 fibers is crushed into very short pieces of 4~ 12 μm by contact pressure. This shows that the contact load is mainly supported by Al_2O_3 fiber instead of Al-matrix from the beginning of test. That is, the Al_2O_3 fibers play a role of certain framework in protecting the matrix. As a result, severe wear does not occur if the volume fraction of fiber is more than 9%. The fiber pieces of the rubbing layer increase and distribute uniformly, so that random crushed Si and fiber separate the matrix. The brittle layer that is mixed with matrix grains and small pieces of Si and fiber is formed and causes the brittle breakaway from the worn surface due to friction. Fig. 10 exhibits clearly the feature of a brittle fracture of worn surface in spite of a smooth and flat surface compared with matrix shown in Fig. 9.

The small wear particle, whose size is 1~ 5 μm, was removed. This mechanism is different from the fiber pulling-out mechanism proposed by Saka[4]. However, observation results support the viewpoint[8] that, when the fibers lie parallel to the wear surface, the small pieces were easily debond and lost from the surface during the test, and there is no advantage to wear property.

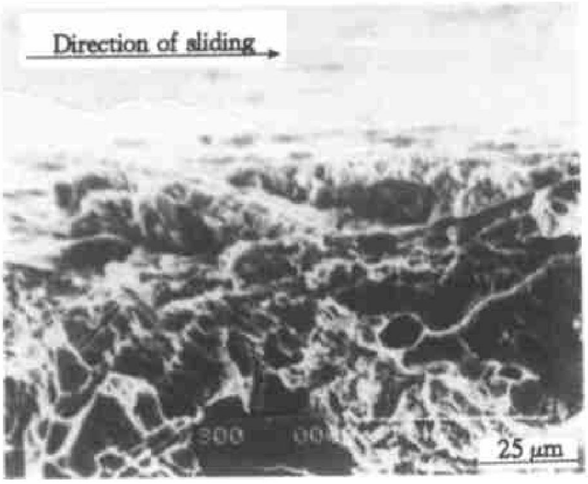

Fig. 9 Adhesive feature of worn surface of matrix

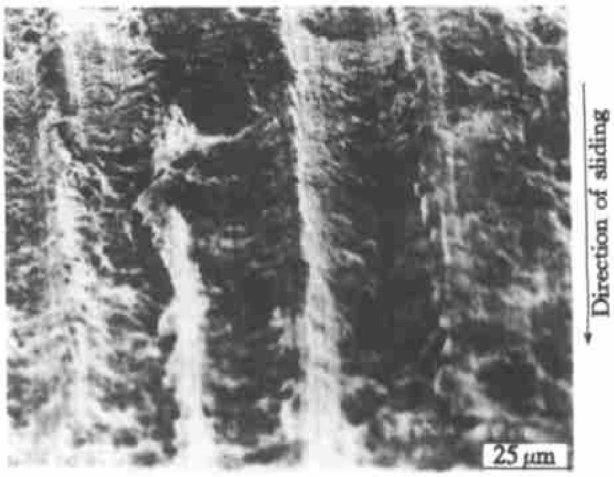

Fig. 10 Brittle feature of worn surface of MMCs with high φ_f of Al_2O_3(9%)

When the content of fiber is low, the worn layer shows an intermediate appearance between the matrix and the MMC with a high content. The wear occurs due to both the adhesive delamination and the brittle breakaway. Thus the wear mechanism can be transformed from adhesive delamination to a brittle breakaway with increasing content of fiber.

Besides, it is well known that the wear behavior of composite materials is related with their structure. With regard to Al_2O_3 fiber MMCs fabricated by a high pressure and low speed die casting technique, the eutectic Al-Si alloy has a good fluidity, which is the most beneficial to produce this material. While the content of Si is high, the fiber eutectic Si becomes the second important factor for wear properties. In order to further improve the wear property of the MMC, the following method can be adopted: 1) the content of Al_2O_3 fiber should be selected in the range of 8%~ 10% when eutectic Al-Si alloy is used; 2) the technique should be adopted to make the eutectic Si finer; 3) the Al-matrix alloy with a lower content of Si should be used; 4) arranging the fibers perpendicular to the sliding surface; 5) different manufacturing methods including the powder metallurgy technique can be used . In addition, the Al-matrix and its reinforcement should be kept at a reasonable proportion, and fiber reinforcement and small disperse reinforcement should be combined as possible in order to eliminate severe wear and improve the wear properties.

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