論文

하이브리드 금속복합재료의 마모특성

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Wear Properties of Hybrid Metal Matrix Composites

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ABSTRACT

The purpose of this study is to investigate the wear properties of Saffil/Al, Saffil/Al2O3/Al and Saffil/SiC/Al hybrid metal matrix composites fabricated by squeeze casting method. Wear tests were done on a pin-on-disk friction and wear tester under both dry and lubricated conditions. The wear properties of the three composites were evaluated in many respects. The effects of Saffil fibers, Al_2O_3 particles and SiC particles on the wear behavior of the composites were investigated. Wear mechanisms were analyzed by observing the worn surfaces of the composites. The variation of coefficient of friction(COF) during the wear process was recorded by using a computer. Under dry sliding condition, Saffil/SiC/Al showed the best wear resistance under high temperature and high load, while the wear resistances of Saffil/Al and Saffil/Al_2O_3/Al were very similar. Under dry sliding condition, the dominant wear mechanism was abrasive wear under mild load and room temperature, and the dominant wear mechanism changed to adhesive wear as load or temperature increased. Molten wear occurred at high temperature. Compared with the dry sliding condition, all three composites showed excellent wear resistance when lubricated by liquid paraffin. Under lubricated condition, Saffil/Al showed the best wear resistance among them, and its COF value was the smallest. The dominant wear mechanism of the composites under lubricated condition was microploughing, but microcracking also occurred to them to different extents.

초 록

본 연구의 목적은 가압주조법에 의해 제조된 Saffil/Al, Saffil/Al_2O_3/Al, Saffil/SiC/Al 과 같은 혼합금속 복합재료의 마모 물성을 조사하고자 하는 것이다. 마모 시험은 건조와 윤활상태 하에서 pin-on-disk 형태의 마모 시험기로 수행되었다. 세가지 금속복합재료의 마모 물성시험에서 Saffil섬유, Al_2O_3입자, SiC입자의 효과들을 조사하였다. 마모 메커니즘은 복합재료의 마모된 표면들을 관찰하여 분석하였다. 마모과정 동안 마찰계수(COF)의 변화는 컴퓨터에서 자동적으로 기록되었으며, 건조 조건에서 Saffil/SiC/Al은 고온과 높은 하중 하에서 가장 좋은 마모 저항을 보여주었다. 한편 Saffil/ Al과 Saffil/Al_2O_3/Al의 마모 저항은 비슷한 결과를 보였다. 건조조건에서 적당한 하중과 상온에서 지배적인 마모 메커니즘은 연삭 마모이며, 하중이나 온도가 증가함에 따라 응착마모로 변화되며, 고온에서는 융착마모를 나타내었다. 건조 상태에서 세가지 복합재료를 비교시 액체 파라핀에 의한 윤활시험시 마모 특성이 가장 좋은 결과를 나타내었다. 윤활조건에서는 Saffil/Al복합재료가 가장 좋은 마모 저항성을 보였으며, 이 경우 마찰계수도 가장 작게 나타났다. 윤활 조건에서 금속복합재료의 주요 마모 메커니즘은 microploughing 이었으나, microcracking 역시 다른 정도에서는 미소 균열도 발생한다.

Key Words: 하이브리드 금속복합재료(Hybrid metal matrix composites), 가압 주조 방법(Squeeze casting method), 마모 특성(Wear properties), 마모 매커니즘(Wear mechanism), 윤활(Lubrication)

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1. Introduction

In recent years, aluminum metal matrix composites (MMCs) used for tribological components have attracted more and more interests. They are widely used as high speed rotating or reciprocating mass items such as pistons, connecting rods, drive shafts, brake rotors and cylinder bores[1]. Compared with the corresponding monolithic alloys, aluminum matrix composites are attractive because of their improved strength, stiffness, creep behavior, wear resistance and low thermal expansion[2]. Moreover, they have light weight and their applications will be greatly expanded in the near future if problems like cost and fabricating are well resolved.

Many researches have been carried out on the wear behaviors of aluminum MMCs recently[3-10]. A transition from mild wear to severe wear of hybrid MMCs can be induced by changes in load or temperature. Any tribological components are supposed to work in the mild wear region and try to avoid the severe wear region, so it is of interest to know the transition load or temperature of the hybrid MMCs. The change of wear mechanism does not always mean an increase in weight loss, but it may result in the increasing of friction force or changing of microstructure or others. There have been many researches related to the wear mechanisms of aluminum MMCs[11-14]. Delamination was considered to be the controlling wear mechanism for Saffil-reinforced Al6061 composites at intermediate load [11]. Under dry sliding at high loads, subsurface fracture was found both within the fibers and at the fiber-matrix interface[12]. The Al6061 composites containing only Saffil had inferior wear resistance to those containing the same volume fraction of SiC_p[13].

Lubricant is widely used in industry field as it contributes to decreasing of friction, transporting of heat and worn debris from system, and bearing of part of the applied loading to the system[15]. The liquid paraffin is a good lubricant for aluminum MMCs. Yoshiro Iwai et al. found that in paraffin oil, the wear rates of Al7004-T6 and Al2024-T4 were about 1/10 the wear rates under dry conditions[16]. Pan *et al.* found that the main wear mechanism of 2124Al-SiCw composite was abrasive wear through plowing and polishing for lubricated sliding[17]. In industry field, the tribological components are inevitably to work under high temperature due to the heat generated or other factors. So the wear behavior under high temperature becomes important sometimes. The dry sliding wear behaviors of aluminum MMCs, which simulate a worst case in which any lubrication initially present has broken down, are available in literature, but the wear properties under lubricated conditions, as well as high temperature, are very limited. As we know, due to the complexity of wear problems, the wear mechanism and the associated wear rate of a particular material depend critically on the precise conditions to which it is subjected[18]. A material showing good wear behavior under one condition does not necessary mean that it would show good wear behavior under another condition.

Saffil fibers, Al_2O_3 particles and SiC particles are usually used as reinforcements of aluminum alloys. But how do these reinforcements effecting on the wear behavior of aluminum MMCs? The answer to this question would be very helpful in getting a general idea of the wear properties of hybrid MMCs and designing of hybrid MMCs for tribological use. In this research, three kinds of hybrid MMCs, named Saffil/Al, Saffil/Al_2O_3/Al and Saffil/SiC/Al, were developed, and the wear properties of them under both dry and lubricated conditions were evaluated.

2. Materials and Experimental Details

2.1 Materials

The three composites all contained 20vol.% reinforcements. Saffil/Al_2O_3/Al contained 5vol.% Saffil fibers and 15vol.% Al_2O_3 particles. Saffil/SiC/Al contained 5vol.% Saffil fibers and 15vol.% SiC particles. The small fraction of Saffil fibers in Saffil/Al_2O_3/Al and Saffil/SiC/Al was used to reinforce the aluminum matrix and make the composites easier to fabricate, but the wear properties of these two kinds of composites were determined by the particles.

The matrix alloy was AC8A. It was widely used for making engine pistons of automobiles due to its excellent wear behavior. Table 1 shows the chemical composition of the aluminum matrix alloy. The main chemical compositions were silicon, copper and magnesium.

The SiC particles were fabricated by Imperial Polychemical Corp.(U.S.A.). The Saffil fibers(δ-alumina fibers) were fabricated by ICI(U.K.). Table 2 shows the specifications of the reinforcements. The Vickers hardness of Saffil fibers and Al_2O_3 particles were very similar, while the hardness of SiC particles was much bigger. Fig. 1 shows the SEM graphs of Saffil fibers, Al_2O_3 particles and SiC particles.

The composites were all fabricated by squeeze casting method. After squeeze casting, cast ingots were treated by T6 heat treatment. The reinforcements were uniformly distributed, as shown in Fig. 2.

Table 1 Chemical composition of Al matrix alloy (AC8A)

Element	Si	Cu	Mg	Zn	Fe	Mn	Ni	Ti	Cr	Al
wt%	11.33	1.10	1.07	<0.15	<0.8	<0.15	1.20	<0.2	<0.1	Rem.

Table 2 Specifications of the reinforcements

Material	Density (g/cm^3)	Diameter (μm)	Length (μm)	Modulus(E) (GPa)	Hardness (kg/mm^2)
Saffil	3.3	3.0	150	310	2000
Al_2O_{3p}	3.95	50	-	380	2000
SiC_p	3.2	30	-	410	2800

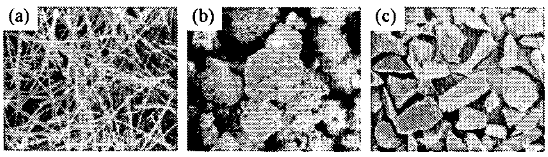

Fig. 1 SEM graphs of Saffil fibers (a), Al_2O_3 particles (b) and SiC particles (c), 500×

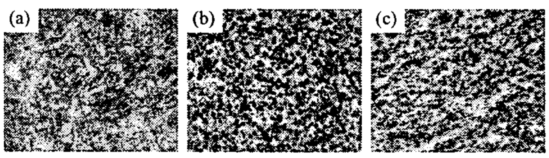

Fig. 2 OM graphs of the surfaces of Saffil/Al (a) Saffil/Al_2O_3/Al (b) and Saffil/SiC/Al, (c) 50×

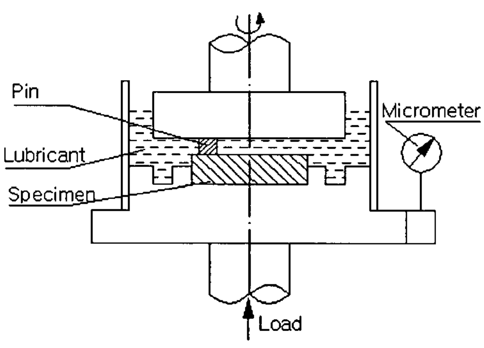

Fig. 3 A schematic diagram of the friction and wear tester under lubricated condition.

2.2 Experimental Details

The wear behavior of Saffil/Al, Saffil/Al_2O_3/Al and Saffil/SiC/Al hybrid MMCs was investigated on a pin-on-disk friction and wear tester. Fig. 3 shows the schematic diagram of the friction and wear tester under lubricated condition.

The specimens were 30mm in diameter and 8mm in thickness. The counter material was SCM 440. The diameter of the steel pins was 5mm, and the diameter of the pin's top surface was 4.3mm after chamfered. The contact surfaces of the specimens and pins were all smoothed by 1500 grit SiC paper. The rotating diameter of the pin on the specimen's surface was 23mm. The sliding speed was 0.36m/s. The weight losses were measured by using an electronic balance with a sensitivity of 0.1mg. The applied load under lubricated condition was 240N. In order to remove the oleaginous organic substances from the specimens' surface, the specimens were cleaned in an acetone bath and dried in hot air before and after the tests. The pins were also cleaned with acetone before the tests. The sliding distances under dry condition were all 250m. The long sliding distance wear tests under lubricated condition were done by an incremental method[15]. The total distance was 8000m and an increment was 2000m. After each increment, the specimen was removed, cleaned by acetone and dried in hot air, then weighted and remounted in the wear tester at the same location, and then the test was continued by using fresh lubricant. The wear process was controlled by a computer. Friction force, coefficient of friction(COF), wear depth and temperature were recorded as a function of time.

3. Results and Discussions

3.1 Results under Dry Sliding Condition

According to the well-known Archard's equation[19], the wear rate was related to the hardness of the material. Generally, hybrid MMCs were composed of two or more kinds of materials with different hardness. Moreover, the hardness of the contacting surface might be different from the bulk hardness due to strain hardening, material transfer or other factors. So the determination of wear properties of the composites became more complicated.

Fig. 4 shows the weight losses under various temperatures at mild load of 1kg, and the transition temperatures of the three materials were obtained. It was obvious that Saffil/SiC/Al showed the best wear resistance at high temperature. It had the highest transition temperature, which was about 200°C. There was little difference between the wear resistance of Saffil/Al and Saffil/Al_2O_3/Al under various temperatures, and the transition temperature of them was both about 150°C. The SiC particles contributed to the good wear

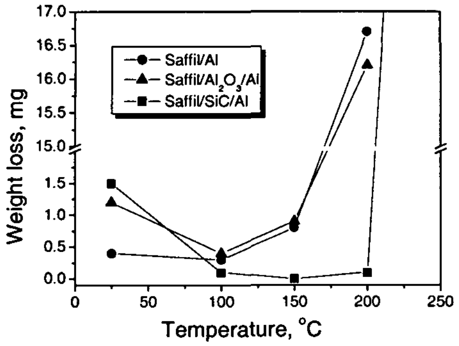

Fig. 4 Weight losses under various temperatures at load of 1kg, Saffil/SiC/Al shows the highest transition temperature.

resistance of Saffil/SiC/Al. The wear resistance of SiC particles was better than that of Saffil fibers and Al_2O_3 particles under high temperature. The hardness of SiC was very high even under high temperature. Under high temperature, the matrix became ductile, so the applied load was conducted to the reinforcements. The wear resistance of the reinforcements under high temperature determined the wear resistance of the composites. Saffil fiber was made from δ-type Al_2O_3, and it had the similar hardness, which played an important role in the wear resistance of the material according to Archard, with the Al_2O_3 particle. So the wear resistance of Saffil/Al and Saffil/Al_2O_3/Al was very similar.

Saffil/SiC/Al had the biggest weight loss under room temperature. This was because in the wear mechanism of abrasion under room temperature, there was a large proportion of three-body abrasion due to the mild load. In the three-body abrasion, the scratch caused by the third body was very important to the weight loss. The harder particles would cause bigger weight loss. The SiC particle was the hardest, so the damage to the surface was the most serious, and the weight loss was the biggest. Moreover, under this mild load, the vibration was easily to be induced. The friction force of Saffil/SiC/Al was the biggest, so its vibration was the most serious. This fact could be found from the COF variations, which was discussed later in Fig. 14. The serious vibration also contributed to the biggest weight loss of Saffil/SiC/Al at room temperature.

When the temperature increased to 100°C, the proportion of adhesion in the wear mechanism also increased. The material became relatively soft and there was even a decrease of friction force, so the vibration was not so serious as under room temperature. When the temperature increased to 150°C, the dominant wear mechanism was adhesion. Saffil/Al and Saffil/Al_2O_3/Al failed to resist the adhesive wear, so the weight loss increased. Saffil/SiC/Al could resist the wear under this temperature due to the SiC particles, so the weight loss remained very small.

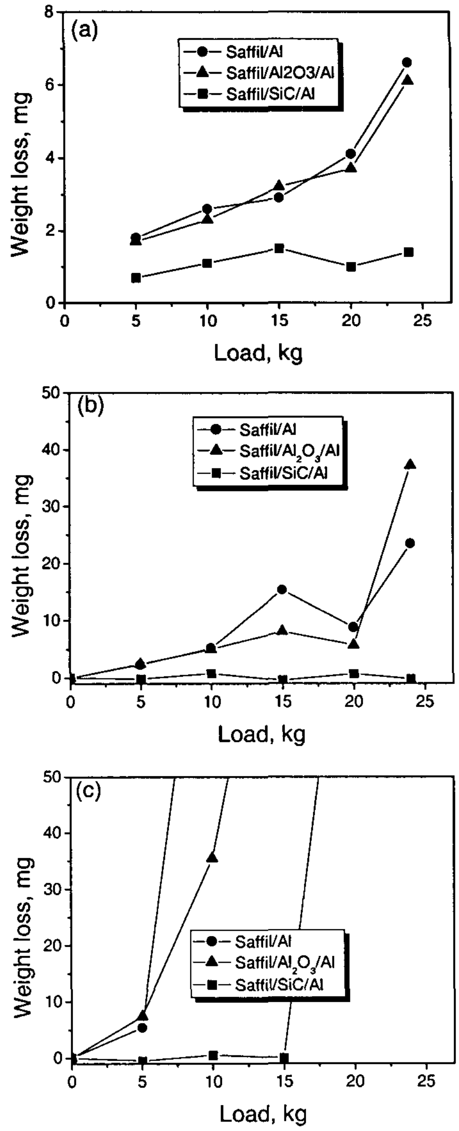

Fig. 5 Weight losses under various loads at temperature of R.T. (a), 100°C (b) and 150°C (c)

When the temperature was higher than the transition temperature, the dominant wear mechanism changed from adhesion to molten wear. The molten wear was characterized by the severe surface damage and large-scale material transferring to the counterface, so the weight loss increased dramatically after the transition temperature.

Fig. 5 shows the weight losses under various loads and temperatures. Under room temperature, Saffil/SiC/Al showed the best wear resistance under these intermediate loads, as shown in Fig. 5(a), while the wear resistance of Saffil/Al and Saffil/Al_2O_3/Al was almost the same. Under room temperature and intermediate load, the vibration was not so serious and most of the wear debris was removed from the wear track due to the relative big load. The dominant wear mechanism was two-body abrasion.

Under temperature of 100°C, Saffil/SiC/Al still showed the best wear resistance under various loads, as shown in Fig. 5(b), and there was little difference between the wear resistance of Saffil/Al and Saffil/Al_2O_3/Al. Some minus data occurred for Saffil/SiC/Al. This was because some wear debris were transferred to the surface of the specimen.

Under temperature of 150°C, Saffil/SiC/Al showed the highest transition load, which was around 15kg, as shown in Fig. 5(c). The transition load of Saffil/Al and Saffil/Al_2O_3/Al was both about 5kg. Saffil/Al_2O_3/Al only showed very little advantage over Saffil/Al at this temperature. The transition load of Saffil/SiC/Al was the highest. When the applied load was bigger than the transition load, the dominant wear mechanism was molten wear, and very big weight loss would occur as a result.

We could also study Fig. 5 from the respect of transition temperature. It was obvious that the transition temperatures of Saffil/Al and Saffil/Al_2O_3/Al were both about 150°C under load of 5kg, and the transition temperature of Saffil/SiC/Al was about 150°C under load of 15kg. So under various loads, we could get the same result as shown in Fig. 4.

3.2 Results under Lubricated Condition

Fig. 6 shows the result of weight losses under various sliding distances and temperatures. The weight losses of Saffil/SiC/Al and Saffil/Al_2O_3/Al increased abruptly at the early stage of sliding distance, as shown in Fig. 6(a), and increased slightly, or even ceased to increase, after sliding distance of 2000m. As for Saffil/Al, the weight loss increased slightly from the beginning of the test. Saffil/Al showed the best wear resistance, while Saffil/SiC/Al showed the worst wear resistance under room temperature.

As shown in Fig. 6(b), Saffil/Al still exhibited the best wear resistance under temperature of 100°C. But the wear resistance of Saffil/SiC/Al and Saffil/Al_2O_3/Al was different from room temperature, the wear resistance of Saffil/SiC/Al was better than that of Saffil/Al_2O_3/Al under temperature of 100°C.

At room temperature, the wear resistance of Saffil/Al_2O_3/Al was better than that of Saffil/SiC/Al. This was because SiC particle was harder than alumina particle. The hard particle was destructive to the wear resistance of the composite. But at high temperature, it was different. The wear resistance of Saffil/Al_2O_3/Al was worse than Saffil/SiC/Al. This was because at high temperature, the matrix became ductile, so the applied load was conducted to the particles. The wear resistance of SiC particles was better than that of Al_2O_3 particles, so at this temperature, the weight loss of Saffil/Al_2O_3/Al was bigger than that of Saffil/SiC/Al.

Fig. 7 shows the two kinds of wear modes. Saffil/Al exhibited the best wear resistance because there were no hard particles acting as abrasives, while there were some hard particles acting as abrasives for Saffil/SiC/Al and Saffil/Al_2O_3/Al, so the weight loss of Saffil/SiC/Al and Saffil/Al_2O_3/Al was bigger than that of Saffil/Al. As shown in Fig. 6(a), the weight loss of Saffil/SiC/Al and Saffil/Al_2O_3/Al increased only slightly after sliding distance of 2000m. This was because most of the particles on the surface were pulled out at the early stage, and after sliding distance of 2000m, there were few particles acting as abrasives.

The wear depths of them increased abruptly at the early stage and kept increasing with sliding distance, as shown in Fig. 8. It was obvious that Saffil/SiC/Al had the deepest wear depth under lubricated condition.

Fig. 9 shows the schematic diagram of wear depth. The total wear depth included the wear of the pin and the wear of the specimen. The total wear depth was mainly caused by the wear of the pin and the wear depth caused by the wear of the specimen could be ignored. Actually, the pin's length was measured after the test, and it was found that the decreased length of the pin was almost equal to the ultimate wear depth as shown in Fig. 8.

It was not difficult to find that the weight loss almost ceased to increase after sliding distance of 2000m, while the wear depth increased all the time. This seemly contradiction result might be explained like this. As the particles were pulled out and became debris, pits occurred, but at the same time, some debris trapped into the pits and might form a transfer layer. So the transfer layer prevented the wear of the specimen and the weight loss ceased to increase. It could be concluded that it was the wear of the steel pin, instead of the specimen, that caused the increasing of the wear depth. The wear depth of Saffil/SiC/Al was the deepest, which was because that the SiC particle was the hardest and the damage to the steel pin was the most serious. The total wear depth

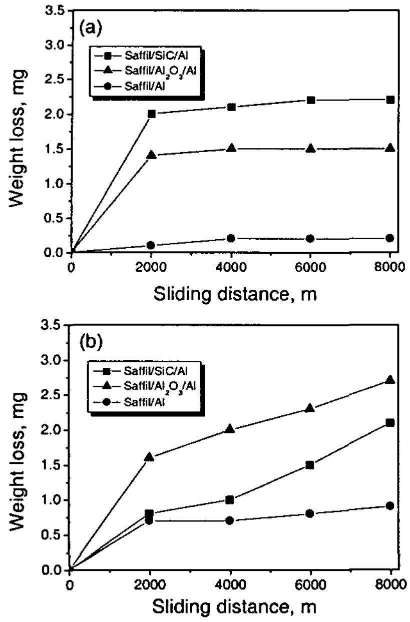

Fig. 6 Weight losses under various sliding distances at room temperature (a) and 100°C (b)

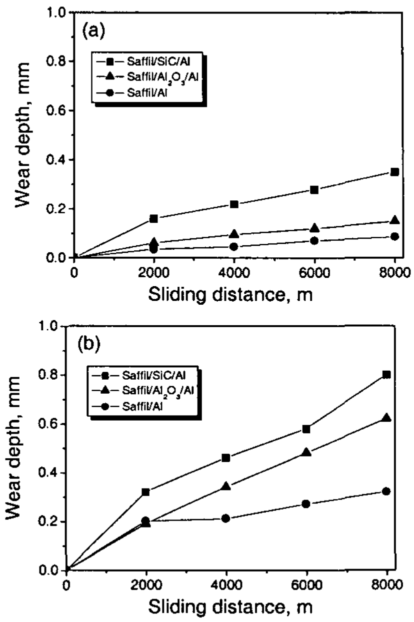

Fig. 8 Wear depths under various sliding distances at room temperature (a) and 100°C (b)

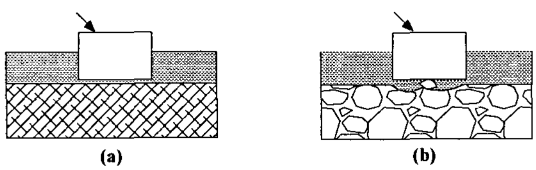

Fig. 7 Wear modes of Saffil/Al (a) Saffil/Al2O3/Al and Saffil/SiC/Al (b)which was discussed later.

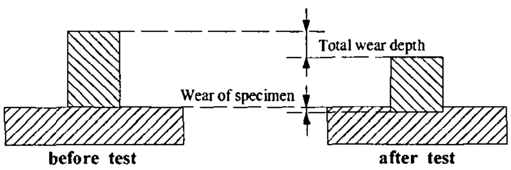

Fig. 9 A schematic diagram of wear depth.

under 100°C was deeper than that of room temperature, this was because the materials became ductile under high temperature, and the materials were easily to be removed from the surface. Moreover, there was a decreasing of viscosity of the lubricant as temperature increased, and the load carried by the lubricant film decreased according to Eq. (1), i.e., Reynolds' equation in one dimension. The lubricant film might break down at this temperature.

$$\frac{dp}{dx} = 6U\eta\left(\frac{h-\bar{h}}{h^3}\right) \quad (1)$$

Where dp/dx was the pressure per unit dimension, U is the sliding speed, η is the viscosity, h is the thickness of the lubricant film and is film thickness where dp/dx=0.

3.3 Worn Surfaces Analysis

The worn surfaces were observed though SEM. Fig. 10 shows the morphologies of the worn surfaces of the composites under dry sliding. It was found from Fig. 10 (a),(c),(e) that the worn surfaces of Saffil/Al_2O_3/Al and Saffil/SiC/Al were filled with grooves paralleling to the sliding direction, while the grooves on the worn surface of Saffil/Al were not so obvious. This was because that the wear mechanism under room temperature was abrasive wear. For Saffil/Al_2O_3/Al and Saffil/SiC/Al, some hard particles were pulled out and acted as three-body abrasives, which resulted in the serious grooves.

Fig. 10(b),(d),(f) shows the SEM graphs of the worn surfaces at 150°C. The worn surfaces of Saffil/Al and Saffil/Al_2O_3/Al were very smooth, which was because of the shear deformation of the composites. Under this temperature, the matrix became ductile, so the wear behavior of the

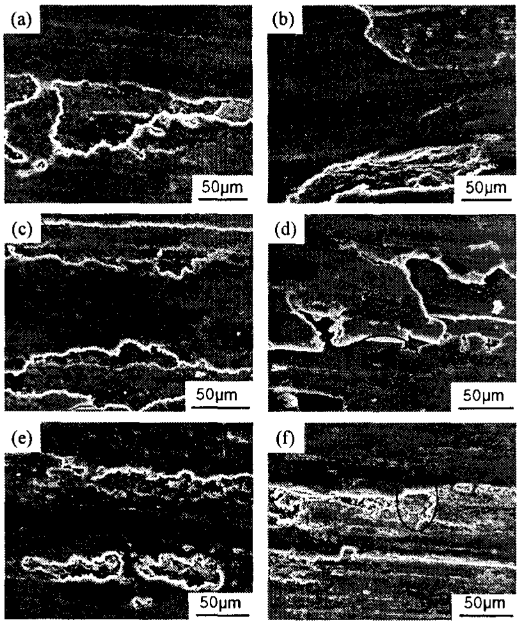

Fig. 10 *SEM graphs of the worn surfaces of Saffil/Al (a),(b),* **Saffil/Al_2O_3/Al (c),(d) and Saffil/SiC/Al (e),(f) under dry sliding, (a),(c),(e) for room temperature and load of 10kg, and (b),(d),(f) for 150°C and load of 1kg.**

reinforcements played an important role on the wear behavior of the composites. The reinforcements could be found on the worn surfaces of Saffil/Al2O3/Al and Saffil/SiC/Al, as shown by an ellipse in Fig. 10(d),(f). Under this temperature, the dominant wear mechanism was adhesion wear.

As the load increased at 150°C, molten wear occurred for Saffil/Al, and the adhesion for Saffil/Al_2O_3/Al became very serious. The grooves on the worn surfaces of Saffil/Al_2O_3/Al were very wide and deep, as shown in Fig. 11(a). As the pin sliding across the surface the specimen under this temperature, strain hardening occurred, and some hardened layers were attached to the worn surface of the pin because of the high temperature and pressure. The transferred hard layer on the surface of the pin scratched through the surface of the specimen, and resulted in the wide and deep grooves on the surface of the specimen. At the same time, some layers on the surface of the pin might flake and become big size debris.

As for Saffil/SiC/Al, the grooves were not so wider and deeper compared with Saffil/Al, but pits and cracks were found on the worn surfaces, as shown in Fig. 11(b). The grooves were not so wider and deeper because the SiC reinforced composites remained very hard at this temperature,

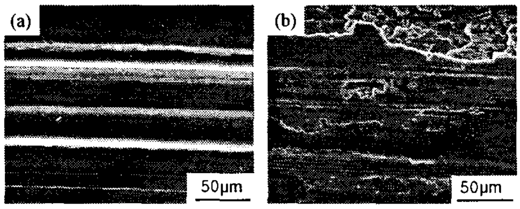

Fig. 11 SEM graphs of the worn surfaces of Saffil/Al_2O_3/Al (a) and Saffil/SiC/Al (b) under 150°C and load of 10kg.

and it was not easy to penetrate. The friction force increased greatly when adhesion occurred, which resulted in the cracks on the worn surfaces. The occurrence of pits was because of the pulling-out of the SiC particles.

Fig. 12 shows the morphologies of the worn surfaces of the composites under lubricated condition and sliding distance of 8000m. It was found that the worn surfaces of Saffil/Al_2O_3/Al and Saffil/SiC/Al were filled with grooves paralleling to the sliding direction, while the grooves on the worn surface of Saffil/Al were not so obvious. The grooves occurred here could be thought as a characteristic of microploughing. The grooves in Fig. 12(c),(d),(e),(f) were discontinuous and cracks were found on the worn surfaces. The occurrence of cracks was due to the pulling-out of some particles. Microcracking of Saffil/SiC/Al was serious than Saffil/Al_2O_3/Al.

As for Saffil/Al, microcracking was not obvious, and grooves were almost not found on the worn surfaces. This was because that there were no hard particles acted as abrasives, but the grooves could be found on the surface of the pin, as shown in Fig. 13(a),(b). Saffil fibers could be found on the worn surface, but they were not pulled out, which suggested a good bonding between the fibers and the matrix, as shown in Fig. 12(a) by an ellipse. The worn surfaces were very smooth and flat, which was due to the polishing of the surfaces.

It was also found that wear of the pin against Saffil/SiC/Al was serious than that of the pins against Saffil/Al and Saffil/Al_2O_3/Al. The grooves in Fig. 13(e),(f) were deeper and wider than Fig. 13(a),(b) and (c),(d). It was the high strength of Saffil/SiC/Al and the hard SiC particles that caused the serious wear of the pin. This fact was also obvious from the wear depth data as shown in Fig. 8, which was mainly caused by the wear of the pin. There was little difference between the worn surfaces of the pins under room temperature and 100°C, which suggested that the dominant wear mechanism remained unchanged at 100°C.

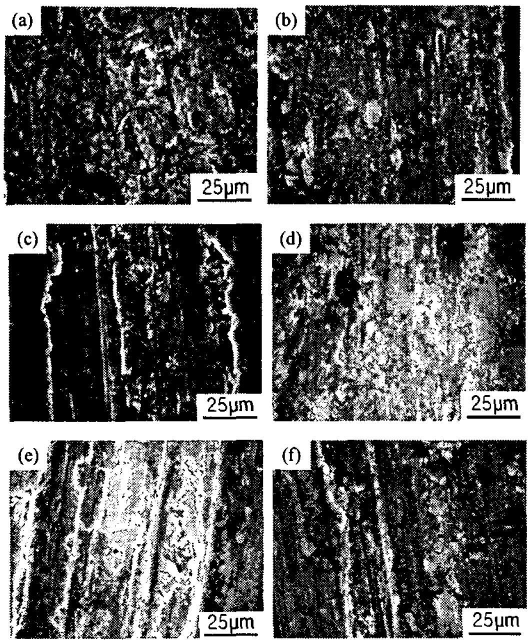

Fig. 12 SEM graphs of the worn surfaces of Saffil/Al (a),(b), Saffil/Al_2O_3/Al (c),(d) and Saffil/SiC/Al (e),(f), (a),(c),(e) for room temperature and (b),(d),(f) for 100°C.

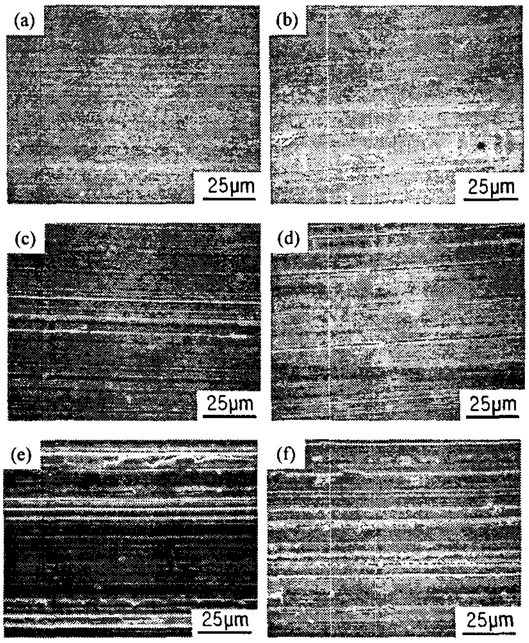

Fig. 13 SEM graphs of the pins' surfaces against Saffil/Al (a),(b), Saffil/Al_2O_3/Al (c),(d) and Saffil/SiC/Al (e),(f), (a),(c),(e) for room temperature and (b),(d),(f) for 100°C.

3.4 COF Characteristics

The COF was generally determined by the following equation:

$$\mu = \frac{\tau_c \cdot A}{F_N} \qquad (2)$$

where τ_c was the critical shear strength of the material,A was the contacting area and F_N was the normal load. COF increased with increasing critical shear strength. Critical shear strength decreased with increasing temperature, so the COF of room temperature should be bigger than that of high temperature if the dominant wear mechanism did not change.

The COF characteristics under dry sliding at load of 1kg and various temperatures were shown in Fig. 14. The fluctuations of COF became serious after 150°C,which was due to the occurrence of adhesion. The COF variation of Saffil/SiC/Al was the most serious. There were some sharp changes of COF, as shown in Fig. 14(c). This was due to the suddenly broken off of some adhesive bonds.

Table 3 shows the average COFs in Fig. 14. It was obvious Saffil/SiC/Al had the maximum COF. The COF increased with increasing temperature on the whole, but it was also found that the COFs of Saffil/Al2O3/Al and Saffil/SiC/Al under 100°C were smaller than that under room temperature. This was due to the difference of dominant wear mechanism. The bigger COF was easily to cause bigger weight loss, as shown in Fig. 4, the weight loss under room temperature was bigger that under 100°C.

Table 4 shows the average COF under lubricated condition. It was obvious that the COF under 100°C was smaller than that under room temperature for each material. This was due to the decrease of critical shear strength as temperature increased.

Table 3 Comparison of COFs under dry sliding condition

Material	R.T.	100°C	150°C	200°C
Saffil/Al	0.25	0.30	0.35	0.40
Saffil/Al_2O_3/Al	0.28	0.25	0.40	0.45
Saffil/SiC/Al	0.35	0.33	0.45	0.50

Table 4 Comparison of COFs under lubricated condition

Material	R.T	100°C
Saffil/Al	0.15	0.12
Saffil/Al_2O_3/Al	0.16	0.14
Saffil/SiC/Al	0.17	0.15

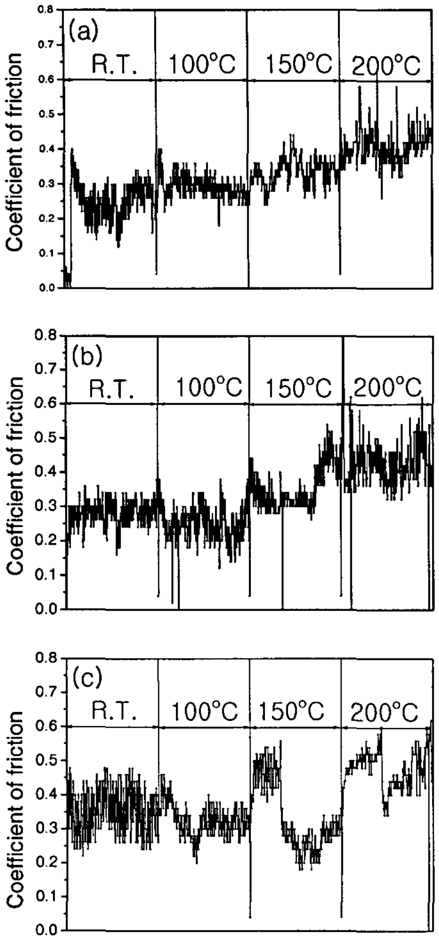

Fig. 14 COF characteristics of dry sliding of Saffil/Al (a), Saffil/ Al_2O_3/Al (b) and Saffil/SiC/Al (c) under load of 1kg and various temperatures.

According to Eq. (2), the COF was proportional to the critical shear strength. Saffil/Al had the minimum COF, while Saffil/SiC/Al had the maximum COF among the three materials. This was also due to the difference of critical shear strength.

The COF characteristics under room temperature and 100°C were different. Fig. 15 shows the COF characteristics of Saffil/SiC/Al. It was obvious that COF fluctuated greatly at the initial stage, and tended to reach some constant value as sliding distance increased.

The wear in the initial stage was very serious, which could also be found from the weight loss data in Fig. 6. The COF characteristics of Saffil/Al and Saffil/Al_2O_3/Al were similar to those of Saffil/SiC/Al, i.e., the COF in the initial stages were

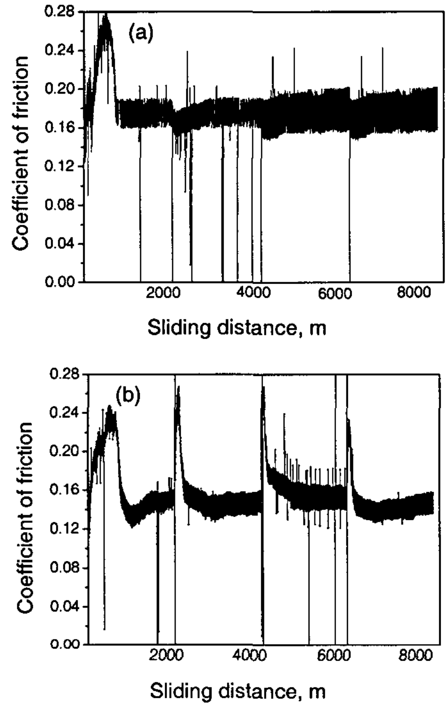

Fig. 15 COF characteristics of Saffil/SiC/Al at room temperature (a) and 100°C (b).

very serious and tended to reach some constant value as sliding distance increased. But the COFs of Saffil/Al and Saffil/Al_2O_3/Al at the initial stages were not so big. It was because the materials were relatively soft and the reinforcements could not resist the plastic deformation on the surfaces. The COF of variation of Saffil/SiC/Al was the biggest. This was due to its greater strength, rendering the composite more difficult to deform. The seriously variations at the initial stages were mainly due to the contacting and lubricating conditions. The three materials responded differently to these conditions.

The COF characteristics under room temperature and 100°C were a little different. Fig. 15(b) shows the COF characteristics of Saffil/SiC/Al under 100°C. Fig. 15(b) was different from Fig. 15(a) that the COF varied greatly at the early stage of each increment, while in Fig. 15(a), the COF only varied greatly at the first increment. This was because the materials became ductile at high temperature, and the misfitting of the remounted specimen would cause serious wear of the specimen. On the other hand, the viscosity of the lubricant decreased as the temperature increased, which resulted in the decreasing of the thickness of the lubrication film, so the real contacting area increased, and the load carried by the lubricant decreased, which would also cause the serious direct contacting of the metals and therefore cause the increasing of COF. But the COF would decrease as contacting conditions improved.

4. Conclusions

The wear behaviors of Saffil/Al, Saffil/Al_2O_3/Al and Saffil/SiC/Al hybrid MMCs were investigated under both dry and lubricated conditions. The following conclusions were drawn.

Under dry sliding condition, Saffil/SiC/Al showed the best wear resistance under high temperature and high load, while the wear resistances of Saffil/Al and Saffil/Al_2O_3/Al were very similar. Under dry sliding condition, the dominant wear mechanism was abrasive wear under mild load and room temperature, and the dominant wear mechanism changed to adhesive wear as load or temperature increased. Molten wear occurred at high temperature. Saffil/Al shows the best wear resistance under lubricated sliding. Under lubricated condition, the wear resistance of Saffil/Al_2O_3/Al is better than that of Saffil/SiC/Al under room temperature, but under high temperature, Saffil/SiC/Al shows better wear resistance.

The dominant wear mechanism of these composites under lubricated sliding is microploughing, but microcracking also occurs to them to different extents, and the worn surface of Saffil/Al has the fewest cracks. Saffil/Al has the minimum COF under long sliding distance. Particles, especially hard particles, are detrimental to the wear resistance of aluminum MMCs under lubricated sliding.

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