論文

온도 상승에 따른 혼합금속복합재료의 건식 마찰특성 평가

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Evaluation of Dry Tribological Characteristics of Hybrid Metal Matrix Composites with Temperature Rising

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ABSTRACT

Al_2O_3 fiber and SiC particle hybrid metal matrix composites (MMCs) were manufactured by squeeze casting method investigated for their tribological properties. The pin specimens had different ratios of fiber to particle content but their total weight fraction was constant at 20 wt. %. Tribological tests were performed with a pin-on-disk friction and wear tester. The investigation of the dry tribological characteristics of hybrid MMCs were carried out at room temperature and elevated temperature of 100 °C and 150 °C. The morphologies of worn surfaces were examined by scanning electron microscope (SEM) to observe tribological characteristics and investigate wear behavior. The results revealed that the wear resistance improved with the content of SiCp increased of the planar random (PR) MMCs at room temperature. At the elevated temperature, it revealed that the wear resistance of normal (N) MMCs was superior to that of the PR-MMCs due to PR-fibers were easily pulled out holistically from the worn surface. Meanwhile, the coefficient of friction decreased with the temperature increasing.

초 록

가압주조법으로 제조된 알루미나 섬유와 SiC 입자 혼합금속복합재료의 마찰특성을 조사하였다. 핀 형태의 마모 시험편은 전체 부피비 20%에 섬유와 입자의 서로 다른 비를 갖고 있다. 혼합금속복합재료의 윤활마모시험은 핀과 디스크 타입의 마모 시험기를 사용하여 수행되었는데, 상온과 고온 100 °C와 150 °C.에서의 건식마찰특성을 각각 수행하였다. 마모면의 미시분석은 주사전자현미경(SEM)으로 조사하여 마찰특성과 마모거동을 분석하였다. 시험 결과 마모저항은 상온에서는 섬유와 같은 방향인 (PR) 방향에서는 SiC입자의 증가에 따라 향상되었다. 고온에서는 섬유와 수직한 방향(N)의 마모특성은 PR방향의 섬유가 마모면으로 전체적으로 쉽게 뽑히기 때문에 PR방향의 금속보합재료의 마모특성보다 우수하였다. 한편 마찰계수는 온도 증가에 따라 감소하였다.

Key Words : 마찰(Tribology), 금속복합재료(Metal matrix composites), 섬유방향(Fiber orientation), 마모저항(Wear resistance, 마모기구(Wear mechanism)

1. Introduction

During the past several decades, metal matrix composites (MMCs) have attracted lots of attentions due to the excellent physical and mechanical properties, such as lightweight, high strength, and specific stiffness and so on [1-2]. Especially,

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the MMCs play an important role of wear resistant material. The wear properties of MMCs are improved in comparison with conventional monolithic alloys when reinforcing materials are incorporated into metal matrices. Many researchers have focused on the contributions of the MMCs for the tribological applications. The effects of adding harder particles and fibers to reinforce MMCs on their wear behavior are also investigated. Some researchers found that the wear loss was remarkably reduced after hard particles (SiC) [3-9], fibers (Al_2O_3) [10-12], or whiskers ($K_2Ti_4O_9$) [13]were added. Having the superior mechanical properties, these composites can be used in high speed rotating and reciprocating elements such as pistons, connecting rods, drive shafts, brake rotors, and cylinder bores [1].

As for the single reinforced MMCs, Sahin [3] reported that the wear resistance of MMCs with normal (N) orientation of fibers was higher than that with planar random (PR) orientation of fibers in the case of single alumina fibers reinforced aluminium-zinc-copper alloy composites for the dry sliding wear. Kato [4] reportedthe effects of size (5 μm, 15 μm, 120 μm, and 200 μm) of SiC particles on wear of Ni matrix (ductile matrix). He found that the wear resistance was improved with the sizes of the particles increased from15 μm to 200 μm, but the wear resistance was reduced in case of 5 μm particle size and effects of the volume fraction of about 10 % SiC particles reduced the matrix wear by a half.

The hybrid reinforced aluminium MMCs were also investigated. Fu *et al.* [14] showed that Saffil/SiC/Al hybrid MMCs presented the best wear properties in comparison with Saffil/Al, Saffil/Al_2O_3/Al, and Saffil/SiC/Al hybrid MMCs under dry sliding wear condition. The wear properties of Saffil/Al MMCs were the best among them when lubricated by liquid paraffin. Du *et al.* [15] reported that with the increase of the volume percentage of the reinforcement with a 1:1 constant hybrid ratio, the wear value of the composites decreased. And for an equal volume fraction of the reinforcement phase, wear-resisting property of 7A04-matrix composites was better than that of 2A14-matrix composites.

Although various aspects of wear behavior of hybrid MMCs have been investigated. The detailed effects of reinforcement types, reinforcement volume fraction, hybrid ratio, and different matrices on wear have been examined. However, the effects of fiber orientation and fibers to particles hybrid ratio on wear behavior of these composites have not been so far considered systematically. Therefore, the present study focuses on the investigation of an elevated temperature dry and lubricant sliding wear behavior of Al_2O_{3f}/SiC_p/Al hybrid aluminum alloy MMCs fabricated by squeeze casting method. The effects of fiber orientation and fibers to particles hybrid ratio on the wear behavior are discussed in details. In addition, the scanning electronic microscope (SEM) images of the wear surfaces and debris are examined in order to understand the modes of wear.

2. Experimental

2.1 Specimen preparation

Common materials are selected to prepare the MMC specimens. The cast aluminum alloy, A356 Al-Si, is used as matrix and Alumina fibers (Al_2O_{3f}) and silicon carbide particles (SiC_p) are used as the reinforcing materials. The mechanical and physical properties of the reinforcing materials are shown in Table 1. Table 2 shows three different categories of preforms prepared by vacuum extraction method along with their hybrid ratios. For each category, the total volume fractions of the reinforcing materials were kept constant at 20 %. The hybrid ratio of Al_2O_{3f} volume fraction to SiC_p volume fraction is denoted by $F_{n_1}P_{n_2}$, where F and P indicate fiber and particle, respectively while n_1 and n_2 denote the percentage quantity of fibers and particles, respectively. For hybrid MMCs, if 13 vol. % of Al_2O_{3f} and 7 vol. % of SiC_p are used as the reinforcements, their hybrid ratio is denoted by F13P7 (n_1= 13, n_2= 7). After the ingots produced by the preforms using squeeze casting method, T6 heat treatment was performed to improve the mechanical properties of them.

Table 1 Mechanical and physical properties of Al_2O_{3f} and SiC_p

Material	Density [g/cm^3]	Diameter [μm]	Length [μm]	Modulus [GPa]	Hv
Al_2O_{3f}	3.3	3.0	150	310	2000
SiC_p	3.2	30	-	410	2800

Table 2 Hybrid ratio of preforms

Preform	Vol.%			Hybrid ratio
	Total	Al_2O_{3f}	SiC_p	
F20P0	20	20	0	Fiber only
F13P7		13	7	2 : 1
F7P13		7	13	1 : 2

Pin specimens with two different orientations of fibers, PR-orientation and N-orientation, were prepared from each category of MMC ingot. As shown in Fig. 1, specimens with PR-orientation of fibers are obtained when they are cut in such a way that the fibers are aligned parallel to the sliding surface of the specimen. On the other hand, specimens with normal orientation of fibers have fibers aligned in perpendicular direction to the sliding surface of the specimen. The length and diameter of pin specimens were 15 mm and 5 mm, respectively. The steel counter disk of the pin-on-disk friction and wear tester was made of 42CrMo4 and machined to 7 mm height and 30 mm diameter. The surfaces of pin specimen and disks were polished with 800-grit sandpaper and washed by acetone. Then, they were used in the wear testing experiment. The weight loss of the pin specimens and disk due to sliding wear was measured by a precision electronic balance having an accuracy of 0.01 mg. The results were expressed in terms of wear rate (mm^3/N m).

Figure 2 shows the specimen's optical micrographs for two different orientations, planar-random (PR) and normal (N) with a hybrid ratio of 13% fibers and 7% particles. In Fig. 2 (a), we can easily observe the fiber and their planar-random orientation. In Fig. 2 (b), the presence of black spots instead of long marks ensures that the specimen has the N-orientation of fibers. From the polished surface, pores cannot be found. It means that the density of each kind of MMCs is close to the theoretical density. The area ratios of fiber-to-matrix and particle-to-matrix of each category of MMCs are analyzed by Image-Pro Plus 6.0 are shown in table 3.

Table 3 Area ratio and hardness of each category of MMCs

Orientation	Hybrid ratio	Area ratio (%)		Hv
		Fiber-to-matrix	Particle-to-matrix	
PR	F20P0	6.06	-	129.2
	F13P7	5.54	3.34	143.2
	F7P13	3.20	12.71	149.8
N	F20P0	4.92	-	124.8
	F13P7	4.22	5.26	141.8
	F7P13	3.05	15.11	146.7

2.2 Procedure of experiment

The wear tests were performed by using a pin-on-disk friction and wear tester as shown in Fig. 3. In the working space, the pin specimen was held tightly by the rotor against this fixed steel counter disk with the help of an applied load. The steel counter disk was rotated at a constant speed of 570 rpm which was equivalent to the linear speed of 0.36 m/s at the center line of wear track of the pin specimen. For the dry sliding wear test at room temperature, a series of contact loads of 30 N, 50 N, and 80 N were considered while the test was run for a total sliding distance of 2500 m. For comparison, while temperature increased the dry sliding wear tests were carried out under the contact load of 30 N only for the same sliding distance of 2500 m.

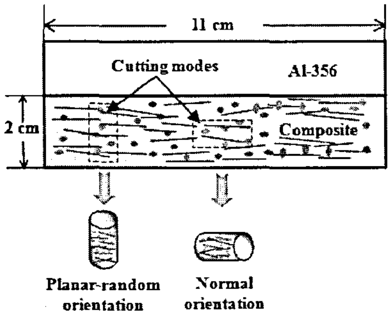

Fig. 1 Schematic of cross section of MMC.

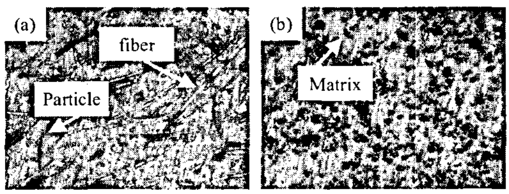

Fig. 2 Optical Microstructures of F13P7 (a) PR- and (b) N-orientation MMCs.

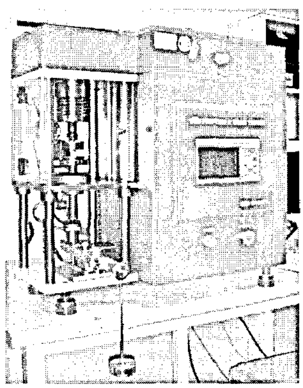

Fig. 3 Pin-on-disk friction and wear tester.

3. Results and discussion

3.1 Dry sliding wear behavior at room temperature

Figure 4 displays the weight loss as a function of hybrid ratio and applied load for PR- and N-orientations of fibers. It is observed that the wear resistance of F20P0 unhybrid MMCs with N-orientation of fibers is better than that of F20P0 unhybrid MMCs with PR-orientation of fibers. The same phenomenon was observed by Sahin [3] in an investigation of MMCs reinforced with fibers only (unhybrid MMCs). However, for PR-orientation of fibers, the wear resistance monotonically increases, *i.e.*, the weight loss monotonically decreases, with the addition of SiC_P for the same applied load as seen from Fig. 4 (a). On the other hand, for N-orientation of fibers, the wear resistance was initially degraded by adding fewer amounts of SiC_P which was later improving by further addition of the particles as seen in Fig. 4 (b). However, for both the orientations of fibers, it is observed that the weight loss of MMCs due to wear increases with the increase of the applied load.

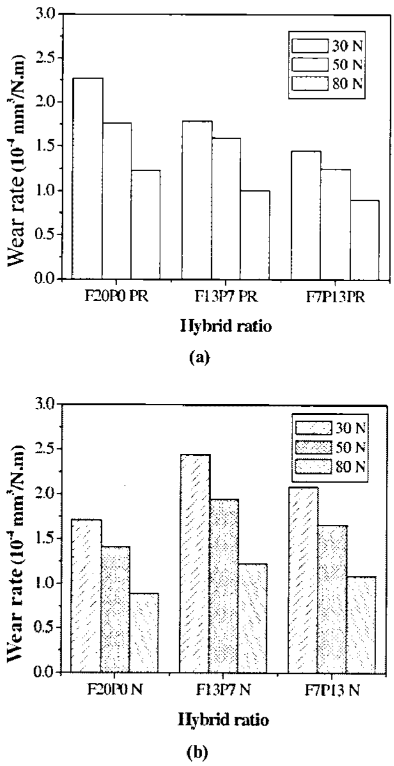

Fig. 4 Effects of hybrid ratio and load on dry sliding wear: (a) PR-orientation of fibers, (b) N-orientation of fibers.

To understand the wear mechanisms, the worn surfaces of the specimens corresponding to the 30 N applied load were investigated by SEM. The SEM images of worn surfaces of specimens with different hybrid ratios and fiber orientations are shown in Fig. 5. Figures 5 (a) and (b) show the worn surfaces of specimens of F20P0 MMCs with PR- and N-orientations of fibers, respectively. It is observed that the worn surface of the specimen with PR-orientation of fibers has more fragmentations in the worn surface than that with N-orientation of fibers. This is due to the fact that the whole fibers were spalled out from the surface of the specimen with PR-orientation of fibers which causes the fragmentations in the worn surface and causes more weight loss. For N-orientation of fibers, the whole fibers were not pulled out. Rather, only ends of the fibers were worn out causing less weight loss and a relatively smoother surface in which the phenomenon of surface fatigue can be observed easily.

Figures 5 (c) and (d) show the worn surfaces of F13P7 hybrid MMC specimens with PR- and N-orientations of fibers, respectively. The comparison of Fig. 5 (a) with Fig. 5 (c) shows that the F13P7 hybrid MMC specimens have fewer spalling of fibers than that of the F20P0 unhybrid MMC specimens. This is due to the obvious fact that the F13P7 hybrid MMC specimens contain fewer fibers than F20P0 unhybrid MMC specimens as the total volume of reinforcing materials is constant (20%). So, it is more likely that only fewer fibers spall out from the F13P7 MMC specimens with less fiber content. On the other hand, for N-orientation of fibers, the whole longitudinal surfaces of all the fibers are firmly gripped by the matrix and only the ends of the fibers come in contact with the sliding surface during wear. So, the fibers do not spall out, rather they wear out due to abrasion. When silicon carbide particles (SiC_P) are added to MMCs with N-orientation of fibers, they replace some firmly gripped fibers. It is obvious that the silicon carbide particles (SiC_P) at the contact surface are not as firmly gripped as fibers. Therefore, these particles are more likely to spall out during wear. As a result, the surface of F13P7 MMC specimen with N-orientation of fibers shows more fragmentations (Fig. 5 (d)) than that of F20P0 MMC specimen (Fig. 5 (b)). This conforms to the results shown in Fig. 4 (b) which shows that the F13P7 MMC specimen has more weight loss than that of F20P0 MMC specimen due to wear.

Figures 5 (e) and (f) show the worn surfaces of F7P13 hybrid composite specimens with PR- and N-orientations of fibers, respectively. For PR-orientation of fibers, the further smoother surface was obtained by adding more SiCp as seen

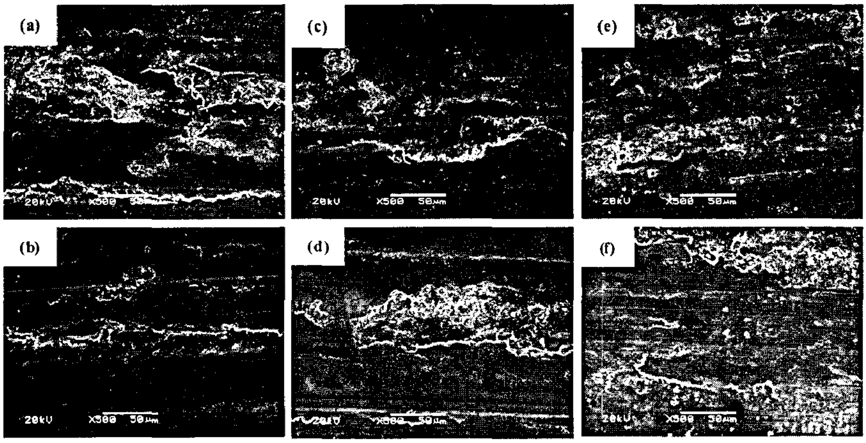

Fig. 5 SEM images of worn surfaces of MMC specimens with PR- and N-orientations of fibers: (a) F20P0 PR, (b) F20P0 N, (c) F13P7 PR, (d) F13P7 N, (e) F7P13 PR, and (f) F7P13 N for dry sliding wear at room temperature.

from the comparison of Figs. 5 (a) and (e). For N-orientation of fibers, the further addition of SiCp caused less number of fragmentations than previous F13P7 specimen as seen from the comparison of Figs. 5 (d) and (f).

3.2 Dry sliding wear behavior at elevated temperature of 100 °C and 150 °C

Figures 6 illustrated that effect of hybrid ratio on wear rate of MMCs with PR- and N-orientation of fibers for dry sliding wear at 100 °C and 150 °C. The wear resistance monotonically decreased by adding the SiC_p for both PR- and N-MMCs. It was easy to find that the wear resistance of N-MMC was superior to that of PR-MMC for each hybrid ratio.

For F20P0 MMCs with PR-orientation of fibers, although the fibers were easily pulled out holistically from the matrix due to the different orientations of the reinforced fibers and caused higher weight loss in the case of dry sliding wear. It was the main reason that weight loss of PR-MMC was high. Nevertheless, elevating the temperature to 100 °C, the counter disk became ductile, so the tribological behavior of the reinforcements played an important role on that of the composites.

The reasonable explanation for the experimentresults can be concluded as the interactions of the hardness of reinforcements and the elevated temperature.

For the physical properties of the fiber and particle reinforcements, they were harder than the matrix sothat they could bear the load and attained the expected purpose of improving wear behavior. However, for the hybrid MMCs, the weight loss increased with particle content added. It could be considered that the effect of particle to increase hardness cannot offset the influence of elevated temperature on the tribology of our tested specimens. In other words, compared with the single fiber reinforced MMCs, the wear resistance of the hybrid MMCs declined while the composites were tested at the elevated temperature.

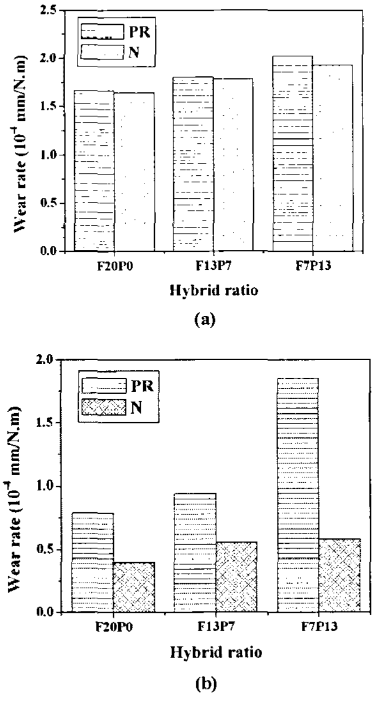

Fig. 6 Effects of hybrid ratio and hybrid ratio on dry sliding wear at elevated temperature of (a) 100 °C and (b) 150 °C.

From the T6 treatment, we found that the elevated temperature of 150 °C was in the range of aging treatment temperature. During the solution treatment, the second phase solid solved in the matrix, and then in the state of aging treatment, the A356 Al-Si alloys were strengthened by precipitation of Mg_2Si. Therefore, the hardness was increased to resist the weight loss. This was the reasonable explanation for the weight loss of dry sliding wear at the elevated temperature of 100 °C was more than that of dry sliding wear at the elevated temperature of 150 °C. However, when it reached to a balanceable level in a certain time, the grains of Mg_2Si precipitation grew and coarsened gradually which caused the hardness decreased.

3.3 Coefficient of Friction

Figure 7 shows the variation of the friction coefficients of the sliding pairs at a sliding speed of 0.36 ms^{-1} with applied loads of 3, 5, and 8 kgf, respectively, at room temperature. It is found that the friction coefficients of the sliding pair are almost invariable with change of fiber orientations under the same applied load. And the friction coefficient has a slight growth trend with increase of SiC_P content. However, it is noted that the friction coefficient is increasing with the applied load decreased which is consistent with the following equation (1):

$$\mu = \frac{\tau_c A}{F_N} \tag{1}$$

where μ is the friction coefficient, τ_c is the shearing stress, A is the contact area, and F_N is the applied load

Furthermore, while temperature increases the coefficient of friction decreases under same load applied as shown in Fig. 8.

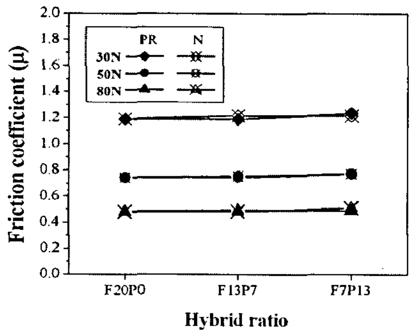

Fig. 7 Variation friction coefficients of the composites for the dry sliding wear at room temperature.

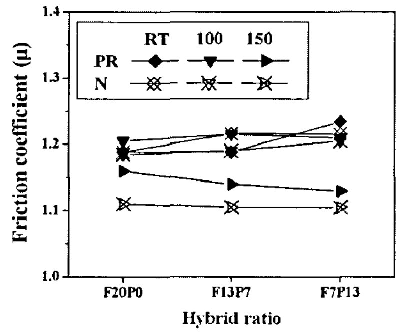

Fig. 8 Variation friction coefficients of the composites for the dry sliding wear under load of 30 N at room temperature, 100 °C, and 150 °C.

3.4 Wear mechanism

Therefore, the wear mechanisms of dry sliding wear of F20P0 unhybrid PR-MMCs could be inferred that although the fibers were not totally consumed away by wear, the fibers were pulled out holistically from the matrix due to the adhesive wear that produced coarsegrooves on the wornsurface and consequently caused higher weight. On the other hand, only the ends of the fibers in F20P0 unhybrid N-MMC were worn out that caused little weight loss. The weight loss of these types of specimens was principally caused by the abrasive wear.

The wear mechanism of hybrid MMCs with PR-orientation of fibers could be concluded that the addition of harder SiC_P reduced the volume of fibers that were prone to spall out. This increased the hardness of pin specimens which, in turn, improved the wear resistance. In the case of N-orientation, fibers were firmly gripped over the whole length by the matrix and did not spall out. However, addition of SiC_P reduced the volume of firmly gripped fibers and provided with the surface with relatively loosely gripped SiC_P. Thus, with the addition of few SiC_P, more debris was produced during wear which contributed to the abrasive wear behavior substantially. Therefore, the wear resistance of hybrid MMCs containing fewer SiC_P was found to be lower than that of unhybrid MMCs with N-orientation of fibers. The further addition of particles improved the hardness significantly which played the main role in reducing the weight loss and consequently improved the wear resistance. That meant the wear resistance was improved only after adding enough SiC_P in case of hybrid MMC with N-orientation of fibers.

Furthermore, elevating the temperature to 100 °C and 150 °C, matrix material became softer compared with when it was under room temperature. Thus, even the content of harder reinforcements (SiC_P) added, the wear resistance could not be improved. As shown in Fig. 6, the wear rate is increasing with increasing SiC_p content.

4. Conclusion

The hybrid MMCs were tested for dry wear behaviors by pin-on-disk friction and wear tester at room temperature and elevated temperature of 100 °C and 150 °C with PR- and N-orientations of the fiber and three kinds of hybrid ratios. Through the above analysis and comparisons with the results of test, the following can be summarized:

1) Compared with N-MMCs, the fibers of PR-orientation were easily pulled out holistically from the matrix that caused higher weight loss of PR-MMC than N-MMC. The main wear mechanism of PR-MMCs was adhesive wear. The weight loss of N-MMCs was caused by abrasive wear.
2) Wear resistance decreased with SiCp content increasing at elevated temperature of 100 °C and 150 °C.
3) The coefficient of friction decreased with load increasing. When the temperature increased, the coefficient of friction also decreased.

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