論文

Al_2O_{3f}/SiC_p 금속복합재료의 섬유방향과 혼합비가 윤활마모특성에 미치는 영향

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Effects of Fiber Orientations and Hybrid Ratios on Lubricant Tribological Characteristics of Al_2O_{3f}/SiC_p Reinforced MMCs

Yi-Qi Wang* and Jung-Il Song*+

ABSTRACT

The lubricant tribological characteristics of Al_2O_3 fiber and SiC particle hybrid metal matrix composites (MMCs) fabricated by squeeze casting method was investigated using a pin-on-disk wear tester. The wear tests of the MMCs were performed according to fiber/particle hybrid ratio in the planar-random (PR) and normal (N) orientations sliding against a counter steel disk at a fixed speed and 25 kg_f loading under different sliding distances and temperatures. The test results showed that the wear behavior of MMCs varied with fiber orientation and hybrid ratio. At room temperature, the lubricant wear behavior of F20P0 unhybrid PR-MMCs was superior to that of N-MMCs while the hybrid composites exhibited the reverse lubricant wear behavior. It was also revealed that the wear resistance of PR-MMCs was superior to that of the N-MMCs due to the joint action of reinforcements and lubricant film between the friction surfaces at an elevated temperature of 100 °C for both fiber only and hybrid cases. In case of 150 °C, although the trend of weight loss was similar to that of others, the wear resistance of PR-MMCs was better than that of N-MMCs for hybrid MMCs.

초 록

가압주조법으로 제조한 Al_2O_3 섬유와 SiC 입자 혼합 보강 금속복합재료(MMCs)의 상온과 고온에서 윤활마모특성을 조사하였다. 마모시험은 거리와 온도의 변화에 따라 속도를 고정시켜 25Kgf의 하중하에서 수행하였으며 MMCs의 시험편은 가압의 수평(PR)방향과 수직(N)방향에서 채취하였다. 혼합비의 영향을 관찰한 결과 상온에서는 20%섬유만 보강한 PR방향 MMCs의 마모거동은 N방향 보다 우수한 결과를 보였으나, 혼합보강 MMCs는 반대로 나타내었다. 고온(100°C)에는 모든 MMCs에서 PR방향의 마모거동이 N 방향보다 우수한 결과를 보인 것은 보강재와 마찰면간 윤활필름이 상호작용에 기인한 것으로 밝혀졌다. 150°C에서는 혼합 MMCs의 마모거동은 온도영향으로 PR이 N 보다 우수한 결과를 보였다.

Key Words : 윤활마찰(Lubricant Tribology), 혼합금속복합재료(Hybrid Metal Matrix Composites), 가압주조법(Squeeze Casting Method) 섬유/입자방향(Fiber/Particle Orientation), 마모기구(Wear Mechanism)

1. 서 론

In the recent decades, aluminum metal matrix composites

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(MMCs) have received wide attention in the field of tribology [1-4], where these composites are used in high speed rotating and reciprocating elements such as pistons, connecting rods, drive shafts, brake rotors, and cylinder bores. In comparison with the corresponding monolithic alloys, aluminum MMCs exhibit superior performance in wear resistance among other mechanical properties [5-7]. So far, a series of papers have been published on wear behaviors of aluminum MMCs [8-13]. The effects of adding harder particles to fiber reinforced aluminum MMCs on their wear behaviors are also investigated in some of the studies mentioned above. In those studies, it was found that the fiber/particle hybrid MMCs had better wear resistance than MMCs reinforced with fibers only. Although various aspects of wear behaviors of hybrid MMCs had been investigated in details, it was found that the effects of fiber orientation and fiber to particle hybrid ratio on wear behaviors of these composites had not been so far investigated systematically. Therefore, the present study focuses on the investigation of lubricant sliding wear behaviors of alumina fibers (Al_2O_{3f}) and silicon carbide particles (SiC_p) hybrid reinforced aluminum alloy MMCs fabricated by squeeze casting method at room temperature, elevated temperatures of 100 °C and 150 °C. The effects of fiber orientation and fiber to particle hybrid ratio on the wear behaviors are discussed in details. Further, the SEM images of the wear surface are examined in order to understand the wear mechanisms.

2. Experimental procedures

2.1 Preparation of MMCs specimen

The MMC specimens were prepared by using the cast aluminum alloy, A356 Al-Si, as matrix and alumina fibers, Al_2O_{3f}, and silicon carbide particles, SiC_p, as reinforcing materials. The mechanical and physical properties the reinforcing materials are shown in Table 1. In hybrid MMCs, both the reinforcing materials Al_2O_{3f} and SiC_p are used and their ratio is denoted by Fn_1Pn_2, where F and P designate fiber and particle, respectively, and n_1 and n_2 denote the percentage quantity of fibers and particles, respectively. For an unhybrid MMC specimen, only fibers are used and the hybrid ratio is denoted by Fn_1P0 ($n_2 = 0$).

The preforms of MMC specimen were prepared by vacuum extraction method, which were next used for producing the ingots by squeeze casting method. The ingots were passed through T6 heat treatment process where they were heated for 4 hours at 540 °C followed by water quenching. Later, they were artificially aged by heating at 155 °C for 4 hours followed by air cooling. Three different categories of ingot were prepared for the experiment as shown in Table 2. For each category, the total volume fractions of the reinforcing materials were kept constant at 20 %.

The pin specimens were machined in two cutting modes so that they appeared planar-random (PR) and normal-random (N) orientations of the fibers as shown in Fig. 1. The length and diameter of pin specimens were 15 mm and 5 mm, respectively. Steel counter disk was made of SCM440 and machined as 7 mm height and 30 mm diameter size. The surfaces of pins and disks were polished by sand paper of the standard 800 and washed by acetone. And the average surface roughness values of pin and disk surfaces were measured as 0.20 and 0.13, respectively. Then, they were used in the wear testing experiment. The weight loss of the pins due to sliding was recorded by a precision electronic balance having an accuracy of 0.01 mg.

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. Form the polished surface, pores cannot be found. It means that the density of each kind of MMCs is close to the theoretical density.

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

Material	Density [g/cm^3]	Diameter [μm]	Length [μm]	Modulus [GPa]	Hardness [kg/mm^2]
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

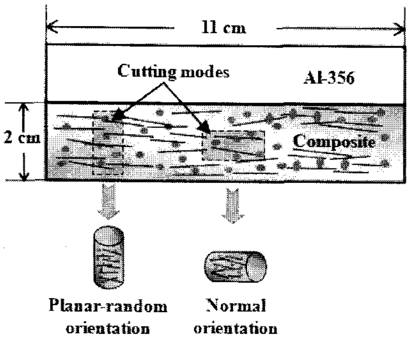


Fig. 1 Schematic of cross section of MMC.

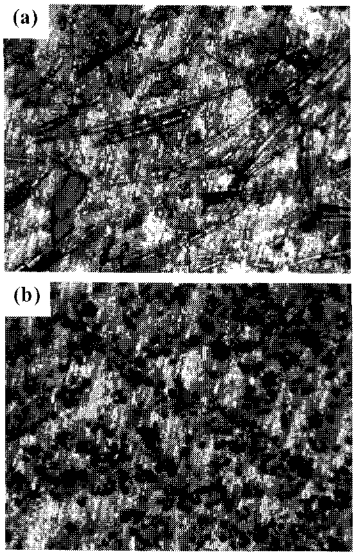


Fig. 2 Optical Microstructures of F13P7 (a) PR- and (b) N-orientation MMCs.

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

2.2 Lubricant sliding wear test

Figure 3 shows the pin-on-disk friction and wear tester. The pin specimen was held tightly by the rotor against this fixed steel counter disk with the help of an applied load. In the case of the lubricant sliding wear test, the surface of the steel counter disk was lubricated with engine oil stored by oil chamber. At the elevated temperature, the heater having both heating and storing functions was applied instead of the oil chamber. 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 of the pin specimen. The lubricant sliding wear tests were carried out under the contact load of 25 kgf only. Moreover, the tests were performed for three different sliding distances of 2500 m, 5000 m, and 7500 m with the same contact load of 25 kgf.

3. Results and discussion

3.1 Microhardness of MMCs specimen

As the contents of the reinforcements changed in the hybrid MMCs, the microhardness of these composites varied. The microhardness of the matrixes at each 5 different places was measured by VLPAK2000 Mitutoyo Hardness Test Machine using 0.1 N loading energy in 30 seconds dwell time, and then the average microhardness was calculated. Figure 4 shows the microhardness of the matrix in composites with different orientations at different hybrid ratio. It is found that fiber orientation has less influence on the microhardness. There is small difference between the MMCs having same hybrid ratio and different fiber orientations. However, the value of microhardness decreases to half when the volume fraction of SiCp increases to 13 %, *i.e.*, the case of F7P13.

3.2 Lubricant sliding wear behavior at room temperature

For the lubricant sliding wear, the liquid lubricating film formed between the surfaces of pin specimen and steel counter disk retards wearing behavior through improving status of the friction surfaces. It reduced the shear stress on the friction surfaces during the lubricant sliding wear. Therefore, due to the contribution of the lubricant film, fibers could not be pulled out, or particles also could not spall off from the

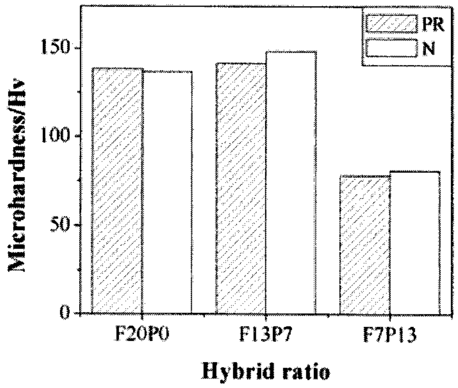
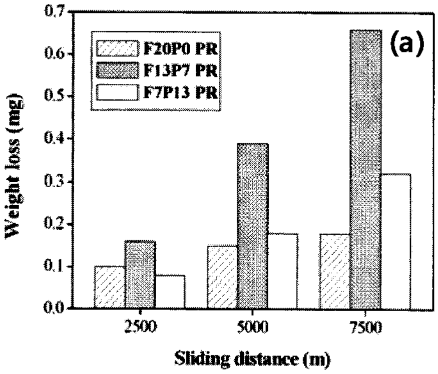


Fig. 4 Microhardness of the MMCs at different hybrid ratio.



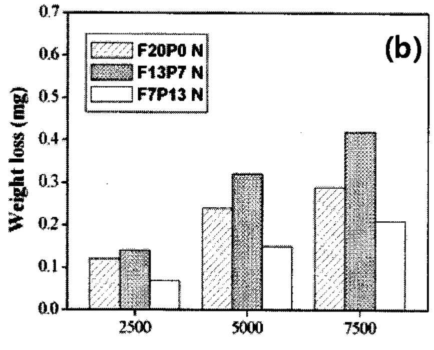


Fig. 5 Effects of hybrid ratio and sliding distance on lubricant wear: (a) PR-orientation of fibers, (b) N-orientation of fibers for lubricant sliding wear at the room temperature.

matrix. Figure 5 shows the weight loss comparison of MMC specimens with PR- and N-orientations of fibers as a function of hybrid ratio and sliding distance. The results correspond to the applied load of 25 kgf. It is observed that the wear resistance of F20P0 (unhybrid) MMC specimen with N-orientation of fibers is worse than that with PR-orientation of fibers. The lying fibers on the worn surfaces of the PR-MMCs can support the worn surfaces to reduce weight loss. However, for the case of hybrid MMCs, the wear resistance is better for normal orientation of fibers than that for PR-orientation of fibers. For both the PR- and N-orientation of fibers, the weight loss initially increases with the addition of fewer SiC_p as seen from the comparison of F20P0 unhybrid and F13P7 hybrid MMC specimens as shown in Figs. 5 (a) and (b), respectively. The possible reason is that few particles was added which would produce harder abrasive debris to increase the weight loss. The further addition of SiC_p (F7P13) improves the wear resistance, *i.e.*, the weight loss decreases for both the PR- and N-orientation of fibers. Particularly for N-orientation of fibers, the weight loss of F7P13 hybrid specimen is even lower than that of F20P0 unhybrid specimen. Further, it is noted that the weight loss increases with the increase of sliding distance which agrees with the intuitively predicted results.

Figure 6 displays the SEM images of the worn surfaces of MMC specimens after lubricant wear at room temperature. The comparison between Figs. 6(a) and (b) reveals that the worn surface of unhybrid MMC specimen with N-orientation of fibers has more plastic deformation zones than that with PR-orientation of fibers. This tells that the lubricant wear resistance of unhybrid MMCs with PR-orientation of fibers is better than that with N-orientation of fibers.

Figures 6 (c) and (d) represent the worn surfaces of F13P7 hybrid MMC specimens with the addition of 7 % SiC_p. The granulation phenomenawere observed in the worn surfaces of the F13P7 hybrid MMC specimens with both the PR- and N-orientations of fibers. From the comparison between Figs. 6(a) and (c), we observed that more fibers of F13P7 hybrid composites were damaged than that of F20P0 unhybrid composites. This is due to the obvious fact that the hardness of the SiC particles in F13P7 MMCs is much higher than that of the matrix and the fibers. Thus, fibers and matrix were severely worn. It caused higher weight loss of the F13P7 hybrid MMCs. On the other hand, although SiC_p were added to the MMCs with N-orientation of fibers, the fibers could not be damaged as severely as that of

MMCs with PR-orientation of fibers. Therefore, for N-orientation of fibers, the less weight loss was measured. This indicated that the hybrid MMCs with N-orientation of fibers had a better wear resistance than that with PR-orientation of fibers.

The worn surfaces of F7P13 hybrid MMCs with PR- and N-orientations of fibers are shown in Figs. 6 (e) and (f), respectively. For PR-orientation of fibers, the surface of the F7P13 MMC specimen was relatively smoother than that of previous F13P7 hybrid MMC specimen as seen from Figs. 6 (c) and (e). For N-orientation of fibers, the addition of more SiC_p improved the wear resistance and we observed further smoother surface in comparison with the previous F13P7 specimens as seen from Figs. 6 (d) and (f). This also conforms to the results of Fig. 5 (b).

3.3 Lubricant sliding wear behavior at elevated temperature

Figures 7 (a) and (b) illustrated that effect of hybrid ratio on weight loss of MMCs with PR- and N-orientation of fibers for lubricant sliding wear at the elevated temperature of 100 °C and 150 °C. The wear resistance monotonically increased by adding the $SiC_p$for both PR- and N-MMCs. It was easily to find that the weight loss was less than 1.0 mg at a high applied load and long sliding distance. Furthermore, the wear resistance of N-MMC was a little superior than that of PR-MMC for each hybrid ratio for the lubricant sliding wear at the elevated temperature of 100 °C as shown in the Fig. 7 (a). In case of 150 °C, it was observed that the wear resistance of F20P0 (unhybrid) MMC specimen with N-orientation of fibers was worse than that with PR-orientation of fibers. It is a reverse wear behavior compared with the results at room temperature. It is referred to that the matrix became ductile during the tests while the temperature was increased. And the weight loss was increased in case of F20P0 MMCs. In case of F13P7 MMCs, the ductile matrix surrounded hard particles more easily which would reduce the opportunity for producing the debris of particles. Thus, the weight loss was definitely decreased at elevated temperatures. Furthermore, it was found that the wear resistance of MMC specimens with N-orientation of fibers was worse than that with PR-orientation of fibers, *i.e.*, the weight loss of MMC specimens with N-orientation of fibers was higher than that with PR-orientation of fibers. For both the PR- and N-orientation of fibers, the weight loss gradually decreased with the addition of fewer SiC_p which meant that the wear resistance was improved by the additional content of SiC_p as shown in Fig. 7 (b).

The morphology of worn surfaces presented in Fig. 8 and 9was examined by SEM to observe tribological characteristics and investigate wear behavior.

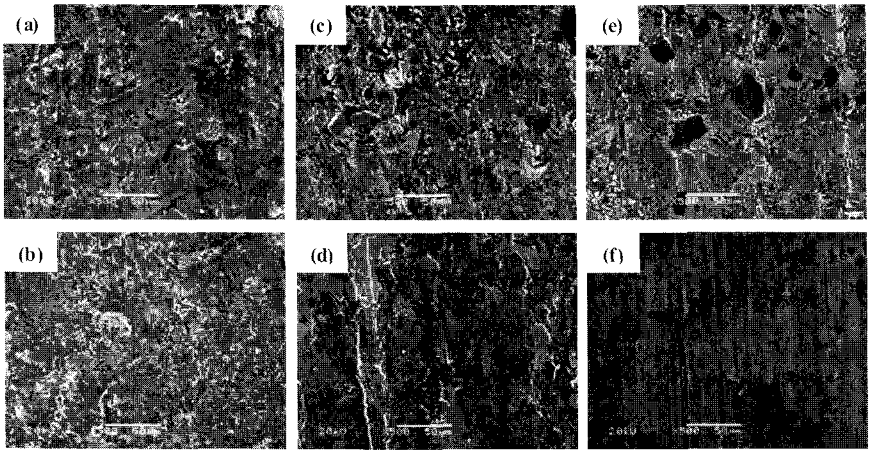


Fig. 6 SEM images of worn surfaces of MMC specimens: (a) F20P0 PR, (b) F20P0 N, (c) F13P7 PR, (d) F13P7 N, (e) F7P13 PR, and (f) F7P13 N for lubricant sliding wear at the room temperature.

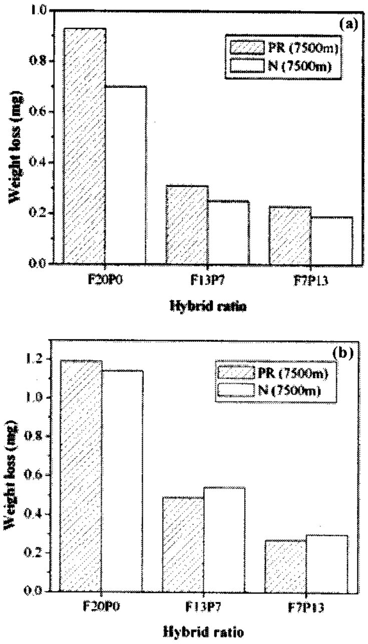


Fig. 7 Effect of hybrid ratio on weight loss of MMCs with PR- and N-orientations of fiber for lubricant sliding wear at (a) 100 °C and (b) 150 °C.

Compared Fig. 8 (a) with (b), the worn surface of F20P0 PR-MMC revealed more severe tribological behavior due to the fragmentation, which was caused by the adhesive wear as shown in Fig. 8 (a). Furthermore, Fig. 8 (b) presented that the weight loss of F20P0 N-MMCs were principally caused by the abrasive wear behavior with the characteristic grooves on the worn surface. The particles were observed on the worn surfaces of F13P7 and F7P13 for both PR- and N-MMC which also observed after the room temperature lubricant sliding wear as shown in Fig. 8 (c), (d), (e) and (f). The worn surfaces were protected by the SiC_p particles which were harder than any other materials in the experiments. They were hard enough to resist the friction force acting on the worn surfaces. It indicated that during lubricant sliding wear the particles played a certain function for improving the wear resistance at the elevated temperature of 100 °C. Most of the applied load was shared by the particles on the worn surface. While more SiC_p content was added, a part of the fiber content was substituted by it that also could increase the hardness of composite. Therefore, the worn surfaces became smoother and presented in Fig. 8 (e) and (f). It was the reasonable explanation that the weight loss was reduced with the rise of the SiC_p content which was consistent with the result as shown in Fig. 7 (a).

Figure 9 displayed the SEM images of the worn surfaces of MMC specimens after lubricant sliding wear at an elevated temperature of 150 °C. In the worn surface of unhybrid MMC specimen with PR-orientation of fibers, the fragmentations were obvious, which were mainly caused by the abrasive wear, that induced high weight loss as shown in Fig. 9 (a). However, in the worn surface of unhybrid MMC specimen with N-orientation

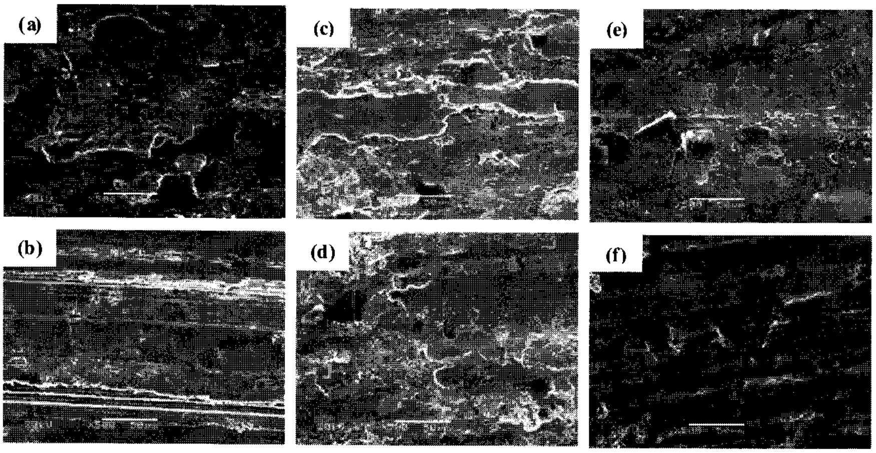


Fig. 8 SEM images of worn surface of (a) F20P0 PR, (b) F20P0 N, (c) F13P7 PR, (d) F13P7 N, (e) F7P13 PR, and (f) F7P13 N for lubricant sliding wear at the elevated temperature of 100 °C.

of fibers, more laminations were observed after the lubricant sliding wear as shown in Fig. 9 (b). The comparison between Figs. 9 (a) and (b) revealed that the lubricant wear resistance of unhybrid MMCs with PR-orientation of fibers was worse than that with N-orientation of fibers.

Figures 9 (c) and (d) represented the worn surfaces of F13P7 hybrid MMC specimens with the addition of 7 % SiC_p. The laminations and fragmentations were observed in the worn surfaces of the F13P7 hybrid MMC specimens with both the PR- and N-orientations of fibers. Due to the hardness of the SiC_p in F13P7 MMCs is much higher than that of the matrix and the fibers, it was easily observed that F13P7 hybrid composites had a smoother worn surface than that of F20P0 unhybrid composites from the comparison between Figs. 9 (a) and (c). Thus, although fibers and matrix of F13P7 MMCs with PR-orientation of fibers were severely worn, the weight loss was reduced, *i.e.*, the wear resistance was improved by the additional SiC_p content. On the other hand, as SiC_p were added to the F13P7 MMCs with N-orientation of fibers, although the hardness was improved, as shown in the Fig. 9 (d), the lamination was also observed in the worn surface of that which might cause more weight loss. However, the testing result indicated that the wear resistance of F13P7 MMCs with N-orientation of fibers is better than F20P0 MMCs with N-orientation of fibers. The reasonable explanation was that the effect of improved hardness was more efficient even the weight loss caused by lamination was effectively offset. The worn surfaces of F7P13 hybrid MMCs with PR- and N-orientations of fibers are shown in Figs. 9 (e) and (f), respectively. For both PR- and N-orientations of fibers, the surfaces of the F7P13 MMC specimens were relatively smoother than that of previous F13P7 hybrid MMC specimens as seen from Figs. 9 (c) and (e) for PR-orientation of fibers, Figs. 9 (d) and (f) for N-orientation of fibers. This also conformed to the results of Fig. 7 (b). In this case, both of the testing results and the SEM images indicated that the hybrid MMCs with PR-orientation of fibers had a better wear resistance than that with N-orientation of fibers.

3.4 Friction coefficient of lubricant sliding wear

The coefficient of friction (COF) is interpreted as the probability of formation of wear debris in a tribological system. Also the change in COF signals a change in material properties. However, in this present work, accompanied the help of lubricant, it is observed that COF values are very small which were in the range of 0.145 - 0.165 as shown in Fig. 10. The COF values of PR-MMC at room temperature and that of N-MMC at 100 °C were around 0.16, in other cases the COF values were around 0.15. Although the weight loss was affected due to the hybrid ratios, the COF was not greatly influenced.

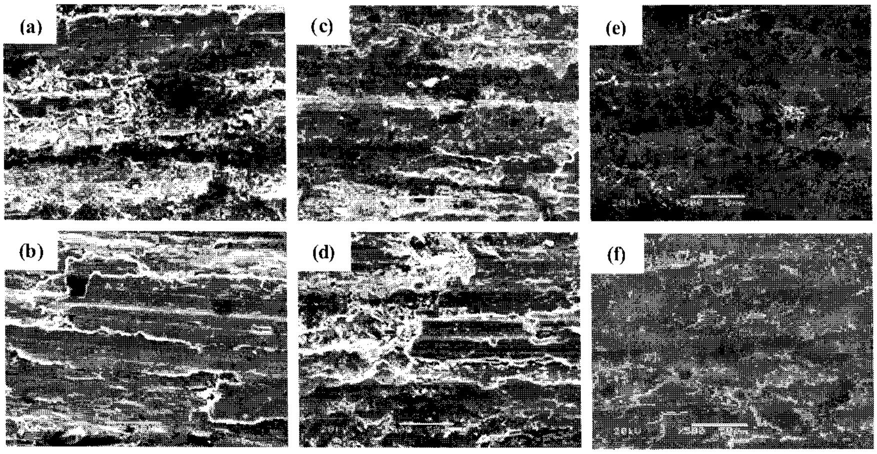


Fig. 9 SEM images of worn surface of (a) F20P0 PR, (b) F20P0 N, (c) F13P7 PR, (d) F13P7 N, (e) F7P13 PR, and (f) F7P13 N for lubricant sliding wear at the elevated temperature of 150 °C.

3.5 Lubricant sliding wear mechanism

The matrix was initially worn at the interface between the matrix and the reinforcements due to low hardness of the matrix in comparison with that of the reinforcements. Therefore, after a while, the harder reinforcements became plateaus that shared the total load. Consequently, the reinforcements were partially damaged. The subsequent wear was due to the three-body abrasion along with associated adhesion. At room temperature, although the fibers in N-MMCs did not supported the worn surface along their entire length as that of PR-MMCs, more parts of the fibers appeared on the worn surface due to fibers cannot be broken after a while of test. For this reason, the MMCs with N-orientation of fibers exhibited superior wear resistance in comparison with MMCs with PR-orientation of fibers.

When the temperature was increased, the matrix became softer caused a higher weight loss. Moreover, the SiC_p, is harder than fibers and matrix. It should play a role in increasing the wear resistance. As a result, the better wear behavior was observed in case of F7P13 MMCs with both the PR- and N-orientations of fibers than any other hybrid ratios.

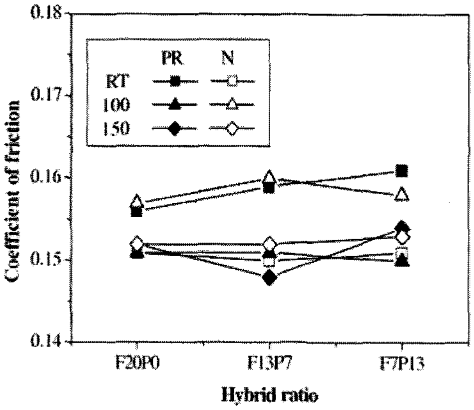


Fig. 10 The coefficient of friction of MMCs with PR- and N-orientations of fiber for lubricant sliding wear at RT, 100 °C, and 150 °C.

6. Conclusion

MMC slubricant tribological characteristics were investigated by pin-on-disk friction and wear tester at room temperature, elevated temperatures 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 conclusions can be summarized.

(1) The lubricant film had the especial function on reducing weight loss and improving the wear resistance of the friction surfaces.

(2) At room temperature few SiC_p(the case of F13P7 MMCs) added cannot improve the wear properties, but made it worse. At the elevated temperatures matrix became ductile, the trend of weight loss monotonically decreased while the addition of SiC_p increased for both cases PR- and N-orientations of fibers. Especially, the wear resistance of MMCs with N-orientation of fibers was superior to others except for the case of hybrid MMCs under 150 °C.

(3) The wear mechanisms of unhybrid MMCs with PR-orientation of fibers were adhesive while it was principally abrasive for hybrid MMCs with PR-orientation of fibers and both the unhybrid and hybrid MMCs with N-orientation of fibers.

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