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Tribological properties of MoS_2 and carbon fiber reinforced polyimide composites

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Abstract The tribological properties of carbon fiber reinforced polyimide (PI) composites with different MoS_2 containing sliding against GCr15 steel were comparatively evaluated on an M-2000 model ring-on-block test rig. The wear mechanisms were also comparatively discussed, based on scanning electron microscopic examination of the worn surface of the PI composites and the transfer film formed on the counterpart. It was found that small incorporation of MoS_2 was harmful to the improvement of friction and wear behaviors of carbon fiber reinforced PI composites. However, it was found that the increasing filler of MoS_2 significantly improved the wear resistance and decreased the friction coefficient of carbon fiber reinforced PI composites. It was also found that the tribological properties of MoS_2 and short carbon fiber reinforced PI composites were closely related with the sliding condition such as sliding rate and applied load.

Introduction

Polymers and coatings filled with solid lubricants have been extensively studied because of the increasing industrial and martial applications [1–4]. Polyimide (PI) possesses some extraordinary characteristics, such as excellent mechanical and electrical (insulating) properties, good thermal stability and chemical inertness, high wear resistance, and resistance against high energy radiation [5, 6]. Yet, it cannot be widely used as self-lubricant material because of its high friction coefficient. Carbon fibers (CF) possess high specific strength, specific modulus, high thermal and electric conductivity, low expansion coefficient and good self-lubricancy, which were widely used in resins and metals as reinforcements to fabricate high performance composites [7, 8]. It is difficult to develop low friction and high anti-wear PI composites reinforced only with short cut CF. In order to increase the applicability of short CF reinforced PI composites, it is imperative to seek for effective ways to improve the friction and wear behaviors of these kinds of composites. Some solid lubricants such as MoS_2, can improve the friction reducing and anti-wear ability of CF reinforced PI composites effectively.

In this paper, we fabricated MoS_2 and CF reinforced PI composites. The effects of the content of MoS_2, sliding time, sliding rate, and applied load on the tribological properties of the composites were discussed in detail. The wear mechanisms were also comparatively discussed, based on scanning electron microscopic examination.

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Experimental

Materials and preparation of PI composites

PI(YS-20) powders (<75 μm) were commercially obtained from Shanghai Synthetic Resin Institute (Shanghai, China). The short CF (1–2 mm) were about 7.8 μm in diameter, and their density was about 1.8 g/cm^3. The commercial short CF was dipped in acetone for 24 h and then cleaned ultrasonically with acetone for 0.5 h. Finally, they were dried at 100 °C for 5 h before used. MoS_2 powders were screened to be less than 75 μm.

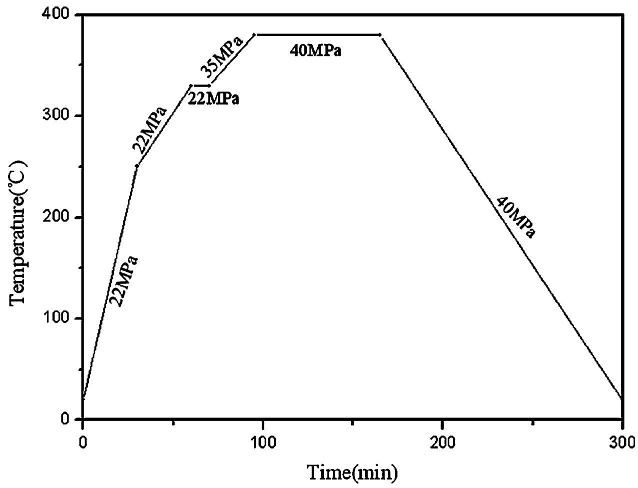

Fig. 1 The hot press program of molding

The content of CF in PI composite was 10 wt%. MoS_2 and CF were mixed with PI powders to prepare mixtures for the preparation of the PI composites. The hot press program of molding is shown in Fig. 1. At the end of each run of compression sintering, the resulting specimens were cooled with the stove in air, cut into pre-set sizes for the tribological properties tests.

Tribological properties test

The friction and wear behaviors of the PI composites sliding against GCr15 steel were evaluated on an M-2000 model ring-on-block test rig (made by Jinan Testing Machine Factory, China). The contact schematic diagram is shown in Fig. 2, the blocks in a size of 30 × 7 × 6 mm^3 were made of the PI composites, the rings of Φ40 × 16 mm^2 were made of the GCr15 stainless steels, the chemical composition of the GCr15 bearing steel (mass fraction, %) is shown in Table 1. The tests were carried out at a linear velocity of 0.431 or 0.862 m/s in a period of 120 min with the loads ranging from 200 to 500 N. Before each test, the stainless steel ring and the PI composite block were polished to a roughness (Ra) of about 0.2–0.3 μm. The block specimen was static and the GCr15 bearing was sliding against the block unidirectionally. The friction force was measured using a torque shaft equipped with strain gauges mounted on a vertical arm that carried the block, which was used to calculate the friction coefficient by taking into account the normal load applied. The width of the wear tracks was measured with a reading microscope to an accuracy of 0.01 mm. Then the specific wear rate (ω) of the specimen was calculated from Eq. 1 where B is the width of the specimen (mm), r is the semi diameter of the stainless steel ring (mm), b is the width of the wear trace (mm), L is the sliding distance in meter, and P is the load in Newton. The tests were repeated for three times and the average was taken as the result. The wear tracks of the composite and stainless steel specimens were examined on a JSM-5600 LV scanning electron microscope (SEM). In order to increase the resolution for the SEM observation, the tested composite specimens were plated with gold coating to render them electrically conductive.

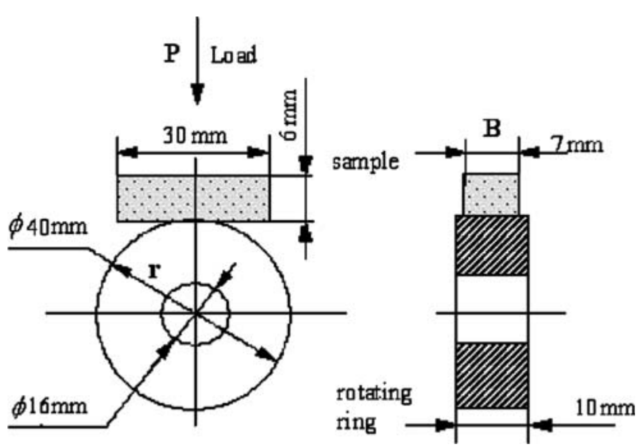

Fig. 2 The contact schematic diagram for the friction couple

Table 1 Chemical composition of the GCr15 steel ring

Chemical composition (mass fraction, %)					
C	Mn	Si	P	S	Cr
0.95–1.05	0.25–0.45	0.15–0.35	≤0.025	≤0.025	1.40–1.65

$$\omega = \frac{B}{L*P}\left[\frac{\pi r^2}{180}\arcsin\left(\frac{b}{2r}\right) - \frac{b}{2r}\sqrt{r^2 - \frac{b^2}{2}}\right](\mathrm{mm^3/N\,m}) \quad (1)$$

.

Results and discussion

Friction and wear properties of MoS_2 and short CF reinforced PI composites

Figure 3 shows the friction coefficient and wear rate of MoS_2 and short CF reinforced PI composites at a sliding speed of 0.431 m/s under 200 N. It is found from Fig. 3 that small incorporation of MoS_2 was harmful to the improvement of friction and wear behaviors of the PI composites, which can improve the friction coefficient and deteriorate the wear resistance of the PI composites. With an increase in the content of MoS_2, it also can be found that the friction coefficient decreased drastically and the wear

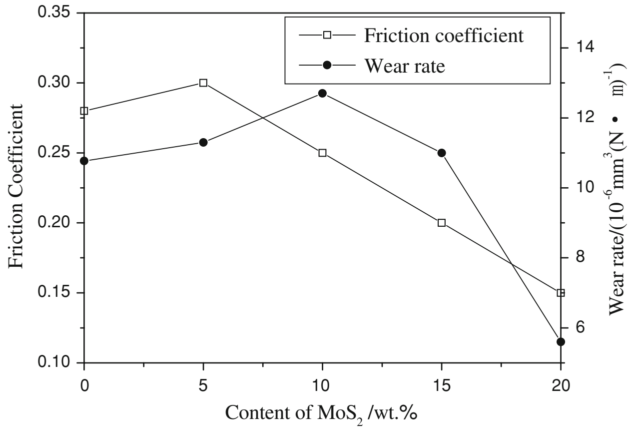

Fig. 3 Variation of the friction coefficient and wear rate of MoS_2 and short carbon fiber reinforced PI composites (200 N, 0.431 m/s)

resistance improved owing to the increase of the anti-shear ability.

10%CF–20%MoS_2–PI composites were selected as example to evaluate the effects of load and sliding time and sliding rate on the friction and wear behaviors of the PI composites. Present in Fig. 4 are the typical evolutions of the friction coefficient of the PI composites as a function of the sliding time under different sliding rate or applied load. It can be seen that the frictional process is composed of two distinct stages: the one is the running-in period and the other is the steady-state period. It took a few minutes to transit from the running-in period to the steady-state period. The friction coefficient of the running-in period was obviously higher than that of the steady-state period. The transfer film can easily form owing to the incorporation of MoS_2. After the formation and the peeling-off of the transfer film came to a balance, the friction coefficient

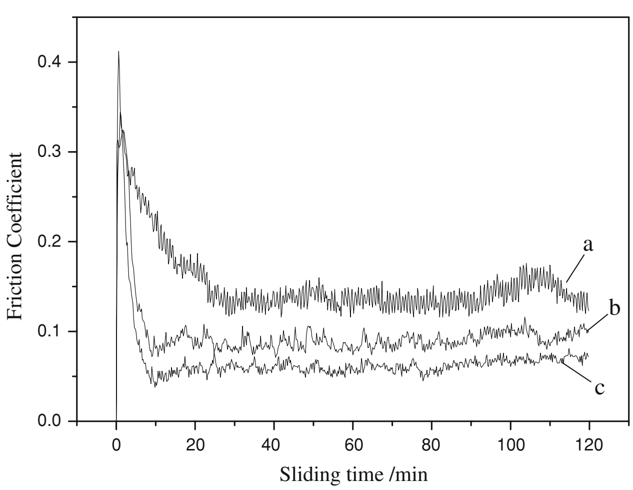

Fig. 4 Typical friction coefficient variation of MoS_2 and short carbon fiber reinforced PI composites with the sliding time (a: 0.431 m/s, 200 N; b: 0.431 m/s, 500 N; c: 0.862 m/s, 200 N)

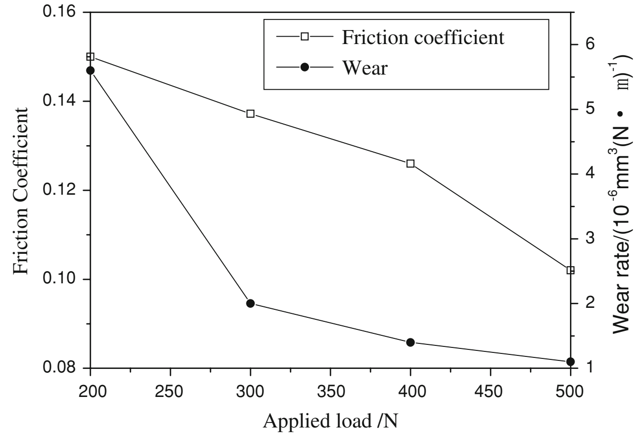

Fig. 5 Variation of the friction coefficient and the wear rate of MoS_2 and short carbon fiber reinforced PI composites under different load (0.431 m/s)

became stable [5]. From Fig. 4, it can be found that it took fewer time in transiting from the running-in period to the steady-state period, and the friction curves were less fluctuant under a higher sliding rate or applied load.

Figure 5 shows the influence of applied load on the friction coefficient and wear rate of MoS_2 and short CF reinforced PI composites. The decreases in friction coefficient and wear rate are clearly seen with the increasing applied load. When applied load is increased, the worn debris can be pressed into the surface and acted as lubricants. Moreover, the transfer film can easily form owing to the increase in adhesive force between the film and counterpart.

The effect of sliding rate on the friction and wear of MoS_2 and short CF reinforced PI composites are shown in Fig. 6. It is clearly seen that both the friction coefficient and the wear rate decrease rapidly under high sliding rate compared with that under low sliding rate. With an increase in sliding rate, there was not enough time to produce more adhesive points owing to the decreased

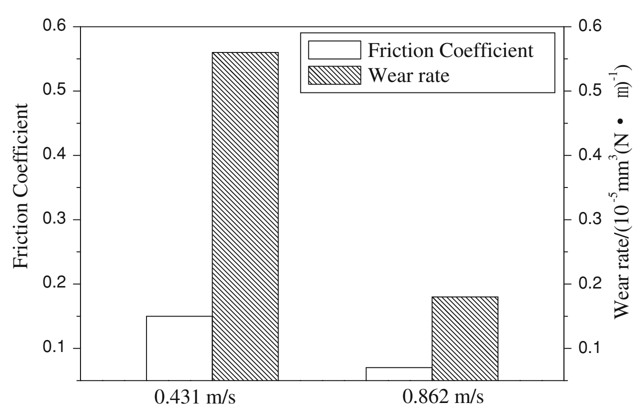

Fig. 6 The effect of sliding rate on the friction and wear of MoS_2 and short carbon fiber reinforced PI composites (200 N)

surface contact time. The friction force can be greatly reduced and the transfer film can easily form and is difficult to rupture. Moreover, when sliding rate or applied load is increased, the newly formed debris would be come a more integrated but thinner film on the worn surface, and as a result, the smaller debris and more integrated but thinner film would bring about small friction coefficient because of the decreased degree of two-body abrasive wear [9].

SEM analysis of the worn surfaces and the transfer films on the surface of GCr15 steel rings

Figures 7 and 8 show the SEM morphologies of the worn surfaces and the transfer films of the PI composites sliding against the GCr15 steel at a sliding speed of 0.431 m/s under 200 N. The worn surface of the10%CF–90%PI composites was characterized by severe deformation wear and fatigue wear (Fig. 7a), while PI debris was observed on the stainless steel counterpart surface and the transfer film was thick and discontinuous (Fig. 8a), which corresponds to its high friction coefficient and wear rate. As for the 10%CF–5%MoS_2–PI composites, the phenomena of deformation wear and fatigue wear were obviously abated and was characterized by severe abrasive wear (Fig. 7b), there appears a great amount of abrasive grain on the worn surface. The transfer film was thick and discontinuous (Fig. 8b). As for the 10%CF–20%MoS_2–PI composite, the worn surface was characterized by adhesion wear and fatigue wear. It also can be seen that the worn surface was smooth and there were no obvious scuffing phenomena (Fig. 7c). Meanwhile, the transfer film became comparatively thinner and uniform (Fig. 8c). It was just the transfer film that was responsible for the decreased friction coefficient and the improved wear resistance of MoS_2 and short

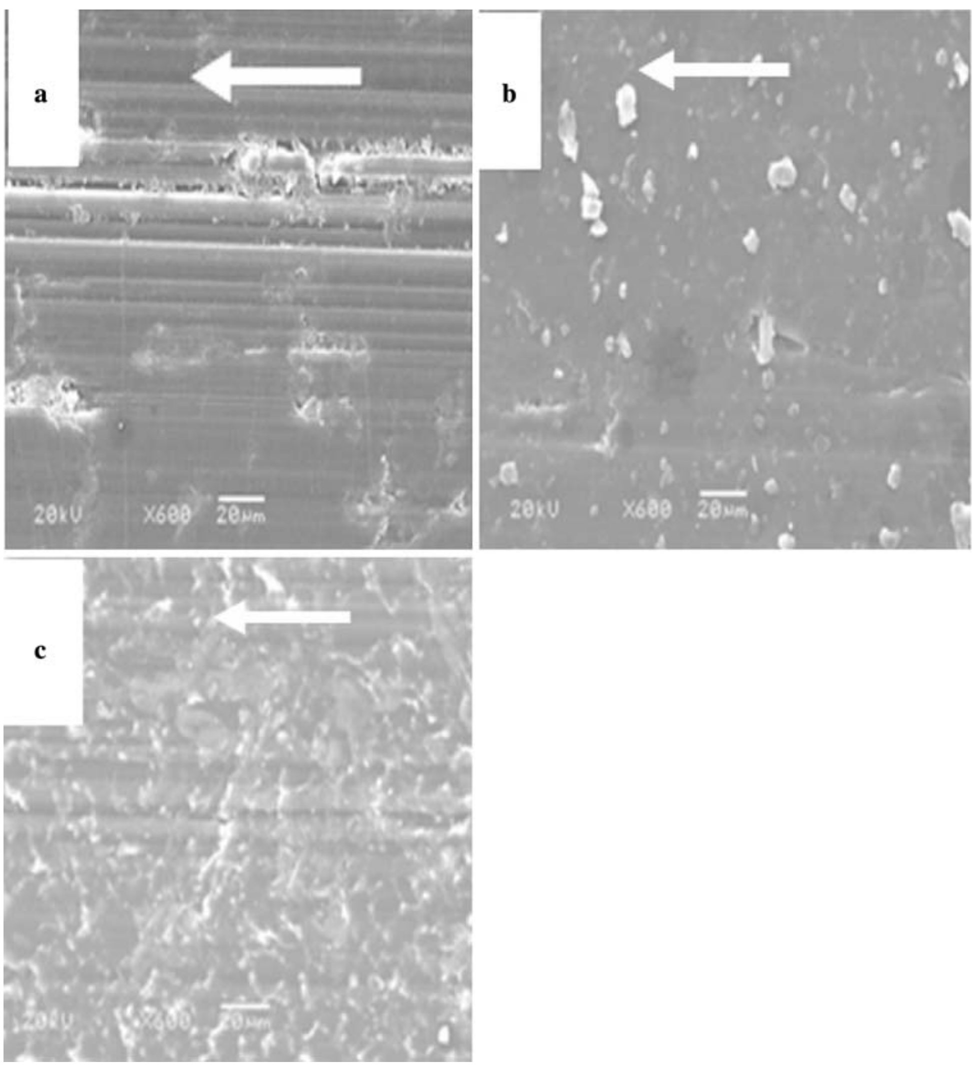

Fig. 7 SEM morphologies of the worn surface of MoS_2 and short carbon fiber reinforced PI composites (600×) (**a**) 10%CF–90%PI; (**b**) 10%CF–5%MoS_2–PI; (**c**) 10%CF–20%MoS_2–PI) (arrow indicates the sliding direction)

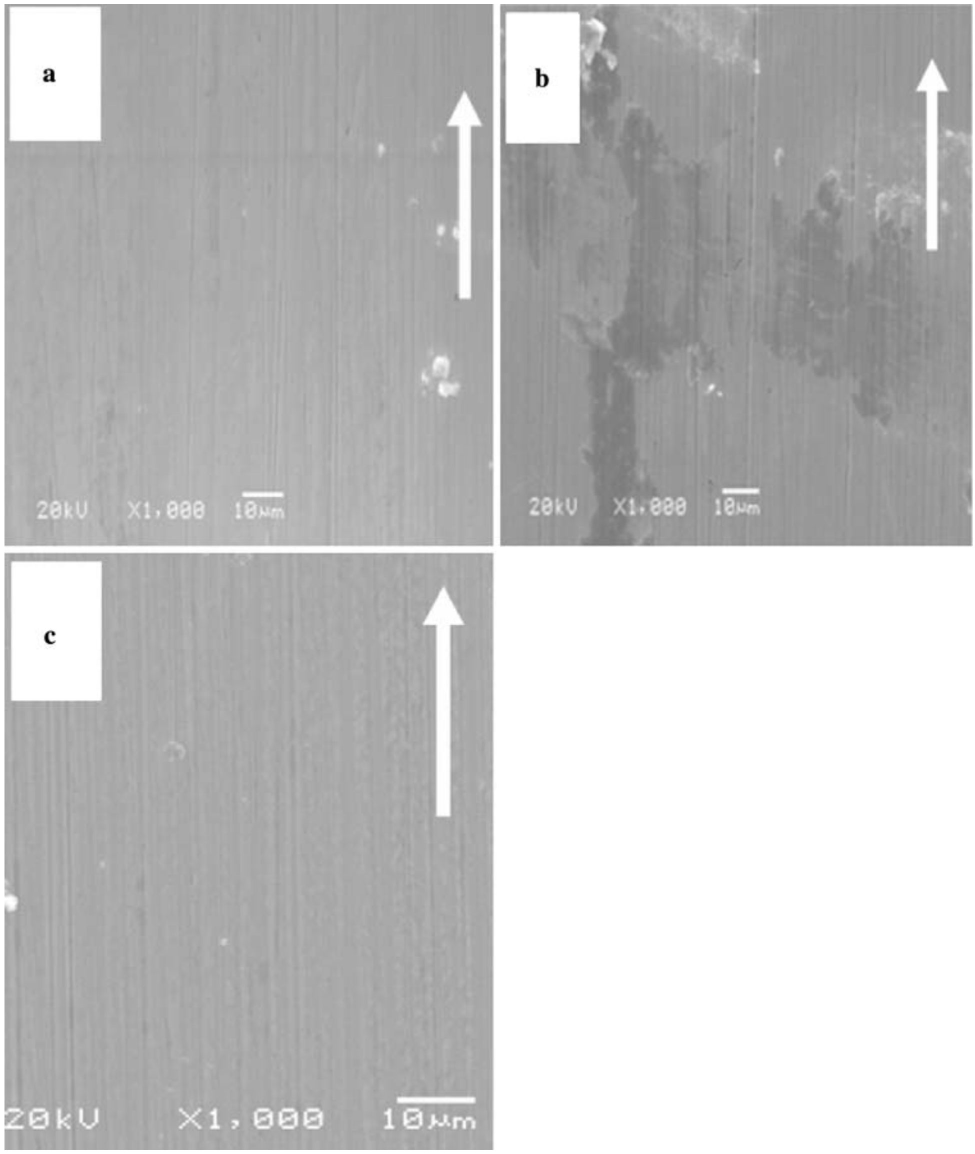

Fig. 8 SEM morphologies of the transfer films on the surface of GCr15 steel counterpart (1,000×) (**a**) 10%CF–90%PI; (**b**) 10%CF–5%MoS_2–PI; (**c**) 10%CF–20%MoS_2−PI) (arrow indicates the sliding direction)

CF reinforced PI composites. That is, with the formation of the relative uniform and coherent transfer film, subsequent sliding occurred between the surface of MoS_2 and CF reinforced PI composites and the transfer film. Hence, the decrease of the friction coefficient and wear rate was inevitable.

Conclusions

(1) Small incorporation of MoS_2 was harmful to the improvement of friction and wear behaviors of CF reinforced PI composites. With an increase in the content of MoS_2, the friction coefficient decreased drastically and the wear resistance improved owing to the increase of the anti-shear ability.

(2) The differences in the friction coefficient and wear properties of MoS_2 and short CF reinforced PI composites are closely related to the sliding condition such as sliding rate and applied load.

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