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Friction and wear studies of polyimide composites filled with short carbon fibers and graphite and micro SiO_2

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Polyimide (PI) composites filled with short carbon fibers (SCFs), micro SiO_2, and graphite (Gr) particles were prepared by means of hot press molding technique. The friction and wear properties of the resulting composites sliding against GCr15 steel were investigated on a model ring-on-block test rig. Experimental results revealed that single incorporation of graphite and SCF significantly improve the tribological properties of the PI composites, but micro SiO_2 was harmful to the improvement of the friction and wear behavior of the PI composite. It is found that a combinative addition of Gr, SCF and micro SiO_2 was the most effective in improving the friction-reducing and anti-wear abilities of the PI composites. Research results also show that the filled PI composites exhibited better tribological properties under higher PV-product.

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1. Introduction

Polymer composites occupy a considerable market share nowadays as one of the most common engineering materials, which provide a combination of various advantages, such as ease in manufacturing, cost effectiveness and excellent performance [1]. In particular, polymer composites are now being used as sliding elements, which were formerly composed of metallic materials only. Polymer composites containing different fillers and/or reinforcements are frequently used for these purposes [2]. Many investigations have shown that the incorporation of fillers improved the wear resistance and reduced the friction coefficient [3–10]. Internal lubricants such as polytetrafluoroethylene (PTFE) flakes are frequently incorporated to improve the tribological properties of polymer composites. One of the mechanisms is the formation of a PTFE-transfer film on the surface of the counterpart [3]. Short aramid (AF), glass (GF) or carbon fiber (CF) are used to increase the creep resistance and the compressive strength of the polymer matrix system used [8–10]. Some inorganic particles are of help to enhance the bonding between the transfer film and the metallic counterpart, which lead to improved wear resistance. Zhang et al. studied the friction and wear of epoxy-based composites reinforced with various amounts of short carbon fiber (SCF) and solid lubricants, additionally filled with different contents of micro-TiO_2 (300 nm) [11,12]. Apart from the polymer composition, sliding conditions can also exert much influence on the tribological properties of polymer composites. Dickens and Sullivan [13] found that the steady state wear rate of polyphenylene oxide (PPO), polyetheretherketone (PEEK), and PTFE increased with increasing sliding speed, and that the friction coefficient of PPO and PEEK was not greatly affected, while the friction coefficient increased in the case of PTFE. In our previous studies, it was found that basalt fiber reinforced polyimide composites exhibited better tribological properties under a higher load and sliding speed [14].

The choice of an appropriate matrix is of great importance in the design of wear resistant polymer composites. The required properties of such a tribo-matrix includes high service temperature, good chemical resistance and outstanding cohesive strength [15]. Polyimide (PI) attract extensive concern from tribological scientists world-wide because of their high mechanical strength, acceptable wear resistance under certain conditions, good thermal stability, high-stability under vacuum, good anti-radiation, and good solvent resistance, They are mainly used in combination with additives and fiber reinforcement for good sliding properties [16]. Unfortunately, few efforts have been done in the study of effects of combinative addition of inorganic particles and conventional fillers on the friction and wear behavior of PI composites.

The purpose of this study is to investigate the synergistic effects of the inorganic particles and conventional fillers on the tribological behavior of PI composites. The effects of the fillers, sliding time, sliding speed, and load on the tribological properties of PI composites were discussed in detail. The wear mechanisms were also comparatively discussed, based on scanning electron microscopic examination.

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2. Experimental

2.1. Materials and preparation of PI composites

PI (YS-20) powders (<75 μm) were commercially obtained from Shanghai Synthetic Resin Institute (Shanghai, China). SiO_2 powders (<15 μm) and Graphite powder (<1.5 μm). The short carbon fiber was about 75 μm in length and 6–9 μm in diameter.

The composites were fabricated by means of hot press molding technique. The volume fractions of SiO_2, graphite and short carbon fiber were 3%, 10% and 10%, respectively. The fillers were mixed with PI powders at selected volume fractions to prepare mixtures for the preparation of PI composites. The mixtures were compressed and heated to 380 °C and held at 40 MPa for 75 min to allow full compression sintering. 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 friction and wear tests.

2.2. Tribological properties tests

The friction and wear behavior of the PI composites sliding against stainless 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. 1. The blocks in a size of 30 mm × 7 mm × 6 mm were made of the PI composites, the rings of Φ40 mm × 16 mm were made of GCr15 stainless steels. The chemical composition of the GCr15 steel ring is shown in Table 1. The tests were carried out at a linear velocity of 0.431 m/s in a period of 120 min with the load of 200 N. Before each test, the stainless steel ring and the PI composite block were polished to a roughness (Ra) of about 0.3 μm. The block specimen was static and the GCr15 bearing was sliding against the block unidirectionally. 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 as follows [17].

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

where B is the width of the specimen (mm), *r* is the semi diameter of the stainless steel ring (mm), and b is the width of the wear trace (mm), *L* is the sliding distance in meter, *P* is the load in Newton. The tests were repeated three times, the worn surface of CFs/PI composites and the transfer films formed on the surface of the counterpart ring sliding against CFs/PI composites were examined on a JSM-5600LV 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.

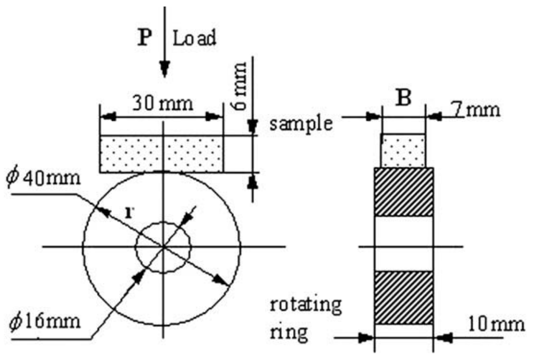

Fig. 1. The contact schematic for the friction couple.

Table 1
Chemical composition of the GCr15 steel ring.

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

Table 2
Friction coefficient and wear rate of PI composites under ry sliding condition at 200 N and 0.43 m/s.

Codes	Composites	Friction coefficient	Wearrate/10^{-6} mm^3 $(\mathrm{N\ m})^{-1}$
PI	Neat PI	0.4	3.85
PI-I	PI-3% SiO_2	0.39	12
PI-2	PI-10% Gr	0.3	2.9
PI-3	PI-10% SGF	0.27	2.66
PI-4	PI-10% Gr-3% SiO_2	0.25	1
PI-5	PI-10% Gr-10% SCF	0.24	0.9
PI-6	PI-10% SCF-3% SiQ_2	0.28	7.23
PI-7	PI-10% Gr-10% SCF-3% SiO_2	0.18	0.85

3. Results and discussion

3.1. Friction and wear properties of the PI composites

The friction coefficient and wear rate of the PI composites at 0.431 m/s and 200 N are comparatively shown in Table 2. It can be seen that micro SiO_2 as single filler was harmful to the improvement of friction and wear behavior of the PI composites. While incorporation of SCF and graphite can significantly improve the wear resistance and decrease the friction coefficient. It can also be seen that addition of SCF or micro SiO_2 to Gr/PI composites resulted in further improvement of the tribological properties. However, further addition of micro SiO_2 to SCF/PI composites worsen the tribological properties owing to serious abrasion of SiO_2. SCF or micro SiO_2 particulates can rub into graphite powder and act as favorable solid lubricants. After continuous grinding, the integrated wear layer became more even, and its strength, hardness and toughness became higher, which resulted in better tribological properties. Experimental results indicated that SCF plays a key role in improving the wear resistance of PI composites as a single or a second reinforcement. A combinative addition of Gr, SCF and micro SiO_2 was the most effective in improving the friction and wear behavior of PI composites due to their synergistic effects.

Fig. 2 show the effect of sliding speed on the friction and wear properties of the PI composites. It can be seen that the PI composites filled with appropriate fillers and reinforcements exhibited better tribological properties than pure PI under higher sliding speed compared with that under low sliding speeds. It is commonly believed that friction-induced heat is generated from the deformation of material in the actual contact spots. Some processes with their molecular mechanism is related to the transformation of mechanical energy into heat [18]. Because of the low thermal conductivity of PI, friction-induced heat surely provokes an increase in the contact temperature and an increase in the sliding speed will result in a higher contact temperature inevitably. The friction coefficient decreased and the wear rate increased remarkably owing to the effects of thermal softening. The degraded mechanical properties of the pure PI composites are also responsible for the higher wear rate under higher sliding speed. As for the filled PI composites, the thermal conductivity increased and the mechanical strength decreased slightly. Moreover, there was not enough time to produce more adhesive points owing to the decreased surface contact time. As a result, the friction force component from adhesion can be greatly reduced, and the transfer film can easily form and difficult to be ruptured, which resulted in better wear resistance under higher sliding speed [14].

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