Friction and Wear Characteristics of Ceramic Particle Filled Polytetrafluoroethylene Composites Under Oil-Lubricated Conditions

ZHAO-ZHU ZHANG, QUN-JI XUE, WEI-MIN LIU, WEI-CHANG SHEN

Laboratory of Solid Lubrication, Lanzhou Institute of Chemical Physics, Chinese Academy of Sciences, P. O. Box 97, Lanzhou 730000, People's Republic of China

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ABSTRACT: Five kinds of polytetrafluoroethylene (PTFE)-based composites were prepared: PTFE, PTFE + 30 vol % SiC, PTFE + 30 vol % Si_3N_4, PTFE + 30 vol % BN, and PTFE + 30 vol % B_2O_3. The friction and wear properties of these ceramic particle filled PTFE composites sliding against GCr15 bearing steel under both dry and liquid paraffin lubricated conditions were studied by using an MHK-500 ring-block wear tester. The worn surfaces and the transfer films formed on the surface of the GCr15 bearing steel of these PTFE composites were investigated by using a scanning electron microscope (SEM) and an optical microscope, respectively. The experimental results show that the ceramic particles of SiC, Si_3N_4, BN, and B_2O_3 can greatly reduce the wear of the PTFE composites; the wear-reducing action of Si_3N_4 is the most effective, that of SiC is the next most effective, then the BN, and that of B_2O_3 is the worst. We found that B_2O_3 reduces the friction coefficient of the PTFE composite but SiC, Si_3N_4, and BN increase the friction coefficients of the PTFE composites. However, the friction and wear properties of the ceramic particle filled PTFE composites can be greatly improved by lubrication with liquid paraffin, and the friction coefficients of the PTFE composites can be decreased by 1 order of magnitude. Under lubrication of liquid paraffin the friction coefficients of these ceramic particle filled PTFE composites decrease with an increase of load, but the wear of the PTFE composites increases with a load increase. The variations of the friction coefficients with load for these ceramic particle filled PTFE composites under lubrication of liquid paraffin can be properly described by the relationship between the friction coefficient (μ) and the simplified Sommerfeld variable *N*/*P* as given here. The investigations of the frictional surfaces show that the ceramic particles SiC, Si_3N_4, BN, and B_2O_3 enhance the adhesion of the transfer films of the PTFE composites to the surface of GCr15 bearing steel, so they greatly reduce the wear of the PTFE composites. However, the transfer of the PTFE composites onto the surface of the GCr15 bearing steel can be greatly reduced by lubrication with liquid paraffin, but the transfer still takes place. Meanwhile, the interactions between the liquid paraffin and the PTFE composites, especially the absorption of liquid paraffin into the surface layers of the PTFE composites, create some cracks on the worn surfaces of the ceramic particle filled PTFE composites; the creation and development of these cracks reduces the load-supporting capacity of the PTFE composites. This leads to the deterioration of the friction and wear properties of the PTFE composites under higher loads in liquid paraffin lubrication. © 1999 John Wiley & Sons, Inc. J Appl Polym Sci 73: 2611–2619, 1999

Key words: polytetrafluoroethylene composites; ceramic particles; oil lubrication; friction and wear; frictional surfaces

Correspondence to: Z.-Z. Zhang.

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Table I Chemical Composition of GCr15 Bearing Steel (wt %)

C	Mn	Si	Cr	P	S	Fe
0.950–1.050	0.200–0.400	0.150–0.350	1.300–1.650	<0.027	<0.020	Remainder

INTRODUCTION

It is well known that the low friction coefficient, excellent chemical resistance, and high thermal stability of polytetrafluoroethylene (PTFE) make it an attractive engineering polymeric material for sliding applications; but its high rate of wear greatly limits the application fields of PTFE in practice. It has been found that solid lubricants, metal powders, metal oxides, and sulfides are the fillers mostly used for modification of the tribological behaviors of polymers. The effects of these fillers on the friction and wear behaviors of polymers (such as PTFE) have been studied by many researchers.[1–8]

Ceramic particles (SiC, Si_3N_4, BN, B_2O_3, SiO_2, TiO_2, ZrO_2, etc.) are also important inorganic fillers for polymers. The effects of some ceramic particles such as B_2O_3, SiO_2, TiO_2, and ZrO_2 on the friction and wear behaviors of PTFE were studied by Gong et al. and Tanaka.[7,9] They found that 20 wt % TiO_2, 40 wt % ZrO_2, and 30 wt % B_2O_3 or SiO_2 decreased the wear rate of PTFE by a factor of 100–1000; SiO_2, TiO_2, and ZrO_2 increased the friction coefficient of PTFE; and B_2O_3 decreased the friction coefficient of PTFE. However, almost all of the studies on the friction and wear properties of ceramic particle filled PTFE composites were carried out under dry friction conditions.

With the enlargement of the number of application fields for PTFE-based composites in practice, more and more PTFE-based composites have been used in fluid environments. It has been found that many polymers wear much more in water than in air,[10,11] and the wear of the PTFE composites filled with only glass fibers is much greater than that of other PTFE composites in water.[9,12] However, until now, much less information has been available on the oil-lubricated friction and wear behaviors of ceramic particle filled PTFE composites. Therefore, it is essential to study the friction and wear characteristics of ceramic particle filled PTFE composites under oil-lubricated conditions.

The purpose of this work was to study the friction and wear behaviors of ceramic particle filled PTFE composites under both dry and oil-lubricated conditions and give some insights into the friction and wear mechanisms of these composites under oil-lubricated conditions. It is expected that this study may be useful in the application of ceramic particle filled PTFE composites under dry and oil-lubricated conditions in practice.

EXPERIMENTAL

Friction and wear tests were carried out on an MHK-500 ring-block wear tester (Timken wear tester) with a steel ring, which was 49.2 mm in diameter and 13.0 mm in length, rotating on a PTFE composite block, which was 12.3 $\times$ 12.3 $\times$ 18.9 mm in size. The steel ring, made of GCr15 bearing steel (chemical composition is listed in Table I), was polished with number 900 grade SiC abrasive paper to a surface roughness (R_a) of 0.15 μm. The surfaces of the PTFE composite blocks were polished with number 800 grade SiC abrasive paper to $R_a = 0.2$–$0.4\ \mu$m.

Materials used for preparing the PTFE composites include PTFE powder with a grit size of about 30 μm, SiC and Si_3N_4 particles of about 76 μm, and BN and B_2O_3 particles of about 154 μm. The proportion of these ceramic particles as fillers in the PTFE in each case was 30% by volume. First, SiC, Si_3N_4, BN, and B_2O_3 particles were completely mixed with the PTFE powder. Second, these mixtures were molded into the blocks by compression molding under a pressure of 50 MPa. Third, the PTFE composite blocks were sintered at 380°C for 3 h in air and then cooled freely to room temperature. Five kinds of PTFE-based composites were prepared in this work: pure PTFE, PTFE + 30 vol % SiC, PTFE + 30 vol % Si_3N_4, PTFE + 30 vol % BN, and the PTFE + 30 vol % B_2O_3. The lubricating oil used in the experiments was liquid paraffin, which was added to the rubbing surfaces at a rate of 30 drops/min during the tests. The typical characteristics of liquid paraffin are listed in Table II.

The friction and wear tests were performed at room temperature in an ambient atmosphere (relative humidity between 35 and 40%) with a sliding speed from 1.0 to 2.5 m/s and loads from 100 to 400 N for dry friction conditions or 100 to 1200

Table II Typical Characteristics of Liquid Paraffin

Viscosity ($\times 10^{-6}$ m^2 s^{-1}) 40°C	100°C	Viscosity Index	Flash Point (°C)	Boiling Point (°C)	Main Composition
21.49	4.42	117	226	>300	Paraffin

N for oil-lubricated conditions. Each friction and wear test was performed for 30 min. Before each test started, the surfaces of the PTFE composite blocks and the GCr15 bearing steel ring were cleaned by rubbing them with a soft cloth dipped in acetone and then drying in air. In this work, three to five samples were tested for each condition; the friction coefficient and wear were the average values of these tests for each condition. The wear was detected by the weight loss of the PTFE composite blocks after each test to an accuracy of 0.1 mg. The friction coefficient was determined by measuring the friction torque, and the friction torque was detected by a torque measuring system. The friction coefficient was the average value of those in the steady stage of friction (the last 10 min) for each test.

Finally, the worn surfaces of these ceramic particle filled PTFE composites were examined by using a JEM-1200EX/S scanning electron microscope (SEM). The transfer films of the PTFE composites formed on the surface of the GCr15 bearing steel ring were investigated using an optical microscope.

RESULTS AND DISCUSSION

Friction and Wear Properties under Dry Friction Conditions

The friction and wear results of ceramic particle filled PTFE composites sliding against GCr15 bearing steel under dry friction conditions are shown in Table III. The results in Table III show that filling SiC, Si_3N_4, or BN to PTFE increases the friction coefficient of PTFE but filling B_2O_3 to PTFE reduces the friction coefficient of PTFE. Of the SiC, Si_3N_4, or BN filled PTFE composites, the friction coefficient of the PTFE + 30 vol % SiC composite is the highest, but the friction coefficient of the PTFE + 30 vol % BN composite is the lowest. Table III shows that the antiwear properties of the PTFE composites can be greatly improved by filling PTFE with SiC, Si_3N_4, BN, or B_2O_3 and the wear of these ceramic particle filled PTFE composites can be decreased by 1–2 orders of magnitude compared to that of pure PTFE. However, the wear-reducing actions of SiC and Si_3N_4 are much more effective than those of BN and B_2O_3. The wear-reducing action of Si_3N_4 is the most effective, and that of B_2O_3 is the worst.

The variations of friction coefficients and wear with load for ceramic particle filled PTFE composites sliding against GCr15 bearing steel under dry friction conditions are shown in Figures 1 and 2, respectively. Figure 1 shows that the friction coefficients of the PTFE + 30 vol % SiC and PTFE + 30 vol % BN composites decrease with the increase of load under dry friction conditions but the load has little effect on the friction coefficient of the PTFE + 30 vol % B_2O_3 composite. However,

Table III Friction and Wear Results of Ceramic Particle Filled PTFE Composites under Dry Friction Conditions

Material	Friction Coefficient	Wear (mg)
PTFE	0.257	385.4
PTFE + 30 vol % SiC	0.502	3.4
PTFE + 30 vol % Si_3N_4	0.362	1.4
PTFE + 30 vol % BN	0.276	16.4
PTFE + 30 vol % B_2O_3	0.234	25.1

Sliding speed, 1.5 m/s; load, 100 N; time, 30 min.

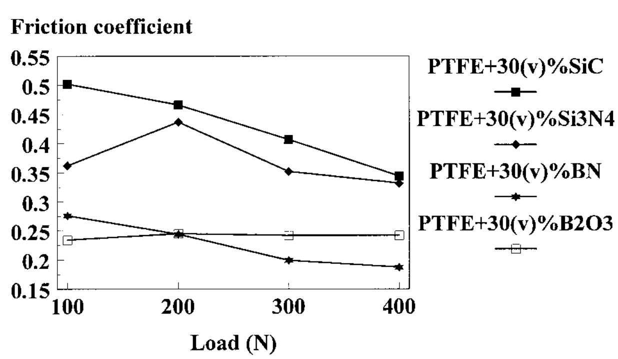

Figure 1 Variations of friction coefficients with load for the ceramic particle filled PTFE composites sliding against GCr15 bearing steel under dry friction conditions (sliding speed, 1.5 m/s).

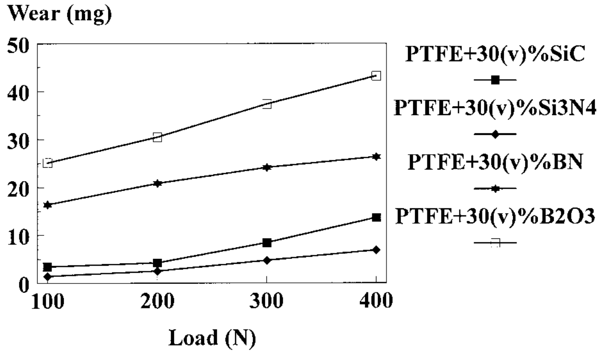

Figure 2 Variation of wear with load for the ceramic particle filled PTFE composites sliding against GCr15 bearing steel under dry friction conditions (sliding speed, 1.5 m/s).

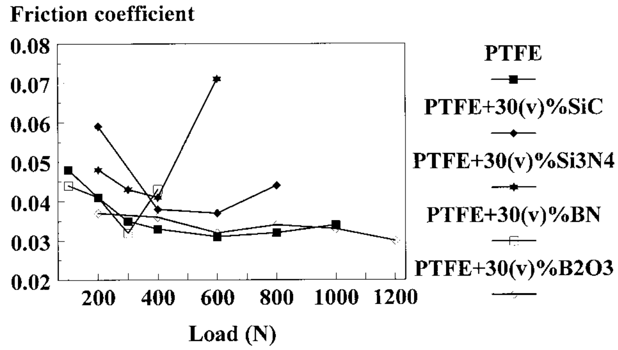

Figure 3 Variations of friction coefficients with load for the ceramic particle filled PTFE composites sliding against GCr15 bearing steel under lubrication of liquid paraffin (sliding speed, 2.5 m/s).

the friction coefficient of the PTFE + 30 vol % Si_3N_4 composite first increases with the increase of load from 100 to 200 N and then decreases as the load increases. When the load is higher than 200 N, the friction property of the PTFE + 30 vol % BN composite is the best and that of the PTFE + 30 vol % SiC composite is still the worst. The results in Figure 2 show that the wear of SiC, Si_3N_4, BN, or B_2O_3 filled PTFE composites increases with the increase of load under dry friction conditions. Under different loads in dry friction conditions, the antiwear property of the PTFE + 30 vol % Si_3N_4 composite is the best, the PTFE + 30 vol % SiC composite is intermediate, and that of the PTFE + 30 vol % B_2O_3 composite is the worst.

Friction and Wear Properties in Oil-Lubricated Conditions

The variations of friction coefficients and wear with load for ceramic particle filled PTFE composites sliding against GCr15 bearing steel under lubrication of liquid paraffin are shown in Figures 3 and 4, respectively. Figure 3 shows that the friction properties of these ceramic particle filled PTFE composites can be greatly improved by lubrication with liquid paraffin, and the friction coefficients of these PTFE composites can be decreased by 1 order of magnitude compared to those under dry friction conditions. The results in Figure 3 show that the friction coefficients of these ceramic particle filled PTFE composites decrease with the increase of load under lubrication of liquid paraffin. But when the load increases to the load limits of the PTFE composites, the friction coefficients of the PTFE composites increase sharply. Under higher loads (>400 N) in liquid paraffin lubrication, the friction properties of PTFE and the PTFE + 30 vol % B_2O_3 composite are better than those of the SiC, Si_3N_4, or BN filled PTFE composites.

Comparison of the wear results in Figure 4 to those under dry friction conditions (see Fig. 2) shows that the antiwear properties of these ceramic particle filled PTFE composites can be greatly improved by lubrication with liquid paraffin. The results in Figure 4 show that under lubrication of liquid paraffin the wear of these ceramic particle filled PTFE composites increases with the increase of load, and the antiwear property of the PTFE + 30 vol % B_2O_3 composite is better than those of the other PTFE composites. When the load increases to the load limits of the PTFE composites, the wear of the PTFE composites increases sharply. Because the PTFE + 30 vol % B_2O_3 composite exhibits excellent friction

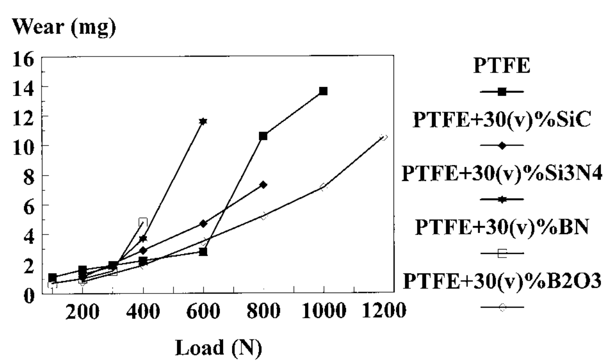

Figure 4 Variation of wear with load for the ceramic particle filled PTFE composites sliding against GCr15 bearing steel under lubrication of liquid paraffin (sliding speed, 2.5 m/s).

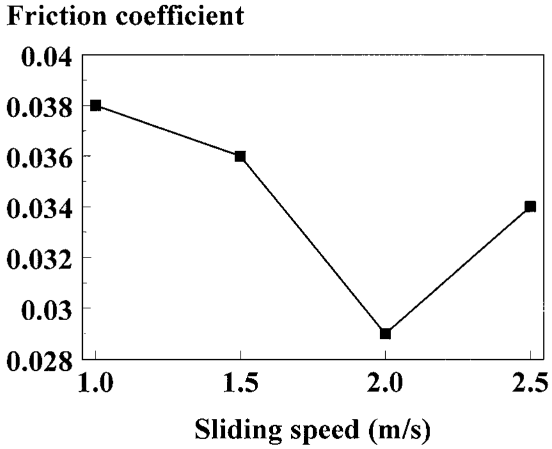

Figure 5 Variation of friction coefficient with sliding speed for the PTFE + 30 vol % B_2O_3 composite sliding against GCr15 bearing steel under lubrication of liquid paraffin (load, 800 N).

and wear properties under lubrication of liquid paraffin, it can be deduced that the PTFE + 30 vol % B_2O_3 composite can be more suitably used in practice than other ceramic particle filled PTFE composites under oil-lubricated conditions.

The variations of the friction coefficient and wear rate with sliding speed for the PTFE + 30 vol % B_2O_3 composite sliding against GCr15 bearing steel under lubrication of liquid paraffin are shown in Figures 5 and 6, respectively. The results in Figures 5 and 6 show that under lubrication of liquid paraffin the friction coefficient and the wear rate of the PTFE + 30 vol % B_2O_3 composite first decrease with the increase of sliding speed and then increase as the sliding speed increases. At the sliding speed of 2.0 m/s in liquid paraffin lubrication, the friction coefficient and the wear rate of the PTFE + 30 vol % B_2O_3 composite are the lowest. It is believed that with the increase of sliding speed under liquid paraffin lubrication a layer of lubricating oil film can be more easily formed on the frictional surfaces; thus, the lubrication condition at the rubbing surfaces can be greatly improved, leading to the decrease of the friction and wear of the PTFE composite. However, with the further increase of sliding speed, the temperature increase at the rubbing surfaces results in the reduction of mechanical strength and load-supporting capacity of the PTFE composite and, in turn, leads to the increase of the friction and wear of the PTFE composite.

When sliding speed is a constant, the variations of friction coefficients with load for the ceramic particle filled PTFE composites sliding against GCr15 bearing steel under lubrication of liquid paraffin can be described by the relationship between the friction coefficient and the Sommerfeld variable $\eta N/P$, where η is the viscosity of liquid paraffin, N is the rotation speed of the GCr15 bearing steel ring, and P is the load applied.[13,14] At a constant sliding speed in liquid paraffin lubrication, the temperature at frictional surfaces increases with the increase of load; the viscosity of liquid paraffin decreases with the increase of temperature but increases with the increase of load. The variations of viscosity with temperature and load result that the effect of viscosity on the Sommerfeld variable $\eta N/P$ is so small compared to the effect of load on it that the $\eta N/P$ can be simplified to N/P. The relationship between the friction coefficient and the simplified Sommerfeld variable N/P (velocity/load) for pure PTFE sliding against GCr15 bearing steel under lubrication of liquid paraffin is shown in Figure 7. The figure shows that the friction coefficient of PTFE decreases with the increase of load at a constant sliding speed under lubrication of liquid paraffin. Therefore, the variations of friction coefficients with load for the ceramic particle filled PTFE composites under liquid paraffin lubrication can be described by the relationship between the friction coefficient and the simplified Sommerfeld variable N/P as shown in Figure 7. However, when the load increases to the load limits of the PTFE composites, the friction and wear of the PTFE composites increase sharply.

It was found in the experiments that under certain loads in liquid paraffin lubrication there were some serious deformations or obvious cracks

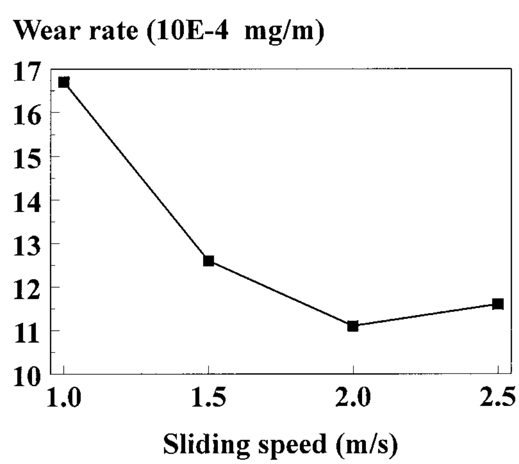

Figure 6 The variation of the wear rate with sliding speed for the PTFE + 30 vol % B_2O_3 composite sliding against GCr15 bearing steel under lubrication of liquid paraffin (load, 800 N).

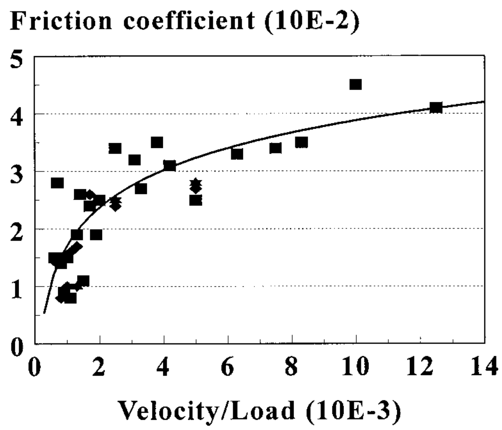

Figure 7 The relationship between the friction coefficient and the simplified Sommerfeld variable *N/P* (velocity/load) for pure PTFE sliding against GCr15 bearing steel under lubrication of liquid paraffin.

on the worn surfaces of ceramic particle filled PTFE composites. These loads occurring on the worn surfaces of the PTFE composites are the load limits of the PTFE composites. Figure 8 shows the load limits of ceramic particle filled PTFE composites sliding against GCr15 bearing steel in liquid paraffin lubrication. The results in Figure 8 show that the load limits of the PTFE + 30 vol % BN, PTFE + 30 vol % Si_3N_4, PTFE + 30 vol % SiC, PTFE, and PTFE + 30 vol % B_2O_3 composite are 400, 600, 800, 1000, and 1200 N, respectively, at a sliding speed of 2.5 m/s in liquid paraffin lubrication. It is believed that the interactions between liquid paraffin and the PTFE composites, especially the absorption of liquid paraffin into the surface layers of the PTFE composites, reduce the mechanical strength and load-supporting capacity of the PTFE composites.[15,16] This would lead to the deterioration of the friction

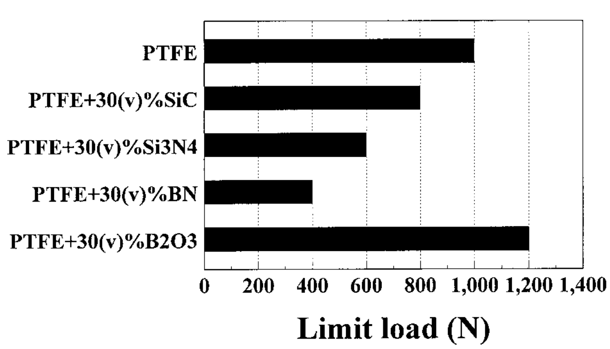

Figure 8 Limit loads of the ceramic particle filled PTFE composites sliding against GCr15 bearing steel under lubrication of liquid paraffin (sliding speed, 2.5 m/s).

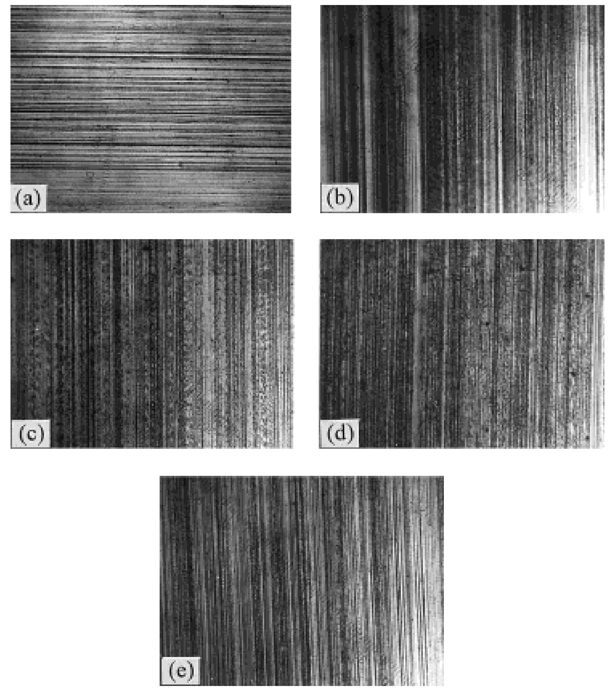

Figure 9 Optical micrographs of the transfer films formed on the surface of GCr15 bearing steel for the ceramic particle filled PTFE composites under the dry friction condition (sliding speed, 1.5 m/s; load, 100 N; original magnification ×128): (a) pure PTFE, (b) PTFE + 30 vol % SiC, (c) PTFE + 30 vol % Si_3N_4, (d) PTFE + 30 vol % BN, and (e) PTFE + 30 vol % B_2O_3.

and wear properties of these ceramic particle filled PTFE composites under higher loads in liquid paraffin lubrication. But when the load increases to the load limits of the PTFE composites, the friction and wear of the PTFE composites increase sharply. Because the load-supporting capacity of the PTFE + 30 vol % B_2O_3 composite is higher than that of the other PTFE composites in liquid paraffin lubrication, the friction and wear properties of the PTFE + 30 vol % B_2O_3 composite are better than those of the other PTFE composites under higher loads in liquid paraffin lubrication.

Optical Microscope Investigation of Transfer Films

The optical micrographs of the transfer films formed on the surface of GCr15 bearing steel for ceramic particle filled PTFE composites under both dry and liquid paraffin lubricated conditions are shown in Figures 9 and 10, respectively. It can be seen from Figure 9 that there are some obvious transfer films formed on the surface of GCr15 bearing steel for SiC, Si_3N_4, BN, or B_2O_3 filled

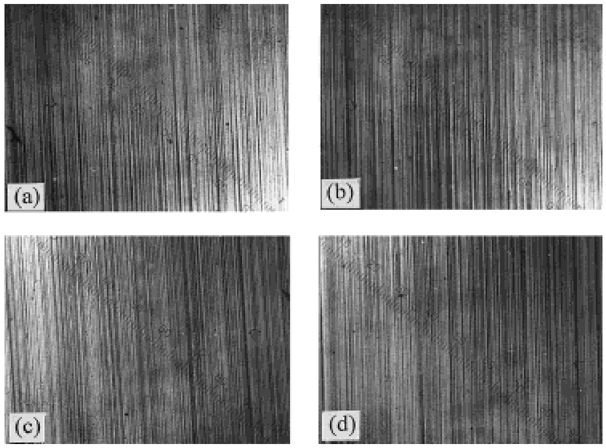

Figure 10 Optical micrographs of the transfer films formed on the surface of GCr15 bearing steel for the ceramic particle filled PTFE composites under lubrication of liquid paraffin (sliding speed, 2.5 m/s; original magnification ×128): (a) PTFE + 30 vol % SiC, 800-N load; (b) PTFE + 30 vol % Si_3N_4, 600-N load; (c) PTFE + 30 vol % BN, 400-N load; and (d) PTFE + 30 vol % B_2O_3, 1200-N load.

PTFE composites under dry friction conditions but no obvious transfer films formed on the surface of GCr15 bearing steel for pure PTFE. Correlating the above investigation results with the results of friction and wear tests under dry friction conditions, it is believed that the ceramic particles SiC, Si_3N_4, BN, and B_2O_3 enhance the adhesion of transfer films to the surface of GCr15 bearing steel and thus promote the transfer of the PTFE composites onto the surface of the steel, so they greatly reduce the wear of the PTFE composites.[3,4] The results in Figure 9 show that the transfer films formed on the surface of GCr15 bearing steel of the Si_3N_4, BN, or B_2O_3 filled PTFE composites are more uniform than those of SiC filled PTFE composite. This indicates that it is difficult to form uniform transfer films on the surface of GCr15 bearing steel for the PTFE + 30 vol % SiC composite. However, Si_3N_4, BN, or B_2O_3 filled PTFE composites can easily form transfer films on the surface of GCr15 bearing steel; then the friction between the PTFE composites and GCr15 bearing steel can be transformed to the friction between the PTFE composites and its transfer films formed on the surface of GCr15 bearing steel. Therefore, the friction properties of Si_3N_4, BN, or B_2O_3 filled PTFE composites are better than that of the SiC filled PTFE composite under dry friction conditions.

Comparison of the results in Figure 10 to those in Figure 9 shows that the transfer of the SiC, Si_3N_4, BN, or B_2O_3 filled PTFE composites onto the surface of GCr15 bearing steel can be greatly reduced by lubrication with liquid paraffin but the transfer still takes place.[17,18] This indicates that the formation of lubricating oil films on the rubbing surfaces greatly improves the lubrication condition of the friction pair, so the friction and wear, as well as the transfer, of these ceramic particle filled PTFE composites can be greatly reduced. These analysis results are consistent with the results of the friction and wear tests.

SEM Examination of Worn Surfaces

We found in the experiments that under dry friction conditions the width of the wear scar on the worn surface of pure PTFE was about 12 mm but the width and the depth of the wear scars on the worn surfaces of SiC, Si_3N_4, BN, or B_2O_3 filled PTFE composites were much smaller than those of pure PTFE. Meanwhile, the width of the wear scars on the worn surfaces of SiC or Si_3N_4 filled PTFE composites was smaller than that of BN or B_2O_3 filled PTFE composites. Figure 11 shows the electron micrographs of the worn surfaces of ceramic particle filled PTFE composites sliding against GCr15 bearing steel under dry friction conditions. It can be seen from the figure that there are still some smaller wear scars in the large wear scars of these ceramic particle filled PTFE composites but the worn surfaces of the SiC or Si_3N_4 filled PTFE composites are rougher than those of the BN or B_2O_3 filled PTFE composite. This indicates that the ceramic particles SiC and Si_3N_4 in the PTFE composites serve as abrasive particles during the friction process, so they increase the friction coefficients of the PTFE composites. However, because the load-supporting capacity of SiC and Si_3N_4 in the PTFE composites is better than that of BN and B_2O_3, the antiwear properties of SiC or Si_3N_4 filled PTFE composites are better than those of BN or B_2O_3 filled PTFE composites. Therefore, it can be deduced from the above investigation and analysis results that the ceramic particles SiC, Si_3N_4, BN, and B_2O_3 can greatly reduce the wear of the PTFE composites but the wear-reducing actions of SiC and Si_3N_4 are much better than those of BN and B_2O_3.

Figure 12 shows electron micrographs of the worn surfaces of ceramic particle filled PTFE composites sliding against GCr15 bearing steel under lubrication of liquid paraffin. The results in Figure 12 show that there are still some obvious wear scars on the worn surface of pure PTFE under lubrication of liquid paraffin but no obvious

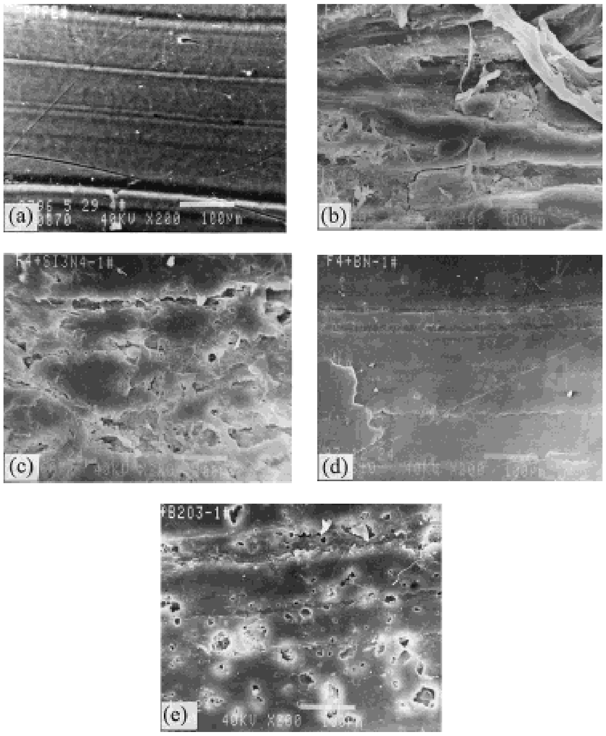

Figure 11 Electron micrographs of the worn surfaces of ceramic particle filled PTFE composites sliding against GCr15 bearing steel under the dry friction condition (sliding speed, 1.5 m/s; load, 100 N): (a) pure PTFE, (b) PTFE + 30 vol % SiC, (c) PTFE + 30 vol % Si_3N_4, (d) PTFE + 30 vol % BN, and (e) PTFE + 30 vol % B_2O_3.

wear scars on the worn surfaces of SiC, Si_3N_4, BN, or B_2O_3 filled PTFE composites. However, there are some obvious cracks on the worn surfaces of SiC, Si_3N_4, BN, or B_2O_3 filled PTFE composites. We believe that the interaction between liquid paraffin and the PTFE composites, especially the absorption of liquid paraffin into the surface layers of the PTFE composites, creates some cracks on the worn surfaces of these ceramic particle filled PTFE composites and the creation and development of the cracks reduces the mechanical strength and load-supporting capacity of these PTFE composites. This would lead to the deterioration of the friction and wear properties of these ceramic particle filled PTFE composites under higher loads in liquid paraffin lubrication. The above investigation and analysis results are consistent with the results of the friction and wear tests.

CONCLUSIONS

1. The antiwear properties of PTFE composites can be greatly improved by filling PTFE with SiC, Si_3N_4, BN, or B_2O_3. The wear of these ceramic particle filled PTFE composites can be decreased by 1–2 orders of magnitude compared to that of pure PTFE under dry friction conditions. However, the wear-reducing actions of SiC and Si_3N_4 are more effective than those of BN and B_2O_3. The wear-reducing action of Si_3N_4 is the most effective, while that of B_2O_3 is the worst.
2. Under dry friction conditions, B_2O_3 reduces the friction coefficient of the PTFE composite but SiC, Si_3N_4, and BN increase the friction coefficients of the PTFE composites. Of the SiC, Si_3N_4, or BN filled PTFE composites, the friction coefficient of the PTFE + 30 vol % SiC composite is the highest and that of the PTFE + 30 vol % BN composite is the lowest.
3. The friction and wear properties of the ceramic particle filled PTFE composites can be greatly improved by lubrication with liq-

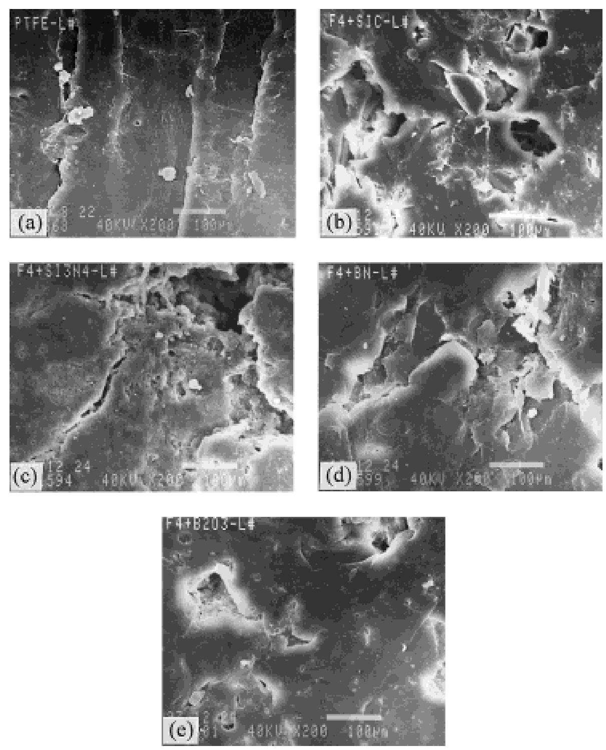

Figure 12 Electron micrographs of the worn surfaces of the ceramic particle filled PTFE composites sliding against GCr15 bearing steel under lubrication of liquid paraffin (sliding speed, 2.5 m/s): (a) pure PTFE, 1000-N load; (b) PTFE + 30 vol % SiC, 800-N load; (c) PTFE + 30 vol % Si_3N_4, 600-N load; (d) PTFE + 30 vol % BN, 400-N load; and (e) PTFE + 30 vol % B_2O_3, 1200-N load.

uid paraffin, and the friction coefficients of these PTFE composites can be decreased by 1 order of magnitude compared to those under dry friction conditions.

4. Under lubrication of liquid paraffin, the wear of the ceramic particle filled PTFE composites increases with the increase of load but the friction coefficients of these PTFE composites decrease with the increase of load. However, when the load increases to the load limits of the PTFE composites, the friction and wear of the PTFE composites increase sharply.
5. The PTFE + 30 vol % B_2O_3 composite exhibits excellent friction and wear properties under lubrication of liquid paraffin. Therefore, the PTFE + 30 vol % B_2O_3 composite can be more suitably used in practice than other ceramic particle filled PTFE composites under oil-lubricated conditions.
6. Ceramic particles of SiC, Si_3N_4, BN, and B_2O_3 enhance the adhesion of the transfer films to the surface of GCr15 bearing steel, so they greatly reduce the wear of the PTFE composites. However, the transfer of the PTFE composites onto the surface of GCr15 bearing steel can be greatly reduced by lubrication with liquid paraffin, but the transfer still takes place.
7. The interaction between liquid paraffin and ceramic particle filled PTFE composites, especially the absorption of liquid paraffin into the surface layers of the PTFE composites, creates some cracks on the worn surfaces of the ceramic particle filled PTFE composites. The creation and development of the cracks reduces the mechanical strength and load-supporting capacity of the PTFE composites, thus leading to the deterioration of friction and wear properties of the PTFE composites under higher loads in liquid paraffin lubrication.

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