Friction and Wear Characteristics of Fiber- and Whisker-Reinforced PTFE Composites under Oil Lubricated Conditions

QUN-JI XUE, ZHAO-ZHU ZHANG, 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

Received 25 July 1997; accepted 25 November 1997

ABSTRACT: Four kinds of polytetrafluoroethylene (PTFE)-based composites, such as pure PTFE, PTFE + 30(vol.)% carbon fiber, PTFE + 30(vol.)% glass fiber, and PTFE + 30(vol.)% $K_2Ti_6O_{13}$ whisker composite, were prepared. The friction and wear properties of these fiber- and whisker-reinforced PTFE composites sliding against GCr15-bearing steel (SAE52100 steel) under both dry and liquid paraffin lubricated conditions were studied by using an MHK-500 ring-block wear tester (Timken wear tester). Then the worn surfaces of these PTFE composites and the transfer films formed on the surface of GCr15-bearing steel were investigated by using a Scanning Electron Microscope (SEM) and an Optical Microscope, respectively. Experimental results show that the friction and wear properties of the PTFE composites reinforced with carbon fiber, glass fiber, and a $K_2Ti_6O_{13}$ whisker can be greatly improved by lubrication with liquid paraffin, and the friction coefficients of these PTFE composites can be decreased by one order of magnitude compared to those under dry friction conditions. Meanwhile, the wear of the fiber- and whisker-reinforced PTFE composites in liquid paraffin lubrication increases with the increase of load, but the friction coefficients of these PTFE composites first decrease with the increase of load, and then increase with the increase of load. The variations of friction coefficients with load for these PTFE composites in liquid paraffin lubrication can be described properly by the Stribeck's curve as given in this article. However, when the load increases to the load limits of the PTFE composites, their friction and wear increase sharply. SEM and optical microscope investigations show that the interactions between liquid paraffin and the PTFE composites, especially the absorption of liquid paraffin into the surface layers of the PTFE composites, create some obvious cracks on the worn surfaces of the PTFE composites. The creation and the development of the cracks reduce the load-carrying capacity of the PTFE composites, and therefore lead to the increase of the friction and wear of the PTFE composites under higher loads. Meanwhile, the transfer of the fiber- and whisker-reinforced PTFE composites onto the counterfaces can be greatly reduced by lubrication with liquid paraffin, but the transfer still takes place. © 1998 John Wiley & Sons, Inc. J Appl Polym Sci 69: 1393–1402, 1998

Key words: PTFE composites; fibers and whiskers; oil lubrication; friction and wear; frictional surfaces

INTRODUCTION

In air, as is well known, the wear rate of polytetrafluoroethylene (PTFE) can be decreased by a factor of 10–100 when fillers such as chopped glass or carbon fibers are used.[1–5] Therefore, the PTFE composites reinforced with glass or carbon fibers have been widely used in practice because of their excellent antiwear properties. However, with enlargement of application fields of PTFE-based composites in practice, more and more PTFE-

Correspondence to: Z.-Z. Zhang.

Journal of Applied Polymer Science, Vol. 69, 1393–1402 (1998)
© 1998 John Wiley & Sons, Inc. CCC 0021-8995/98/071393-10

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

C	M_n	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

based composites have been used in fluid environments, so it is very important to study the friction and wear behaviors of PTFE-based composites in fluid environments. It has been found that many polymers wear much more in water than in air, and the wear of glass fiber-reinforced PTFE composites is especially high in aqueous (water) environments.[4–9] However, until now, much less information has been available about the oil lubricated friction and wear properties as well as the mechanisms of the PTFE composites reinforced with fibers or whiskers. Therefore, it is essential to study the friction and wear behaviors of the PTFE composites reinforced with fibers or whiskers under oil lubricated conditions.

The purpose of this work is to study the friction and wear behaviors of the PTFE composites reinforced with fibers or whiskers under oil lubricated conditions, and gain some insights into the friction and wear mechanisms of these PTFE composites in oil lubrication. It is expected that this study may be helpful to the use of the fiber or whisker reinforced PTFE composites in practice under oil lubricated conditions.

EXPERIMENTAL

The friction and wear tests were carried out on an MHK-500 ring-block wear tester (Timken wear tester) with a steel ring, which is 49.2 mm in diameter and 13.0 mm in length, rotating on a PTFE composite block, which is $12.3 \times 12.3 \times 18.9$ mm in size. The steel ring, made of GCr15-bearing steel (SAE52100 steel, its chemical composition is listed in Table I), was polished with number 900 grade SiC abrasive paper to a surface roughness of Ra = 0.15 μm. Meanwhile, the surfaces of PTFE composite blocks were polished with number 800 grade SiC abrasive paper to a surface roughness of Ra = 0.2–0.4 μm.

Materials used for preparing PTFE composites include PTFE powder with a grit size of about 30 μm, carbon fiber (CF) and glass fiber (GF) with a diameter from 20 to 30 μm, and length from 30 to 300 μm, and potassium titanate ($K_2Ti_6O_{13}$) whisker (PTW) (made by Shenyang Jinjian Whisker Composite Co. Ltd., P.R. China) with a diameter from 0.2–1.0 μm and a length from 10–80 μm. The PTFE powder, carbon fiber, glass fiber, and the $K_2Ti_6O_{13}$ whisker were dried at 120°C for 4 h to remove moisture. The proportion of carbon fiber, glass fiber, and $K_2Ti_6O_{13}$ whisker in PTFE was 30% by volume. This proportion was selected on the basis of the work of critical packing reported by Bahadur and Gong.[10] First, the PTFE powder was mixed completely with the fibers and whiskers, respectively. Second, these mixtures were molded into the blocks by compression molding under the pressure of 50 MPa. Finally, the PTFE composite blocks were sintered at 380°C for 3 h in air, and then cooled freely to the room temperature. Four kinds of PTFE-based composites, such as pure PTFE, PTFE + 30(vol.)% CF, PTFE + 30(vol.)% GF, and PTFE + 30(vol.)% PTW composite, were prepared in this experiment. The lubricating oil used in the experiments was liquid paraffin, which was added to the rubbing surfaces at a rate of 30 drops per minute during the tests. The liquid paraffin used in this experiment is a refined mineral oil—it has no any additives. The main composition of liquid paraffin is paraffin; its typical characteristics are listed in Table II.

The friction and wear tests were performed at room temperature in ambient atmosphere (the

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

Table III Friction and Wear Results of the Fiber- and Whisker-Reinforced PTFE Composites under Dry Friction Condition

Materials	Friction Coefficients	Wear (mg)
PTFE	0.257	385.4
PTFE + 30 (vol.) % carbon fiber	0.288	4.4
PTFE + 30 (vol.) % glass fiber	0.301	2.8
PTFE + 30 (vol.) % $K_2Ti_6O_{13}$ whisker	0.315	5.6

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

relative humidity is between 35 and 40%) with a sliding speed from 1.0 to 2.5 m/s and loads from 100 to 400N for the dry friction condition or 100 to 1200N for the oil-lubricated conditions. Each friction and wear test was performed for 30 min. Before each test started, the surfaces of the PTFE composite block and the GCr15-bearing steel ring were cleaned by rubbing with a soft cloth dipped in acetone and then dried in air. In this experiment, three to five samples were tested at each condition. The friction coefficient and wear were the average values of these tests.

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, while 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 the fiber- and whisker-reinforced PTFE composites and the transfer films formed on the surface of GCr15-bearing steel ring were examined by using a JEM-1200EX/S scanning electron microscope (made in Japan) and an optical microscope, respectively.

RESULTS AND DISCUSSION

Friction and Wear Properties under Dry Friction Conditions

The friction and wear results of fiber- and whisker-reinforced PTFE composites sliding against GCr15-bearing steel under dry friction condition are shown in Table III. The results in Table III show that the reinforcement of PTFE with carbon fiber, glass fiber, or $K_2Ti_6O_{13}$ whisker increases the friction coefficients of the PTFE composites compared to that of pure PTFE. However, for the carbon fiber-, glass fiber-, and $K_2Ti_6O_{13}$ whisker-reinforced PTFE composites, the friction property of the carbon fiber-reinforced PTFE composite is the best, while that of the $K_2Ti_6O_{13}$ whisker-reinforced PTFE composite is the worst. The results in Table III also indicate that the antiwear properties of the PTFE composites can be greatly improved by the reinforcement of PTFE with carbon fiber, glass fiber, and $K_2Ti_6O_{13}$ whisker, and wear of these PTFE composites can be decreased by two orders of magnitude compared to that of pure PTFE. But the antiwear property of the glass fiber-reinforced PTFE composite is the best, and that of the $K_2Ti_6O_{13}$ whisker-reinforced PTFE composite is the worst. This indicates that the wear-reducing action of glass fiber is the most effective, and that of $K_2Ti_6O_{13}$ whisker is the worst under dry friction conditions.

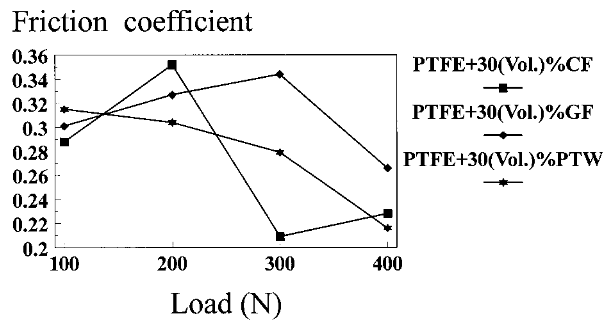

Figure 1 Variations of friction coefficients with load for the fiber- and whisker-reinforced PTFE composites under dry friction conditions (sliding speed, 1.5 m/s).

The variations of friction coefficients and wear with load for the fiber- and whisker-reinforced PTFE composites sliding against GCr15-bearing steel under dry friction conditions are shown in Figures 1 and 2, respectively. It can be seen from Figure 1 that the friction coefficient of the $K_2Ti_6O_{13}$ whisker-reinforced PTFE composite decreases with the increase of load from 100 to 400N. However, the friction coefficients of the carbon fiber- and glass fiber-reinforced PTFE com-

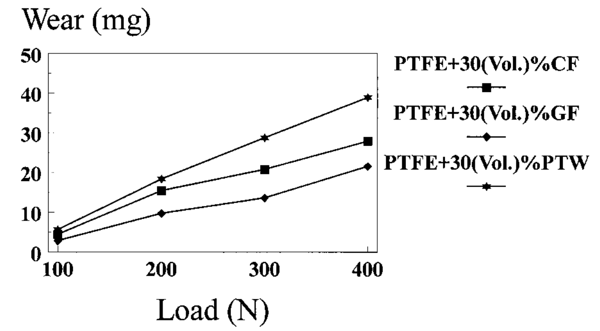

Figure 2 Variation of wear with load for the fiber- and whisker-reinforced PTFE composites in dry friction conditions (sliding speed, 1.5 m/s).

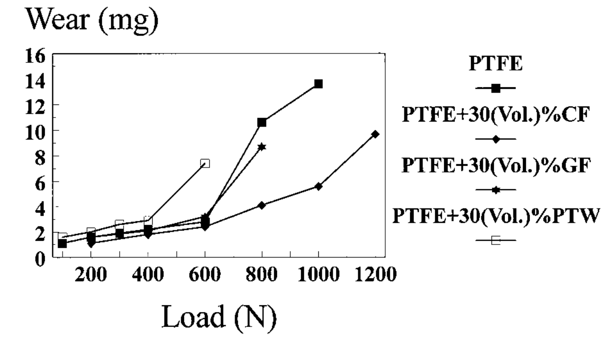

Figure 4 Variation of wear with load for the fiber- and whisker-reinforced PTFE composites under lubrication of liquid paraffin (sliding speed, 2.5 m/s).

posites first increase with the increase of load, and then decrease as the load increases. Under the load of 400*N*, the friction-reducing property of the $K_2Ti_6O_{13}$ whisker-reinforced PTFE composite is the best, and that of the glass fiber-reinforced PTFE composite is the worst. The results in Figure 2 show that the wear of the fiber- and whisker-reinforced PTFE composites increases with the increase of load. Under the load from 100 to 400*N* in dry friction conditions, the antiwear property of the glass fiber-reinforced PTFE composite is the best, that of the $K_2Ti_6O_{13}$ whisker-reinforced PTFE composite is the worst.

Friction and Wear Properties in Oil Lubricated Conditions

The variations of friction coefficients and wear with load for the fiber- and-whisker reinforced PTFE composites sliding against GCr15-bearing steel under lubrication of liquid paraffin are shown in Figures 3 and 4, respectively. The results in Figure 3 indicate that the friction-reducing properties of fiber- and whisker-reinforced PTFE composites can be greatly improved by lubrication with liquid paraffin, and the friction coefficients of the PTFE composites can be decreased by one order of magnitude compared to those under dry friction conditions. Meanwhile, the friction coefficients of the fiber- and whisker-reinforced PTFE composites in liquid paraffin lubrication first decrease with the increase of the load, and then increase as the load increases. The results in Figure 4 indicate that, comparing the wear results to those in the dry friction conditions, the antiwear properties of the fiber- and whisker-reinforced PTFE composites can be greatly improved by lubrication with liquid paraffin, and the wear of the PTFE composites increases with the increase of load. When the load increases to the load limits of the PTFE composites, the friction and wear of the PTFE composites increase sharply. It can also be seen from Figure 3 and 4 that, under higher load ($p \geq 600N$) in liquid paraffin lubrication, the friction and wear-reducing properties of the carbon fiber-reinforced PTFE composite are much better than those of the PTFE composites reinforced with glass fiber or $K_2Ti_6O_{13}$ whisker. Therefore, the PTFE + 30(vol.)% CF composite is much more suitable for application under oil lubricated conditions.

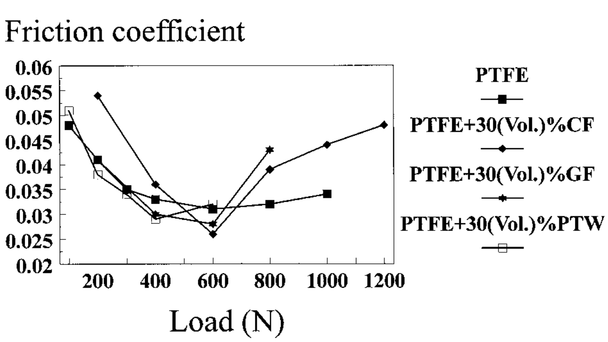

Figure 3 Variations of friction coefficients with load for the fiber- and whisker-reinforced PTFE composites under lubrication of liquid paraffin (sliding speed, 2.5 m/s).

Variations of friction coefficient and wear rate with sliding speed for the glass fiber-reinforced PTFE composite sliding against GCr15-bearing steel under lubrication of liquid paraffin are shown in Figures 5 and 6, respectively. It can be seen from Figures 5 and 6 that the friction coefficient of the glass fiber-reinforced PTFE composite decreases with the increase of sliding speed under lubrication of liquid paraffin, but its wear rate

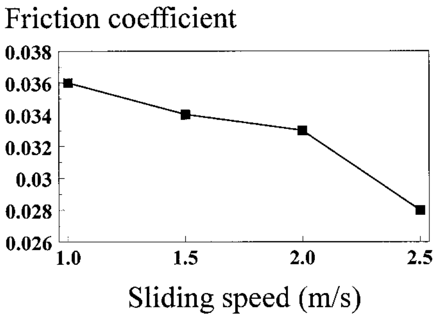

Figure 5 Variation of friction coefficient with sliding speed for glass fiber-reinforced PTFE composite under lubrication of liquid paraffin (load, 600N).

first decreases with the increase of sliding speed, and then increases as the sliding speed increases. It is believed that, with the increase of sliding speed, a layer of lubricating oil film can be more easily formed on the frictional surface, then the lubrication condition of the frictional surface can be greatly improved; therefore, the friction and wear decrease. However, with the further increase of sliding speed, the temperature at the frictional surface increases, this would lead to the reduction of the mechanical strength and the load-carrying capacity of the PTFE composite; therefore, its wear rate increases. It is known that the glass fiber-reinforced PTFE composite wear much more in water than in air,[4,5] but the results in Figures 2, 4, and 6 show that the antiwear property of the glass fiber-reinforced PTFE composite in liquid paraffin is much better than that in air (dry friction condition). Therefore, it can be deduced that the glass fiber-reinforced PTFE composite is much more suitable for application in oil than in air and in water.

It was found in the experiments that there were some serious deformation or obvious cracks on the worn surfaces of the fiber- and whisker-reinforced PTFE composites under certain loads in liquid paraffin lubrication. These loads under which serious deformation or obvious cracks occurred to these PTFE composites were the load limits of the PTFE composites. Figure 7 gives load limits of the fiber- and whisker-reinforced PTFE composites sliding against GCr15-bearing steel under lubrication of liquid paraffin. It can be seen from Figure 7 that, at the sliding speed of 2.5 m/s in liquid paraffin lubrication, the load limit of PTFE is lower than that of the carbon fiber-reinforced PTFE composite, but higher than those of the glass fiber- and the $K_2Ti_6O_{13}$ whisker-reinforced PTFE composites. Therefore, it can be deduced from the results in Figures 3, 4, and 7 that the interactions between the liquid paraffin and the PTFE composites, especially the absorption of liquid paraffin into the surface layers of the PTFE composites, reduce the load-carrying capacity of the PTFE composites and so, in turn, lead to the increase of the friction and wear of the PTFE composites under higher loads.[11–13]

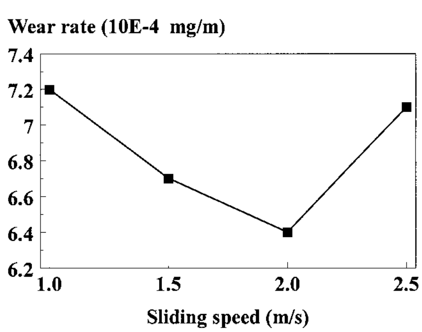

Figure 6 Variation of wear rate with sliding speed for glass fiber-reinforced PTFE composite under lubrication of liquid paraffin (load, 600N).

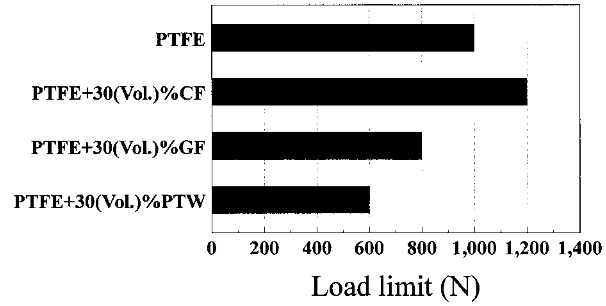

Figure 7 Load limits of the fiber- and whisker-reinforced PTFE composites in liquid paraffin lubrication (sliding speed, 2.5 m/s).

When the sliding speed is a constant, the variations of friction coefficients with load for the fiber- and whisker-reinforced PTFE composites in liquid paraffin lubrication can be described by the Stribeck's curves of friction coefficients against the Sommerfeld variable $\eta N/P$, where η is the viscosity of liquid paraffin, N is the rotation speed of GCr15-bearing steel ring and, P is the load applied.[14,15] At a constant sliding speed, the temperature at the frictional surface increases with the increase of load, while the viscosity of liquid paraffin decreases with the temperature increase 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 N/P is so small compared to the effect of load on it that N/P can be approximated to N/P.

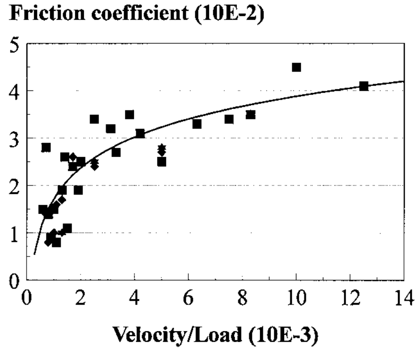

Figure 8 Variation of friction coefficient with the Sommerfeld variable *N*/*P* (velocity/load) for pure PTFE sliding against GCr15-bearing steel under lubrication of liquid paraffin.

Figure 8 gives variation of friction coefficient with the Sommerfeld variable *N*/*P* (velocity/load) for the PTFE sliding against GCr15-bearing steel under lubrication of liquid paraffin. The results in Figure 8 show that, at a constant sliding speed, the friction coefficient decreases with the increase of load. Therefore, the variations of friction coefficients with load for the fiber- and whisker-reinforced PTFE composites in liquid paraffin lubrication can be explained properly by the Stribeck's curve as given in Figure 8. However, under higher loads in liquid paraffin lubrication, the temperature increase at frictional surface can result in reduction of the load-carrying capacity of the PTFE composites, and therefore leads to the increase of friction and wear. When the load increases to the load limits of the PTFE composites, their friction and wear increase sharply.

Optical Microscope Investigation of Transfer Films

The optical micrographs of the transfer films formed on the surface of GCr15-bearing steel for the fiber- and whisker-reinforced PTFE composites under both dry and oil-lubricated conditions are shown in Figures 9 and 10. The results in Figure 9 show that there are obvious transfer films formed on the counterfaces of the fiber- and whisker-reinforced PTFE composites under dry friction conditions, but no obvious transfer films formed on the counterface of the PTFE. Comparing the results in Figure 9 to the results of wear tests under dry friction conditions shows that the

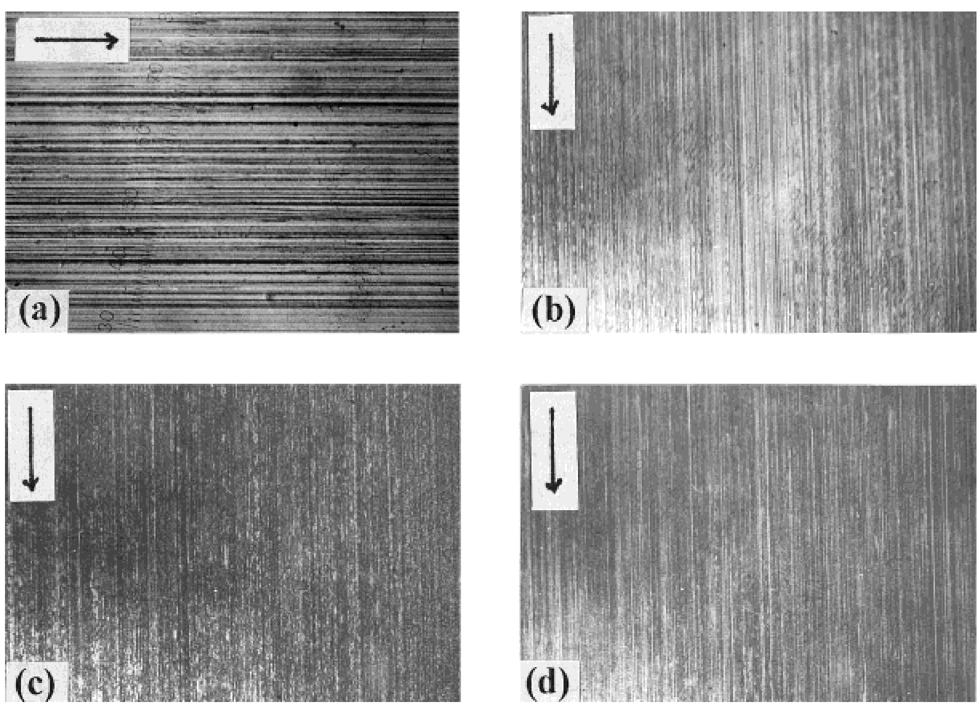

Figure 9 Optical micrographs of transfer films formed on the surface of GCr15-bearing steel for the fiber- and whisker-reinforced PTFE composites under dry friction conditions (128×) (sliding speed, 1.5 m/s) (the arrow shows sliding direction). (a) PTFE, 100*N*; (b) PTFE + 30(vol.)% carbon fiber, 300*N*; (c) PTFE + 30(vol.)% glass fiber, 300*N*; (d) PTFE + 30(vol.)% $K_2Ti_6O_{13}$ whisker, 300*N*.

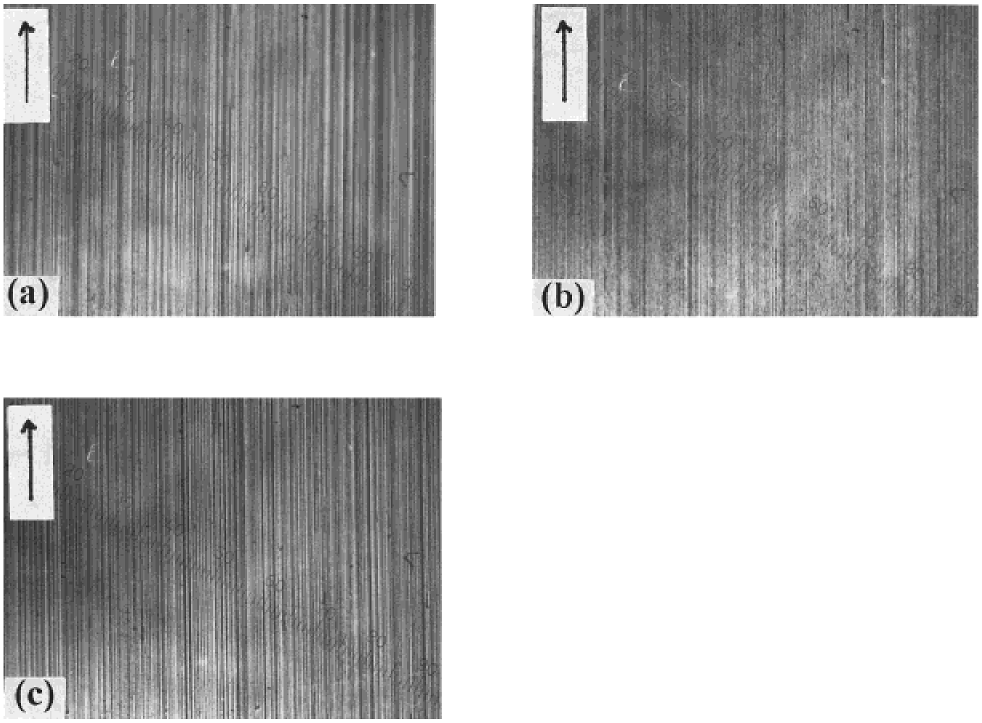

Figure 10 Optical micrographs of transfer films formed on the surface of GCr15-bearing steel for fiber- and whisker-reinforced PTFE composites under lubricaiton of liquid paraffin (128×) (sliding speed, 2.5 m/s) (the arrow shows sliding direction). (a) PTFE + 30(vol.)% carbon fiber, 1200*N*; (b) PTFE + 30(vol.)% glass fiber, 800*N*; (c) PTFE + 30(vol.)% $K_2Ti_6O_{13}$ whisker, 600*N*.

carbon fiber, glass fiber, and $K_2Ti_6O_{13}$ whisker enhance the adhesion of the transfer films to the surface of GCr15-bearing steel, promote the transfer of the PTFE composites onto the surface of GCr15-bearing steel, and, therefore, greatly reduce the wear of the PTFE composites.[16,17] However, it was found in the experiments that the transfer films formed on the surface of GCr15-bearing steel for the $K_2Ti_6O_{13}$ whisker-reinforced PTFE composite were easily rubbed off during the test. This indicates that the adhesion between the transfer film and the surface of GCr15-bearing steel was weak. The transfer film was gradually rubbed off once it formed on the surface of GCr15-bearing steel, so it was difficult to form uniform transfer films on the counterface. Therefore, the friction and wear reducing properties of the $K_2Ti_6O_{13}$ whisker-reinforced PTFE composite are poorer than those of the carbon fiber- and glass fiber-reinforced PTFE composites in dry friction condition.

Comparison the results in Figure 10 to those in Figure 9 shows that 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.[18,19] This indicates that a layer of lubricating oil film was formed on the frictional surfaces of the PTFE composites, so the friction and wear of the PTFE composites were greatly reduced. The above analyses are consistent with the results of friction and wear tests.

SEM Investigation of Worn Surfaces

It was found in the experiments that the width of the wear scar on the worn surface of PTFE was about 12 mm, but the width and the depth of the wear scars on the worn surfaces of the fiber- and whisker-reinforced PTFE composites were much smaller than those of pure PTFE under dry friction conditions. Figure 11 gives electron micrographs of the worn surfaces of the PTFE composites reinforced with fibers and whisker in the dry friction condition. It can be seen from Figure 11 that there are still some smaller wear scars in the large wear scar of the pure PTFE, but the worn surfaces of the fiber- and whisker-reinforced PTFE composites are smoother than that of the PTFE. For the fiber- and whisker-reinforced

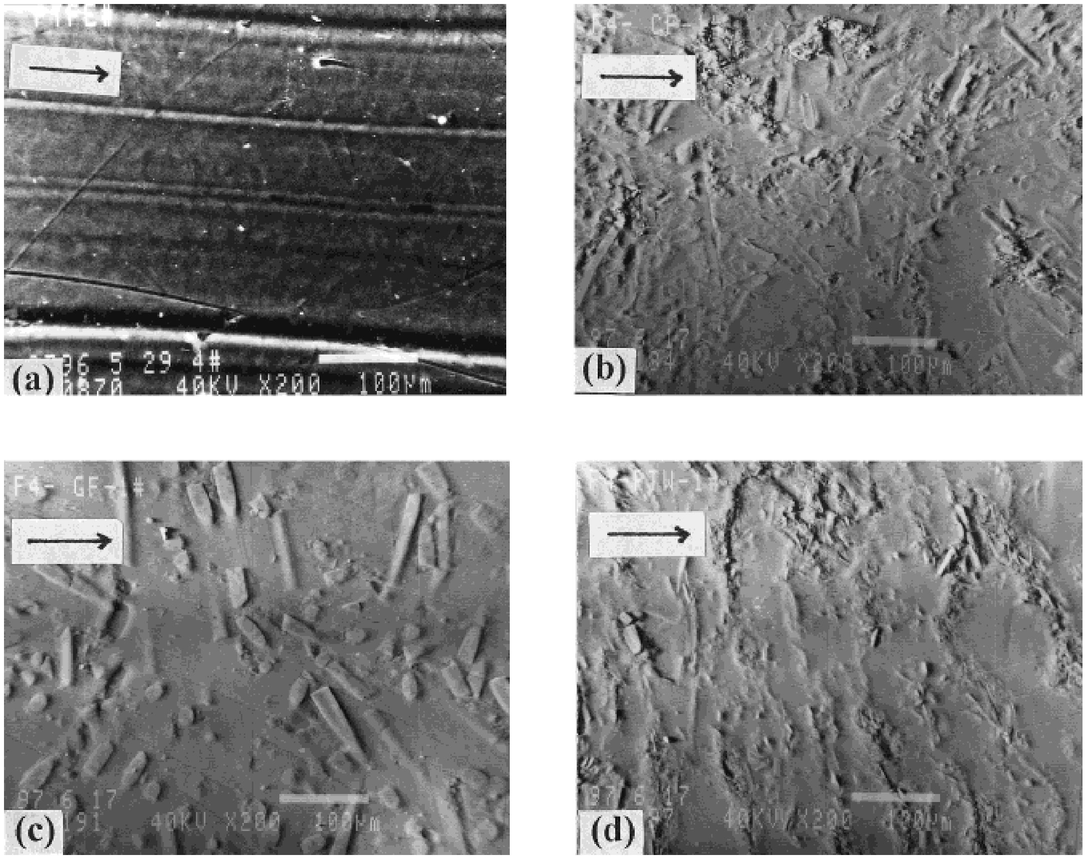

Figure 11 Electron micrographs of the worn surfaces of the fiber- and whisker-reinforced PTFE composites under dry friction condition (sliding speed, 1.5 m/s; load 100N) (the arrow shows sliding direction). (a) PTFE; (b) PTFE + 30(vol.)% carbon fiber; (c) PTFE + 30(vol.)% glass fiber; (d) PTFE + 30(vol.)% $K_2Ti_6O_{13}$ whisker.

PTFE composites in the dry friction condition, the worn surface of the glass fiber reinforced-PTFE composite is the smoothest, while that of the $K_2Ti_6O_{13}$ whisker-reinforced PTFE composite is the roughest. Therefore, it can be deduced from the above investigation results that the glass fiber, carbon fiber, and $K_2Ti_6O_{13}$ whisker raise the load-carrying capacity of the PTFE composites, so they greatly reduce the wear of the PTFE composites.[1,20] Meanwhile, the wear-reducing action of the glass fiber is the most effective, that of the carbon fiber is the second, and that of $K_2Ti_6O_{13}$ whisker is the worst. The above analysis results are consistent with the results of wear under dry friction conditions.

The electron micrographs of the worn surfaces of the fiber- and whisker-reinforced PTFE composites in liquid paraffin lubrication are shown in Figure 12. It can be seen from Figure 12 that there are some obvious cracks on the worn surfaces of the fiber- and whisker-reinforced PTFE composites under the limit loads in liquid paraffin lubrication, but there are only some obvious wear scars on the worn surface of pure PTFE.[21] This indicates that the interactions between liquid paraffin and the PTFE composites, especially the absorption of liquid paraffin into the surface layers of PTFE composites, create some cracks on the worn surfaces of the PTFE composites. The creation and the development of these cracks reduce the load-carrying capacity of the PTFE composites, and therefore lead to the increase of the friction and wear of the PTFE composites under higher loads.[11–13] These analyses are also consistent with the results of the friction and wear tests in liquid paraffin lubrication.

CONCLUSIONS

1. The carbon fiber, glass fiber, and $K_2Ti_6O_{13}$ whisker can reduce the wear of PTFE by a

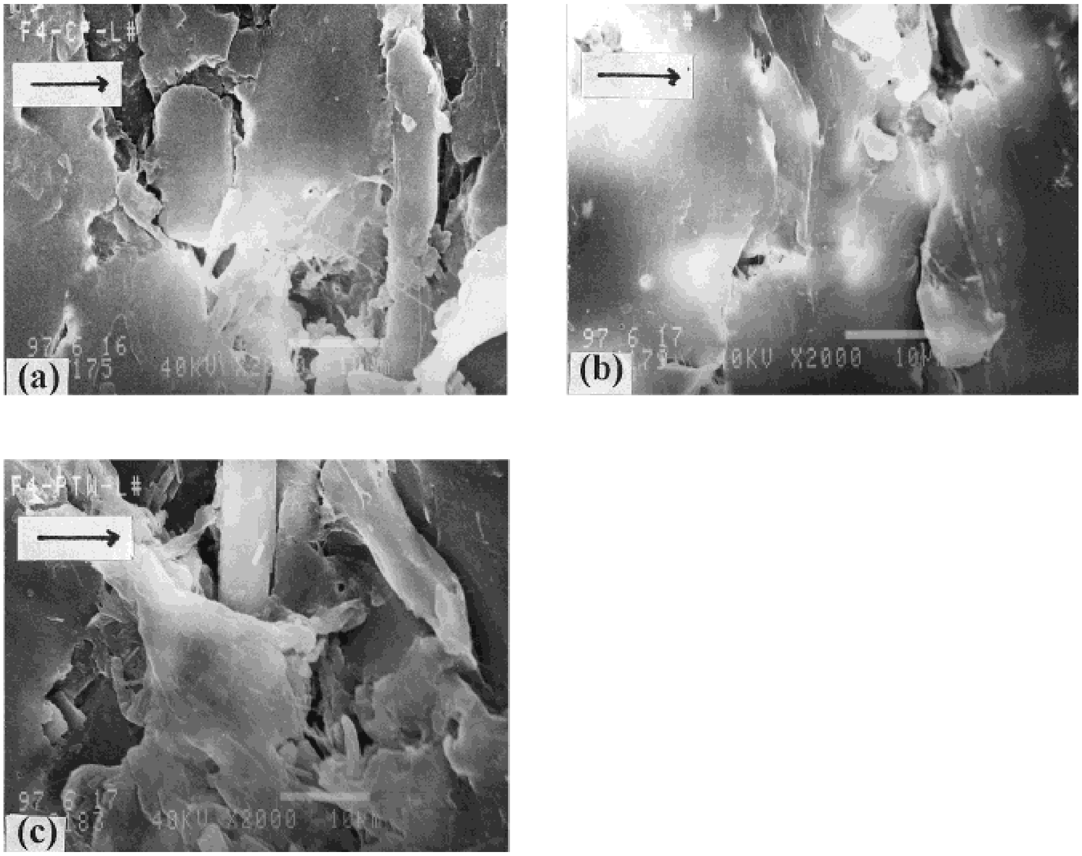

Figure 12 Electron micrographs of the worn surfaces of the fiber- and whisker-reinforced PTFE composites under lubrication of liquid paraffin (sliding speed, 2.5 m/s) (the arrow shows sliding direction). (a) PTFE + 30(vol.)% carbon fiber, 1200*N*; (b) PTFE + 30(vol.)% glass fiber, 800*N*; (c) PTFE + 30(vol.)% $K_2Ti_6O_{13}$ whisker.

factor of about 100 under dry friction conditions, but they increase the friction coefficient of PTFE. The wear-reducing action of glass fiber is the most effective, and that of the $K_2Ti_6O_{13}$ whisker is the worst.

2. The friction and wear-reducing properties of the fiber- and whisker-reinforced PTFE composites can be greatly improved by lubrication with liquid paraffin, and the friction coefficients of these PTFE composites can be decreased by one order of magnitude compared to those under dry friction conditions.
3. Under lubrication of liquid paraffin, the wear of fiber- and whisker-reinforced PTFE composites increases with the increase of load, but their friction coefficients first decrease with the increase of load, and then increase with the increase of load. When the load increases to the load limits of the PTFE composites, the friction and wear of the PTFE composites increase sharply.
4. The antiwear property of the glass fiber-reinforced PTFE composite in liquid paraffin is much better than that in air. Therefore, the glass fiber-reinforced PTFE composite is much more suitable for application in oil than in air or in water.
5. The variations of friction coefficients with load for the fiber- and whisker-reinforced PTFE composites in liquid paraffin lubrication can be explained properly by the Stribeck's curve, as given in this article.
6. The interactions between 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 PTFE composites. The creation and the development of these cracks reduce the load-carrying capacity of the PTFE composites, and therefore lead to the increase of the friction and wear of the PTFE composites under higher loads.

7. The fibers and the whisker enhance the adhesion of the transfer films to the counterfaces, and promote the transfer of the PTFE composites onto the counterfaces; therefore, they greatly reduce the wear of the PTFE composites. However, the transfer of the PTFE composites onto the counterfaces can be greatly reduced by lubrication of liquid paraffin, but the transfer still takes place.

REFERENCES

1. J. K. Lancaster, *J. Phys. D.,* **1,** 549 (1968).
2. J. K. Lancaster, in *New Directions in Lubrication, Materials, Wear, and Surface Interactions,* R. William, Ed., Noyes, Park Ridge, NJ, 1985, p. 320.
3. B. Arkles, J. Theberge, and M. Schireson, *J. Am. Soc. Lubr. Eng.,* **33,** 33 (1977).
4. Y. Yamada and K. Tanaka, in *Fraction and Wear of Polymer Composites,* K. Friedrich, Ed., Elsevier, Amsterdam, 1986, p. 137.
5. M. Watanabe, *Wear,* **158,** 79 (1992).
6. J. K. Lancaster, *Wear,* **20,** 315 (1972).
7. K. Tanaka, in *Wear of Materials,* K. C. Ludeman, Ed., ASME, New York, 1979, p. 563.
8. Y. Zhongqian, L. Manquing, and K. Hailing, in *Wear of Materials,* K. C. Ludeman, Ed., ASME, New York, 1981, p. 153.
9. J. W. M. Mens and A. W. J. de Gee, *Wear,* **149,** 255 (1991).
10. S. Bahadur and D. Gong, in *Wear of Materials,* K. C. Ludeman and R. G. Bayer, Eds., ASME, New York, 1991, p. 177.
11. B. J. Briscoe, T. A. Stolarski, and G. J. Davies, *Tribol. Int.,* **17,** 129 (1984).
12. D. C. Evans, *Proc. 3rd Leeds-Lyon Symp. on Wear of Non-Metallic Materials,* Mechanical Engineering Publications, London, 1978, p. 47.
13. C. Rubenstein, *J. Appl. Phys.,* **32,** 1445 (1961).
14. P. M. Dickens, J. L. Sullivan, and J. K. Lancaster, *Wear,* **112,** 273 (1986).
15. Y. Yamaguchi, *Tribology of Plastic Materials,* Elsevier, Amsterdam, 1990, p. 203.
16. B. J. Briscoe, *Wear,* **27,** 19 (1974).
17. S. Bahadur and D. Tabor, *Wear,* **98,** 1 (1984).
18. Z.-Z. Zhang, W.-C. Shen, and W.-M. Liu et al., *Wear,* **193,** 163 (1996).
19. Z.-Z. Zhang, W.-C. Shen, and W.-M. Liu et al., *Wear,* **196,** 164 (1996).
20. K. Tanaka, in *Wear of Materials,* K. C. Ludeman, Ed., ASME, New York, 1977, p. 510.
21. Z.-Z. Zhang, W.-M. Liu, Q.-J. Xue, and W.-C. Shen, *J. Appl. Polym. Sci.,* **66,** 85 (1997).