Friction and Wear Characteristics of PTFE Composites Filled with Metal Oxides under Lubrication by Oil

ZHAO-ZHU ZHANG, WEI-MIN LIU, QUN-JI XUE, 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 19 December 1996; accepted 30 January 1997

ABSTRACT: Four kinds of polytetrafluoroethylene(PTFE)-based composites, such as pure PTFE, PTFE+30%(v)PbO, PTFE+30%(v)Pb_3O_4, and PTFE+30%(v)Cu_2O composite, were prepared. The friction and wear properties of these metal oxides filled PTFE composites sliding against GCr15 bearing steel in both dry and lubricated conditions were studied by using an MHK-500 ring-block wear tester. Then the worn surfaces of these PTFE composites and the transfer films of these PTFE composites formed on the surface of GCr15 bearing steel were examined by using a Scanning Electron Microscope (SEM) and an Optical Microscope, respectively. Experimental results show that the friction and wear properties of these metal oxide-filled PTFE composites can be greatly improved by liquid paraffin lubrication, and the friction coefficients can be decreased by one order of magnitude. Meanwhile, the interactions between liquid paraffin and metal oxide-filled PTFE composites, especially the absorption of liquid paraffin into the surface layers of these PTFE composites, reduce the mechanical strength and the load-carrying capacity of these metal oxide-filled PTFE composites. This leads to the deterioration of the friction and wear properties of these PTFE composites. Investigations of the frictional surfaces show that Pb_3O_4, Cu_2O, and PbO enhance the adhesion of the transfer films to the surface of GCr15-bearing steel, and thus promote the transfer of the PTFE composites onto the surface of GCr15-bearing steel. Therefore, they greatly reduce the wear of the PTFE composites. However, the transfer of these PTFE composites onto the counterfaces can be greatly reduced by lubrication with liquid paraffin.

Key words: PTFE composites; metal oxides; oil lubrication

INTRODUCTION

Low-friction coefficient, high thermal stability, and chemical resistance make PTFE an attractive polymer for sliding applications. However, its poor mechanical strength, excessive viscoelastic deformation under load, and a high wear rate greatly limit the application of PTFE in practice. Therefore, various fillers have been used to reinforce PTFE, and the friction and wear mechanisms of PTFE composites have been studied by many authors.[1–3] It is found that almost any type of filler or fiber can greatly reduce the wear of PTFE composites.

Metal oxides, such as PbO, Pb_3O_4, etc., have been used as high-temperature lubricants. Their lubricity is usually very poor at room temperature in atmosphere. Briscoe et al.[4] studied the friction and wear behaviors of high-density polyethylene (HDPE) composites filled with CuO and Pb_3O_4. They found that filling CuO or Pb_3O_4 to HDPE can greatly reduce the wear of HDPE composites, but CuO and Pb_3O_4 increase the friction coefficient of the HDPE composites. Pocock et al.[5] studied the interactions between PTFE and metal oxides such as PbO, Pb_3O_4, and CuO, etc., by using

Correspondence to: Z.Z. Zhang.
Journal of Applied Polymer Science, Vol. 66, 85–93 (1997)
 CCC 0021-8995/97/010085-09

differential scanning calorimetry (DSC). They found that no reaction occurred between PTFE and metal oxides from room temperature to 450°C. But Gao et al.[6] found, by using DSC and X-ray photoelectron spectroscopy (XPS), that chemical reaction between PTFE and lead oxide occurred under static and frictional conditions. However, metal oxides as important fillers for PTFE, the effects of metal oxides on the friction and wear behaviors of PTFE composites, the synergistic effects between PTFE and metal oxides, and their effects on the friction and wear properties of PTFE composites should be studied further.

At present, almost all of the studies on the friction and wear properties of metal oxide-filled polymers are related to unlubricated conditions; much less information is available about the lubricated friction and wear of metal oxide-filled PTFE composites. It is known that many plastics wear much more in water than in air.[7–9] Watanabe et al.[10–12] studied the wear behavior of PTFE composites in aqueous environments (water); they found that the wear of PTFE composites filled with glass fibers is especially high in an aqueous environment. Briscoe et al.[13,14] studied the lubricated wear of some polymers. They pointed that the absorption of fluid into the surface layers of polymers can change their mechanical properties and so, in turn, influence the friction and wear of the polymers. However, up to now, systematic studies on the friction and wear properties of metal oxide-filled PTFE composites under oil lubrication have not been reported yet. Therefore, it is essential to study the friction and wear behaviors of PTFE composites filled with metal oxides in oil lubrication.

The purpose of this study is to investigate systematically the friction and wear behaviors of PTFE composites filled with metal oxides under oil lubrication, and gain some insights into the friction and wear mechanisms of metal oxide-filled PTFE composites in oil lubrication. It is expected that this study may be helpful to the application of PTFE composites filled with metal oxides in practice.

EXPERIMENTAL

Materials used for preparing PTFE composites include PTFE powder with a grit size of about 30 μm, Cu_2O, Pb_3O_4, and PbO powders with a grit size of about 76 μm. First, metal oxides of Cu_2O, Pb_3O_4, and PbO were mixed completely with PTFE powder, respectively, then the mixtures were molded and sintered into the blocks (samples). In this experiment, four kinds of PTFE-based composites, such as pure PTFE, PTFE+30%(v)Cu_2O, PTFE+30%(v)Pb_3O_4, and PTFE+30%(v)PbO composites, were prepared. The surface of PTFE composite blocks were polished with number 800 grade SiC abrasive paper, washed in acetone, and dried in air.

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.

In this experiment, the friction and wear tests were performed at room temperature in ambient atmosphere with a sliding speed from 1.0 to 2.5 m/s and loads from 100 to 400*N* for the dry friction condition or 100 to 1000*N* for the oil lubricated condition. Each friction and wear test was performed for 30 min. Before each test, the surfaces of PTFE composite block and GCr15-bearing steel ring were cleaned by rubbing with a soft cloth dipped in acetone and then dried in air. The lubricating oil used in this experiment was liquid paraffin, which was added to the rubbing surfaces at a rate of 30 drops per minute during the test. The wear was detected by the weight loss of the PTFE composite blocks after each test by an analytical scale (precision: 0.1 mg). The friction coefficient was determined by measuring the friction torque. The friction torque was detected by a torque recording system, so the friction coefficient could be calculated by the formula of friction coefficient for the Timken wear tester. The friction coefficient was the average value of those in the last 10 min. Finally, the worn surfaces and the transfer films of these PTFE composites formed on the surface of GCr15-bearing steel were examined by using SEM and optical microscopy.

RESULTS AND DISCUSSION

Friction and Wear Properties in Dry Friction Condition

The friction and wear results of PTFE composites filled with metal oxides sliding against GCr15-bearing steel in the dry friction condition are shown in Table II. The results in Table II indicate

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

that PbO has little effect on the friction coefficient of the composite, while Cu_2O and Pb_3O_4 reduce the friction coefficient of the composites, but the friction reducing action of Pb_3O_4 is better than that of Cu_2O. Meanwhile, the wear of these PTFE composites can be greatly reduced by filling PTFE with PbO, Cu_2O, or Pb_3O_4. The wear-reducing action of Pb_3O_4 is the best, that of Cu_2O is the second, and that of PbO is the worst. Therefore, the PTFE+30%(v)Pb_3O_4 composite exhibits excellent friction and wear-reducing properties in the dry friction condition.

The variations of friction coefficients and wear with load for PTFE composites filled with metal oxides sliding against GCr15-bearing steel in the dry friction condition are shown in Figures 1 and 2, respectively. It can be seen from Figure 1 that the friction coefficient of the PTFE+30%(v)PbO composite decreases with the increase of the load from 100 to 400N, but the friction coefficients of PTFE+30%(v)Pb_3O_4 and PTFE+30%(v)Cu_2O composites decrease with the increase of the load from 100 to 300N, and then increase with the increase of the load. Meanwhile, the friction property of the PTFE+30%(v)Pb_3O_4 composite is better than those of the other two PTFE composites. The results in Figure 2 show that the wear of these PTFE composites increases with the increase of the load. The wear of the PTFE+30%(v)Cu_2O composite increases sharply when the load is higher than 300N, but the wear of the PTFE+30%(v)Pb_3O_4 composite is still very small even under higher loads, and the wear of the PTFE+30%(v)Pb_3O_4 composite is lower than that of the PTFE+30%(v)PbO composite by a factor of 2 orders of magnitude under a different load.

It is known that PTFE composites are viscoelastic materials; their deformation under load is viscoelastic. Therefore, the variation of friction coefficient with the load follows the equation $\boldsymbol{\mu} = \mathbf{KN}^{(\mathbf{n}-1)}$, where $\boldsymbol{\mu}$ is the friction coefficient, $\mathbf{N}$ is the applied load, $\mathbf{K}$ is a constant, and $\mathbf{n}$ is also a constant, its value between 2/3 and 1 ($2/3 < \mathbf{n} < 1$). According to this equation, the friction coefficients of PTFE composites decrease with the increase of the load. But when the load increases to the load limit of the PTFE composites, the friction and wear increase sharply.

Table II The Friction and Wear Results of PTFE Composites Filled with Metal Oxides in Dry Friction Condition

Material	Friction Coefficient	Wear (mg)
PTFE	0.257	385.4
PTFE + 30%(v)Pb_3O_4	0.232	1.1
PTFE + 30%(v)Cu_2O	0.245	5.9
PTFE + 30%(v)PbO	0.261	125.6

Sliding speed: 1.5 m/s; Load: 100 N; Time: 30 min.

Friction and Wear Properties under Oil Lubrication

The variations of friction coefficients and wear with the load for PTFE composites filled with metal oxides sliding against GCr15-bearing steel under lubrication of liquid paraffin are shown in Figures 3 and 4, respectively. It can be seen from Figure 3 that, comparing the friction results to those in the dry friction condition, the friction properties of these 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. Meanwhile, the friction coefficients of these PTFE composites decrease with the in-

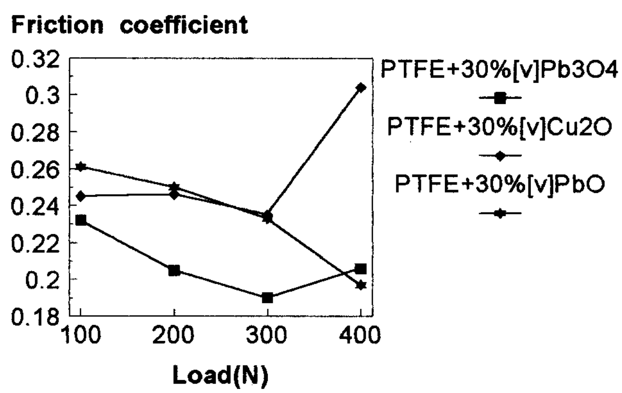

Figure 1 Variations of friction coefficients with the load for PTFE composites filled with metal oxides in the dry friction condition (speed: 1.5 m/s).

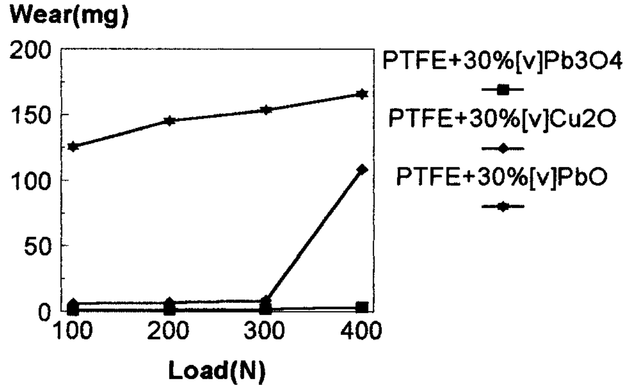

Figure 2 Variations of wear with the load for PTFE composites filled with metal oxides in the dry friction condition (speed: 1.5 m/s).

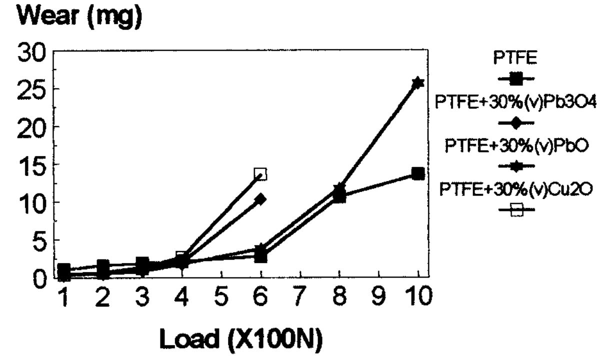

Figure 4 Variations of wear with the load for PTFE composites filled with metal oxides under lubrication by liquid paraffin (speed: 2.5 m/s).

crease of the load. When the load increases to the load limit of the PTFE composites, their friction coefficients increase sharply. The results in Figure 4 show that, comparing the wear results to those in the dry friction condition, the wear-reducing properties of these PTFE composites can be greatly improved by lubrication with liquid paraffin, and the wear of the PTFE composites increases with the increase of the load. When the load increases to the load limit of the PTFE composites, the wear increases sharply.

Variations of friction coefficient and wear rate with sliding speed for the PTFE+30%(v)PbO composite under lubrication by liquid paraffin are given in Figures 5 and 6, respectively. The results in Figures 5 and 6 show that the friction coefficient and wear rate of the PTFE+30%(v)PbO composite decrease with the increase of the sliding speed under lubrication by liquid paraffin. It is known that, with the increase of the sliding speed, a layer of lubricating oil film can be more easily formed on the rubbing surfaces, then the lubrication condition at the rubbing surfaces can be greatly improved. Therefore, the friction coefficient and wear rate decrease with the increase of the sliding speed.

It was found in the experiments that there were some obvious cracks on the worn surfaces of PTFE+30%(v)Cu_2O and PTFE+30%(v)Pb_3O_4 composites under the load of 600N in liquid paraffin lubrication, while there was some serious deformation on the worn surfaces of PTFE and PTFE+30%(v)PbO composites under the load of 1000N. Therefore, 600N is the load limit of PTFE+30%(v)Cu_2O and PTFE+30%(v)Pb_3O_4 composites at the sliding speed of 2.5 m/s under liquid paraffin lubrication, while 1000N is the load limit of PTFE and PTFE+30%(v)PbO composites. Meanwhile, the results from Figures 1–4 show that the friction and wear-reducing properties of PTFE+30%(v)Cu_2O and PTFE+30%(v)Pb_3O_4 composites are better than those of PTFE and PTFE+30%(v)PbO

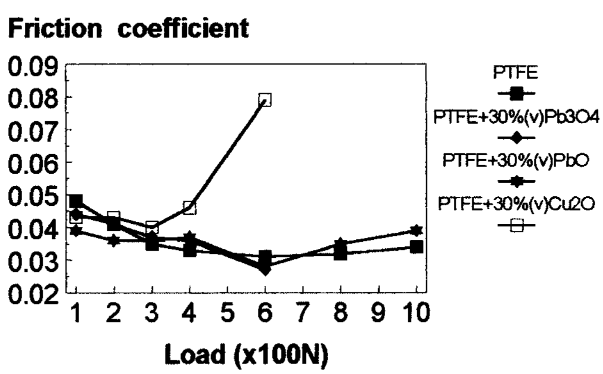

Figure 3 Variations of friction coefficients with the load for PTFE composites filled with metal oxides under lubrication by liquid paraffin (speed: 2.5 m/s).

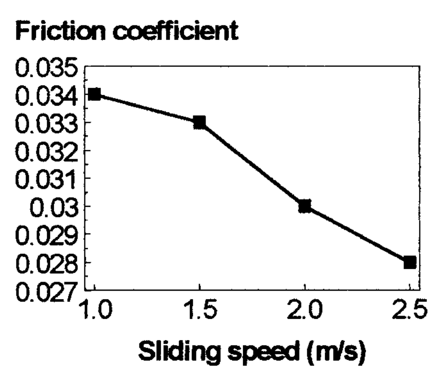

Figure 5 Variation of the friction coefficient with the sliding speed for the PTFE+30%(v)PbO composite under lubrication by liquid paraffin (load: 600N).

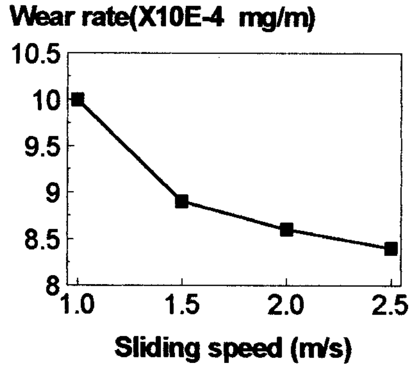

Figure 6 Variation of the wear rate with the sliding speed for the PTFE+30%(v)PbO composite under lubrication by liquid paraffin (load: 600 N).

composites in the dry friction condition, but the friction and wear-reducing properties of PTFE and PTFE+30%(v)PbO composites are much better than those of PTFE+30%(v)Cu_2O and PTFE+30%(v)Pb_3O_4 composites lubricated with liquid paraffin. Therefore, it can be deduced that the interactions between liquid paraffin and PTFE composites, especially the absorption of liquid paraffin into the surface layers of PTFE composites, reduce the mechanical strength and the load-carrying capacity of these metal oxide-filled PTFE composites compared to those of pure PTFE. This leads to the deterioration of the friction and wear properties of the PTFE composites.

When the sliding speed is constant, the variations of friction coefficients with the load for PTFE composites filled with metal oxides under oil lubrication can be described by the formula $\mu \propto \eta \mathbf{N/P}$, where μ is the friction coefficient, η is the viscosity of lubricating oil, **N** is the rotation speed of the steel ring, and **P** is the applied load.[15–17] At a constant sliding speed, the temperature at the rubbing surface increases with the increase of the load. At the same time, the viscosity of the lubricating oil decreases with the increase of temperature, but increases with the increase of the load. The variations of viscosity with load and temperature indicate that the effect of viscosity on the friction coefficient is so small compared to the effect of the load on it that the formula $\mu \propto \eta \mathbf{N/P}$ can be approximated to $\mu \propto \mathbf{N/P}$. Therefore, the friction coefficients of these PTFE composites decrease as the load increases at a constant sliding speed under lubrication by liquid paraffin. However, when the load increases to the load limit of the PTFE composites, the friction and wear of these PTFE composites increase sharply.

According to the above analysis, the formula $\mu \propto \eta \mathbf{N/P}$ can be approximated by $\mu \propto \mathbf{N/P}$ under the conditions in this experiment. The results in Figure 3 show that, when the velocity is constant, the friction coefficient of PTFE composites under lubrication by liquid paraffin decreases with the increase of the load. However, the friction coefficient increases sharply when the load increases to the load limit of PTFE composites. Therefore, the variations of the friction coefficients with the load for PTFE composites filled with metal oxides under lubrication by liquid paraffin can be explained properly by the formula $\mu \propto \eta \mathbf{N/P}$.

SEM Investigation of Worn Surfaces

It was found in the experiments that the width and the depth of the wear scars on the worn surfaces of the PTFE+30%(v)Cu_2O and PTFE+30%(v)Pb_3O_4 composites are much smaller than those of pure PTFE and PTFE+30%(v)PbO composites in the dry friction condition. The width of the wear scar on the worn surface of pure PTFE is about 12 mm, while that of the PTFE+30%(v)PbO composite is about 7 mm. Figure 7 gives electron micrographs of the worn surfaces of PTFE composites filled with metal oxides in the dry friction condition. It can be seen from Figure 7 that the wear scars on the worn surface of the PTFE+30%(v)Pb_3O_4 composite are much smaller than those of the PTFE+30%(v)-Cu_2O composite. Meanwhile, the worn surface of the PTFE+30%(v)PbO composite is very smooth, but there are also some smaller wear scars in the large wear scar of the PTFE. Therefore, it can be deduced from the above investigation results that filling Pb_3O_4, Cu_2O, or PbO to PTFE can greatly reduce the wear of PTFE composites, but the wear reducing action of Pb_3O_4 is the best, that of Cu_2O is the second, and that of PbO is the worst. These analysis results are consistent with the wear data.

Figure 8 gives the electron micrographs of the worn surfaces of PTFE composites filled with metal oxides under liquid paraffin lubrication. It can be seen from Figure 8 that there are some obvious cracks on the worn surfaces of the PTFE+30%-(v)Cu_2O and PTFE+30%(v)Pb_3O_4 composites, but there are only some wear scars on the worn surfaces of PTFE and PTFE+30%(v)PbO composites. Therefore, it can be deduced that the interactions between liquid paraffin and PTFE composites, especially the absorption of liquid paraffin into the surface layers of PTFE composites, reduce the mechanical strength and the load-carrying capacity of the PTFE composites filled with Pb_3O_4 and Cu_2O compared to those of pure PTFE

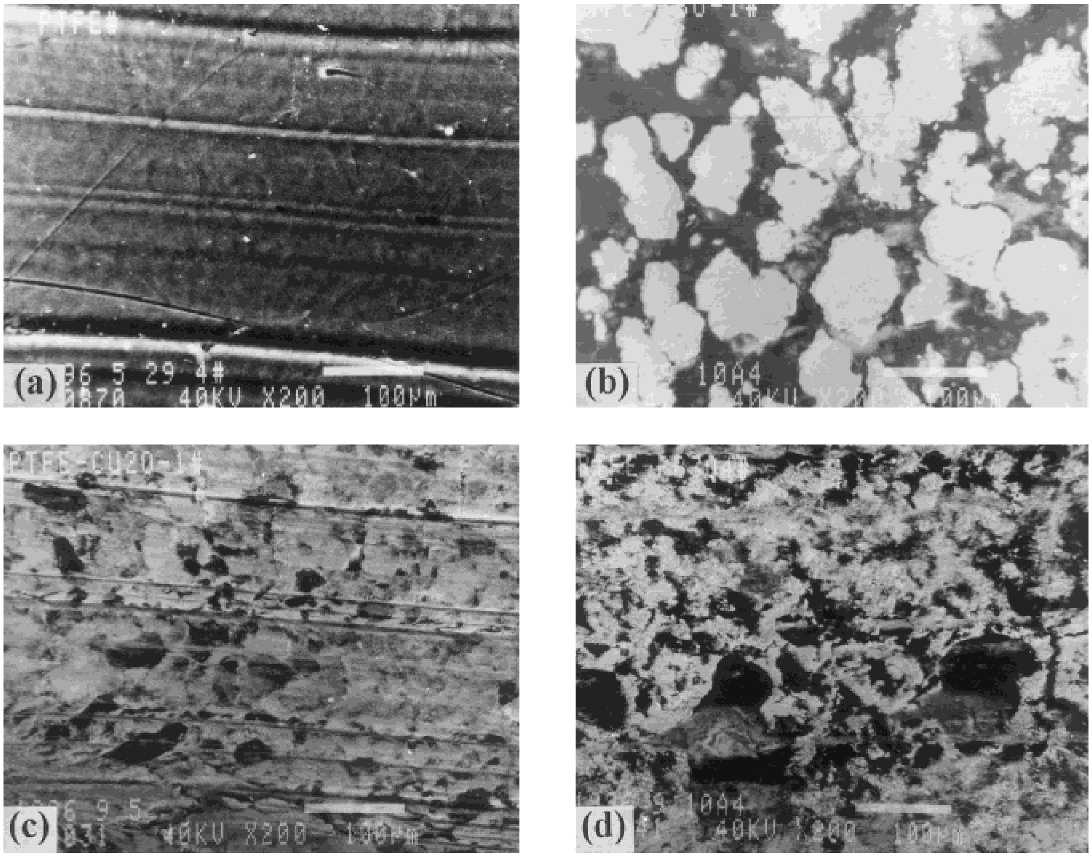

Figure 7 Electron micrographs of the worn surfaces of PTFE composites filled with metal oxides in the dry friction condition. (speed: 1.5 m/s; load: 100*N*). (a) PTFE, (b) PTFE+30%(v)PbO, (c) PTFE+30%(v)Cu_2O, and (d) PTFE+30%(v)Pb_3O_4.

and PTFE+30%(v)PbO composites, and thus influence the friction and wear properties of the PTFE composites.[13,14] These analysis results are also consistent with the experimental results.

Optical Microscopy Examination of Transfer Films

Optical micrographs of the transfer films formed on the surface of GCr15-bearing steel, for PTFE composites filled with metal oxides in the dry friction condition, are shown in Figure 9. It can be seen from Figure 9 that there are obvious transfer films formed on the surface of GCr15-bearing steel for PTFE composites filled with Pb_3O_4, Cu_2O, or PbO, but no obvious transfer film formed on the surface of GCr15-bearing steel for pure PTFE. Correlating the above investigations with the friction and wear results, it can be deduced that metal oxides of Pb_3O_4, Cu_2O, and PbO enhance the adhesion of the transfer films to the surface of GCr15-bearing steel, and thus promote the transfer of PTFE composites onto the surface of GCr15-bearing steel, so the wear of the PTFE composites can be greatly reduced.[3,4] Meanwhile, the results in Figure 9 show that the transfer films formed on the counterfaces of Pb_3O_4 or Cu_2O-filled PTFE composites are much more uniform than those of the PbO-filled PTFE composite. This indicates that the adhesion between the transfer film of the PTFE+30%(v)PbO composite and the surface of GCr15-bearing steel is weak, so it is difficult to form a uniform transfer film on the surface of GCr15-bearing steel. However, Pb_3O_4 or Cu_2O-filled PTFE composites can easily form uniform transfer films on the surface of GCr15-bearing steel, the friction between PTFE composites and GCr15-bearing steel is transformed to the friction between PTFE composites and the transfer films. Therefore, the friction and wear properties of Pb_3O_4 or Cu_2O-filled PTFE composites are better than those of the PbO-filled PTFE composite.

Figure 10 gives the optical micrographs of transfer films formed on the surface of GCr15-bearing steel for PTFE composites filled with metal oxides under lubrication by liquid paraffin.

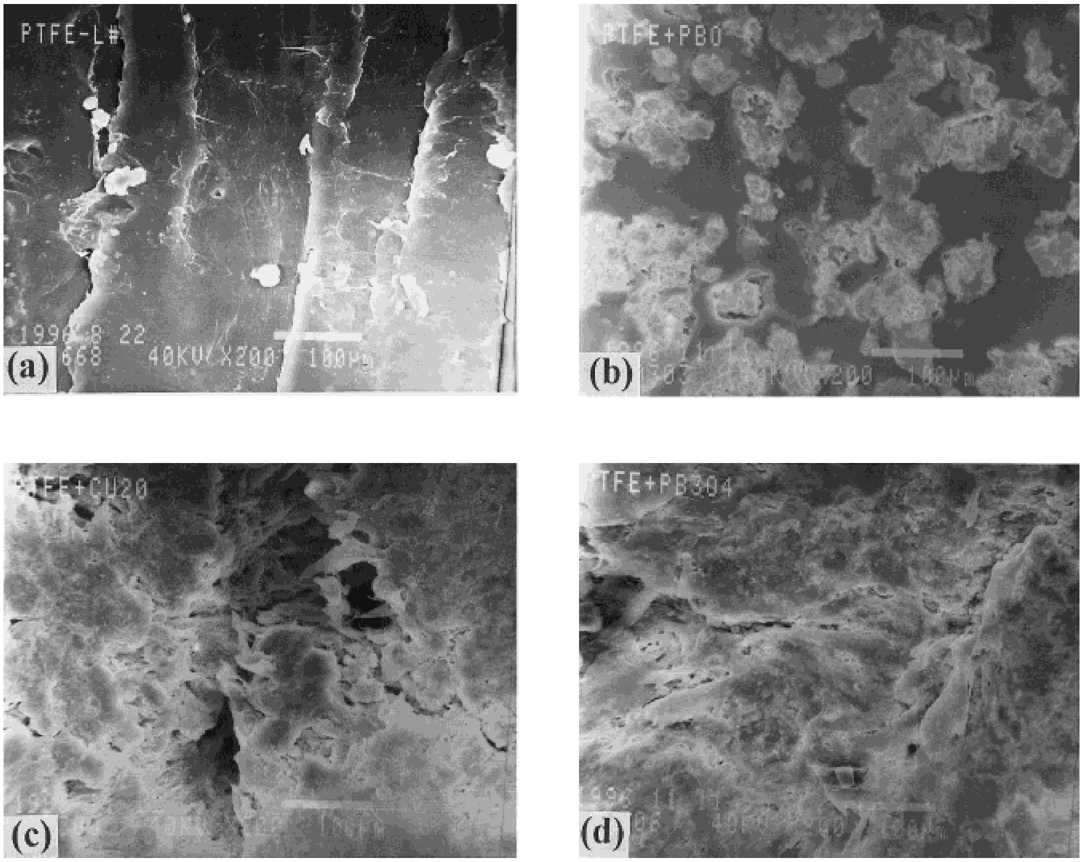

Figure 8 Electron micrographs of the worn surfaces of PTFE composites filled with metal oxides under lubrication by liquid paraffin. (sliding speed: 2.5 m/s). (a) PTFE, 1000*N*; (b) PTFE+30%(v)PbO, 1000*N*; (c) PTFE+30%(v)Cu_2O, 600*N*; and (d) PTFE+30%(v)Pb_3O_4, 600*N*.

It can be seen from Figure 10 that there are not obvious transfer films formed on the counterfaces for PTFE composites in liquid paraffin lubrication. Comparison of the transfer films to those in the dry friction condition indicates that the transfer of PTFE composites onto the counterfaces can be greatly reduced by liquid paraffin lubrication. Therefore, it can be deduced that the wear of PTFE composites filled with metal oxides can be greatly reduced with lubrication by liquid paraffin. All of the above analyses are consistent with the results of friction and wear tests.

CONCLUSIONS

1. Under dry friction condition, PbO has little effect on the friction coefficient, but Pb_3O_4 and Cu_2O reduce the friction coefficients of PTFE composites. Filling PTFE with PbO, Pb_3O_4, or Cu_2O can greatly reduce the wear of these PTFE composites. The wear-reducing action of Pb_3O_4 is the best, and that of PbO is the worst. Therefore, the PTFE+30%(v)Pb_3O_4 composite exhibits excellent friction and wear-reducing properties in the dry friction condition.
2. The friction and wear properties of PTFE composites filled with metal oxides can be greatly improved by liquid paraffin, and the friction coefficients can be decreased by one order of magnitude.
3. The friction coefficients of the PTFE composites filled with metal oxides decrease with the increase of the load under both dry and lubricated conditions, but the wear increases with the increase of the load. Meanwhile, the friction coefficient and the wear rate of the PTFE+30%(v)PbO composite decreases with the increase of the sliding speed under lubrication by liquid paraffin.
4. The interactions between liquid paraffin and these PTFE composites, especially the

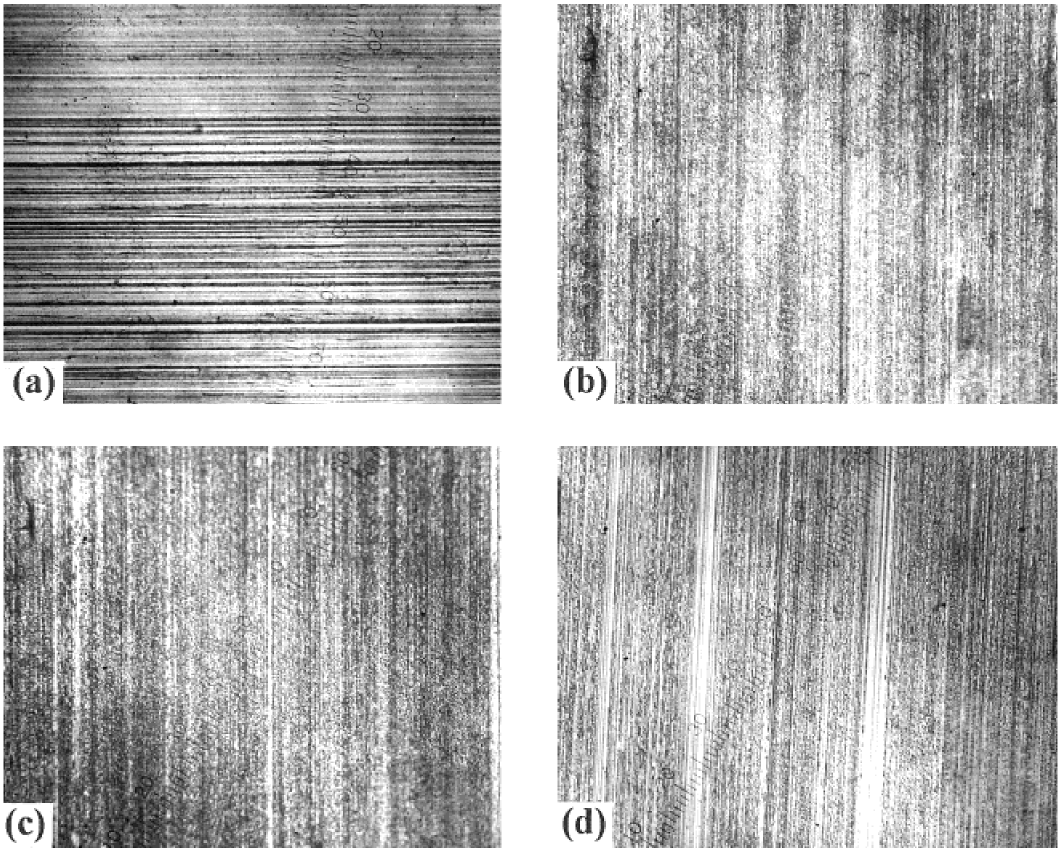

Figure 9 Optical micrographs of the transfer films formed on the surface of GCr15-bearing steel for PTFE composites filled with metal oxides in the dry friction condition (128) (sliding speed: 1.5 m/s). (a) PTFE, 100*N*; (b) PTFE+30%(v)PbO, 300*N*; (c) PTFE+30%(v)Cu_2O, 300*N*; and (d) PTFE+30%(v)Pb_3O_4, 300*N*.

absorption of liquid paraffin into the surface layers of the PTFE composites, reduce the mechanical strength and the load-carrying capacity of these metal oxide-filled PTFE composites compared to those of pure PTFE. This leads to the deterioration of the friction and wear properties of these PTFE composites.

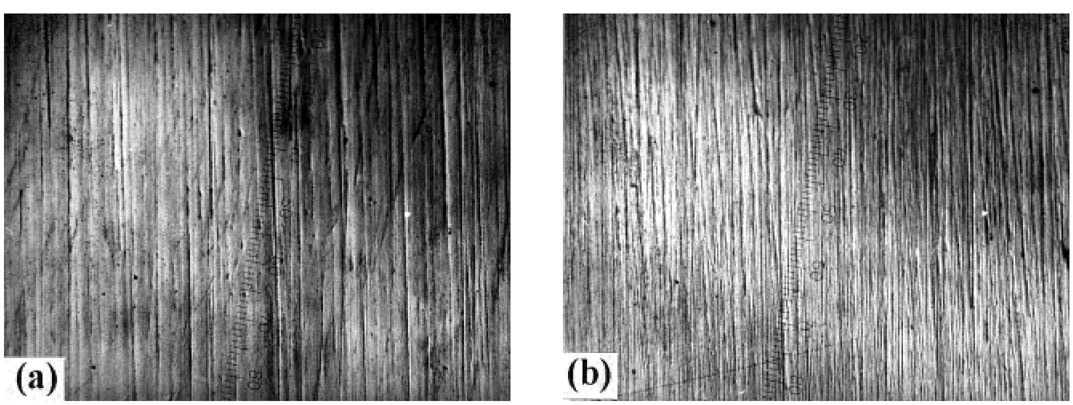

Figure 10 Optical micrographs of the transfer films formed on the surface of GCr15-bearing steel for PTFE composites filled with metal oxides under lubrication by liquid paraffin (128) (sliding speed: 2.5 m/s; load: 300*N*). (a) PTFE+30%(v)PbO; (b) PTFE+30%(v)Pb_3O4.

5. Metal oxides of Pb_3O_4, Cu_2O, and PbO enhance the adhesion of the transfer films to the surface of GCr15-bearing steel 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 these PTFE composites onto the counterfaces can be greatly reduced by lubrication with liquid paraffin.

REFERENCES

1. K. Tanaka and S. Kawakami, *Wear,* **79,** 221 (1982).
2. J. K. Lancaster, *J. Phys. D: Appl. Phys.,* **1,** 549(1968).
3. S. Bahadur and D. Tabor, *Wear,* **98,** 1 (1984).
4. B. J. Briscoe, A. K. Pogosian, and D. Tabor, *Wear,* **27,** 19 (1974).
5. G. Pocock and P. Cadman, *Wear,* **37,** 129 (1976).
6. J. Gao, J. Zhao, and H. Dang, ASLE proc. 3rd Int. Conf. on Solid Lubrication, E. E. Bisson, Ed., ASLE, Park Ridge, NJ, 1984, p. 308.
7. Y. Zhongqian, L. Manquing, and K. Hailing, *Wear of Materials,* S. K. Rhee, A. W. Ruff and K. C. Ludeman, Eds., ASME, New York, 1981, p. 153.
8. T. A. Stolarski, *Wear,* **58,** 103 (1980).
9. C. G. Clarke and C. Allen, *Tribol. Int.,* **24,** 109 (1991).
10. M. Watanabe, *Wear,* **158,** 79 (1992).
11. K. Tanaka, *Friction and Wear of Polymer Composites,* K. Friedrich, Ed., Elsevier, Amsterdam, 1986, p. 137.
12. J. K. Lancaster, *Wear,* **20,** 315 (1972).
13. B. J. Briscoe, T. A. Stolarski, and G. J. Davies, *Tribol. Int.,* **17,** 129 (1984).
14. D. C. Evans, Proc. 3rd Leeds-Lyon Symp. on Wear of Non-metallic Materials, Mechanical Engineering Publications, London, 1978, p. 47.
15. V. Stepina and V. Vesely, *Lubricants and Special Fluids,* Elsevier Science Publishers, Amsterdam, 1992, p. 4.
16. P. M. Dickens, J. L. Sullivan and J. K. Lancaster, *Wear,* **112,** 273 (1986).
17. Y. Yamaguchi, *Tribology of Plastic Materials,* Elsevier, Amsterdam, 1990, p. 203.