Friction and Wear Behavior of PTFE Composites Filled with Rare Earth Compounds Under Oil-Lubricated Conditions

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ABSTRACT: Polytetrafluoroethylene (PTFE)-based composites, filled with CeO_2, CeF_3, and La_2O_3 in volume contents of 5, 10, 15, 20, and 30%, were prepared. Then, the friction and wear behavior of these PTFE composites sliding against GCr15 bearing steel under both dry and liquid paraffin-lubricated conditions was evaluated using an MHK-500 ring-on-block wear tester. Finally, the worn surfaces and the transfer films of these PTFE composites were investigated using a scanning electron microscope (SEM) and an optical microscope. Experimental results showed that filling CeO_2, CeF_3, and La_2O_3 into PTFE can reduce the wear of the PTFE composites by 1–2 orders of magnitude. When the content of CeO_2 in PTFE is 15%, the friction and wear properties of the CeO_2-filled PTFE composite are the best. Meanwhile, when the content of La_2O_3 in PTFE is between 15 and 20%, the PTFE composite filled with La_2O_3 exhibits excellent friction and wear-reducing properties. However, the friction coefficient of the CeF_3-filled PTFE composite increases but its wear decreases with increase in the content of CeF_3 from 5 to 30%. The friction and wear-reducing properties of CeO_2-, CeF_3-, and La_2O_3-filled PTFE composites can be greatly improved by lubrication with liquid paraffin, but the limit loads of the PTFE composites decrease with increase in the content of CeO_2, CeF_3, and La_2O_3 in PTFE (from 5 to 30%) under the same conditions. Investigations of worn surfaces show that the interaction between liquid paraffin and the CeO_2-, CeF_3-, and La_2O_3-filled PTFE composites, especially the absorption of liquid paraffin into the microdefects of the PTFE composites, creates some cracks on the worn surfaces of the PTFE composites and that the creation and development of the cracks reduces the mechanical strength and the load-supporting capacity of the PTFE composites. However, with increase of the content of CeO_2, CeF_3, and La_2O_3 in the PTFE, the microdefects in the PTFE composites also increase, which would lead to increase in the number of the cracks on the worn surfaces of the PTFE composites under load and, so, in turn, lead to the reduction of the limit loads of the CeO_2-, CeF_3-, and La_2O_3-filled PTFE composites under lubrication with liquid paraffin. © 1999 John Wiley & Sons, Inc. J Appl Polym Sci 78: 797–805, 1999

Key words: PTFE composites; rare earth compounds; oil lubrication; friction and wear; frictional surfaces

INTRODUCTION

It is well known that rare earth metals have been widely used in optics, electronics, metallurgy, and chemical engineering because of their special characteristics. In recent years, with the application of rare earth compounds in practice, the application and the study of rare earth compounds in tribology have also become more and more important. At present, the friction and wear properties of rare earth compounds (such as CeO_2, La_2O_3, Y_2O_3, CeF_3, LaF_3, NdF_3, and SmF_3) used

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as high-temperature lubricants, additives in lubricating oil and grease, and bonding coatings have been studied by some coworkers.[1–7] However, until now, much less information has been available about the effect of rare earth compounds as fillers on the friction and wear behavior of polymers (such as PTFE).

Meanwhile, with enlargement of the application fields of 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 better in water than in air,[8–10] and the wear of the PTFE composites filled with only glass fibers is much greater than that of other PTFE composites in water.[11–13] Zhang et al.[14,15] studied the oil-lubricated friction and wear behavior of some PTFE composites; they found that the friction and wear-reducing properties of the PTFE composites filled with metals or metal oxides can be greatly improved by lubrication with liquid paraffin. But up to now, the studies on the friction and wear behavior of the PTFE composites filled with rare earth compounds under oil-lubricated conditions have not been reported. Therefore, it is essential to study the friction and wear behavior of rare-earth-compound-filled PTFE composites in oil-lubricated conditions.

In this work, the effect of rare earth compounds as fillers on the friction and wear of PTFE composites under dry friction conditions was first evaluated with an MHK-500 ring-on-block wear tester. Then, the friction and wear properties of the PTFE composites filled with rare earth compounds under oil-lubricated conditions were studied. Finally, the frictional surfaces were examined by using a scanning electron microscope (SEM) and an optical microscope, and then the friction and wear mechanisms of rare-earth-compound-filled PTFE composites under both dry and oil-lubricated conditions were evaluated. It is expected that this study may be helpful to applications of the PTFE composites filled with rare earth compounds in practice under both dry and oil-lubricated conditions.

EXPERIMENTAL

Preparation of PTFE Composites

PTFE powder with a grit size of about 30 μm, and the rare earth compounds CeO_2, CeF_3, and La_2O_3 with a grit size of about 76 μm were used as the raw materials for preparing the PTFE composites. The proportion of CeO_2, CeF_3, and La_2O_3 as fillers in PTFE was 5, 10, 15, 20, or 30% by volume. First, the PTFE powder was mixed completely with a given content of CeO_2, CeF_3, or La_2O_3. Second, the mixtures were molded into blocks by compression molding under a pressure of 50 MPa. Finally, the PTFE composite blocks were sintered at 380°C for 3 h in air and then cooled freely to room temperature. Fifteen kinds of PTFE-based composites filled with different contents of CeO_2, CeF_3, and La_2O_3 were prepared in this work. The PTFE composite blocks (samples) obtained from the above procedures were $12.3 \times 12.3 \times 18.9$ mm in size. The surfaces of the PTFE composite blocks were polished with no. 800-grade SiC abrasive paper to a surface roughness (R_a) of 0.2–0.4 μm.

Friction and Wear Tests

The friction and wear tests were carried out on an MHK-500 ring-on-block wear tester (Timken wear tester) with a steel ring (diameter, 49.2 mm; length, 13.0 mm) rotating on a PTFE composite block ($12.3 \times 12.3 \times 18.9$ mm in size). The steel ring, made of GCr15 bearing steel (C, 0.950–1.050%; Mn, 0.200–0.400%; Si, 0.150–0.350%; Cr, 1.300–1.650%; P, $<$ 0.027%; S, $<$ 0.020%; Fe, the remainder), was polished with no.900-grade SiC abrasive paper to a surface roughness (R_a) of 0.15 μm. The lubricating oil used in this work was liquid paraffin, which was added to the rubbing surfaces at a rate of 30 drops per minute during the tests.

The friction and wear tests were performed at room temperature in an ambient atmosphere. Each friction and wear test was performed for 30 min. Before each test was started, the surfaces of the PTFE composite blocks and the GCr15 bearing steel ring were cleaned by rubbing with a soft cloth dipped in acetone and then dried in air. The effect of the addition content of CeO_2, CeF_3, and La_2O_3 as fillers on the friction and wear behavior of the PTFE composites was evaluated at the sliding speed of 1.5 m/s under the load of 100 N in dry friction condition. Meanwhile, the friction and wear behavior of the PTFE composites filled with CeO_2, CeF_3, and La_2O_3 of 5, 15, and 30% content under lubrication of liquid paraffin were studied at the sliding speed of 2.5 m/s under the load from 100 to 1600 N. 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

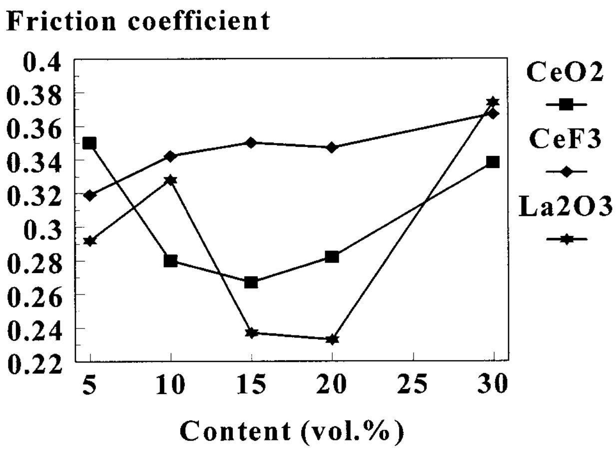


Figure 1 Effect of the addition content of CeO_2, CeF_3, and La_2O_3 as fillers on the friction coefficients of the PTFE composites under the dry friction conditions (sliding speed, 1.5 m/s; load, 100 N).

by a torque-measuring system. The friction coefficient was the average value of those in the steady stage of friction for each test. In this work, three to five replicate tests were conducted for each condition so as to minimize the scattering of the data; the friction coefficient and the wear of the PTFE composites were the average values of these replicate tests for each condition.

Analysis of the Frictional Surfaces

The worn surfaces of CeO_2-, CeF_3-, and La_2O_3-filled PTFE composites were investigated by using a JEM-1200EX/S SEM made in Japan. Meanwhile, the transfer films of these rare-earth-compound-filled PTFE composites formed on the surface of GCr15 bearing steel ring were examined using an optical microscope, for which the magnification used in this work was 128.

RESULTS AND DISCUSSION

Friction and Wear Properties Under Dry Friction Conditions

The effects of the content of CeO_2, CeF_3, and La_2O_3 as fillers on the friction coefficients and wear of the PTFE composites under dry friction conditions are shown in Figures 1 and 2, respectively. The results in Figure 1 show that the friction properties of the CeO_2- and La_2O_3-filled PTFE composites are better than those of the CeF_3-filled PTFE composite under dry friction conditions. Meanwhile, the friction coefficient of CeF_3-filled PTFE composite increases with increase of the content of CeF_3 in PTFE. However, the friction coefficient of the CeO_2-filled PTFE composite first decreases with increase of the content of CeO_2 and then increases as the content of CeO_2 in PTFE increases. When the content of CeO_2 in PTFE is 15%, the friction coefficient of the CeO_2-filled PTFE composite is the lowest. For the La_2O_3-filled PTFE composite, the friction coefficient of the PTFE composite first increases with increase of the content of La_2O_3 and then decreases as the content of La_2O_3 in PTFE increases. When the content of La_2O_3 in PTFE is 20%, the friction coefficient of the PTFE composite is the lowest. But when the content of La_2O_3 in PTFE is higher than 20%, the friction coefficient of the PTFE composite increases sharply with increase of the content of La_2O_3.

A comparison of the wear results in Figure 2 with that of pure PTFE (385.4 mg) under the same conditions[14,15] shows that the antiwear properties of the PTFE composites can be greatly improved by filling PTFE with different contents of CeO_2, CeF_3, and La_2O_3, and the wear of the PTFE composites can be decreased by 1–2 orders of magnitude. However, the wear-reducing actions of CeO_2 and La_2O_3 are more effective than that of CeF_3. The results in Figure 2 also show that the wear of the CeF_3-filled PTFE composite decreases with increase of the content of CeF_3. However, the wear of the CeO_2- and La_2O_3-filled PTFE composites first decreases with increase of the content of CeO_2 and La_2O_3 and then increases as the content of CeO_2 and La_2O_3 increases.

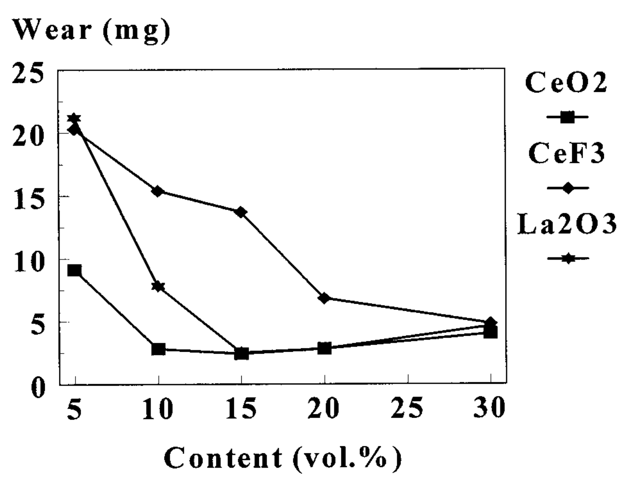


Figure 2 Effect of the addition content of CeO_2, CeF_3, and La_2O_3 as fillers on the wear of the PTFE composites under dry friction conditions (sliding speed, 1.5 m/s; load, 100 N).

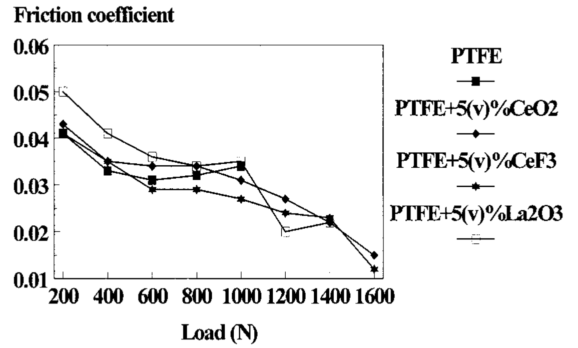
When the content of CeO_2 and La_2O_3 in PTFE is 15(v)%, the wear of the CeO_2- and La_2O_3-filled PTFE composites is the lowest. But when the content of CeO_2, CeF_3, and La_2O_3 in PTFE is 30(v)%, the wear of the CeO_2-, CeF_3-, and La_2O_3-filled PTFE composites is almost the same under the given conditions in this work.

Therefore, it can be briefly concluded from the above results and analyses that the friction and wear-reducing properties of the CeO_2- and La_2O_3-filled PTFE composites are better than those of the CeF_3-filled PTFE composite under dry friction conditions. When the content of CeO_2 in PTFE is 15(v)%, the friction and wear properties of the CeO_2-filled PTFE composite are the best. Meanwhile, when the content of La_2O_3 in PTFE is between 15 and 20(v)%, the La_2O_3-filled PTFE composite exhibits excellent friction and wear-reducing properties. However, the friction coefficient of the CeF_3-filled PTFE composite increases with increase of the content of CeF_3 from 5 to 30(v)%, but its wear decreases with increase of the content of CeF_3 in PTFE.

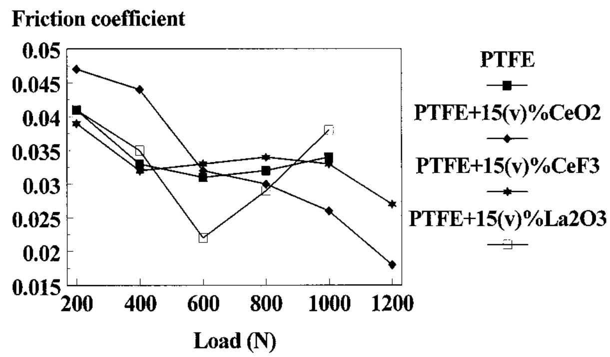
Friction and Wear Properties Under Oil-lubricated Conditions

The variations of friction coefficients with load for the CeO_2-, CeF_3-, and La_2O_3-filled PTFE composites sliding against GCr15 bearing steel under lubrication of liquid paraffin are shown in Figure 3. It can be seen from Figure 3 that the friction properties of the CeO_2-, CeF_3-, and La_2O_3-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. Meanwhile, the friction coefficients of the CeO_2-, CeF_3-, and La_2O_3-filled PTFE composites decrease with increase of the load under lubrication of liquid paraffin. The results in Figure 3 also show that the greater the content of CeO_2-, CeF_3-, and La_2O_3 as fillers in PTFE, the poorer the friction properties of the PTFE composites under higher loads in liquid paraffin lubrication. Therefore, the PTFE composites filled with CeO_2, CeF_3, and La_2O_3 in the content of 5(v)% are more suitable for application in practice under oil-lubricated conditions.

Figure 4 gives the variation of wear with load for the PTFE composites filled with CeO_2, CeF_3, and La_2O_3 in the content of 15(v)% sliding against GCr15 bearing steel under lubrication of liquid paraffin. Comparison of the wear results in Figure 4 to those under dry friction conditions shows that the antiwear properties of the CeO_2-, CeF_3-, and La_2O_3-filled PTFE composites can be greatly improved by lubrication with liquid paraffin. Meanwhile, the results in Figure 4 show that the wear of the CeO_2-, CeF_3-, and La_2O_3-filled PTFE composites increases with increase of the load under lubrication of liquid paraffin. But when the



3(a)



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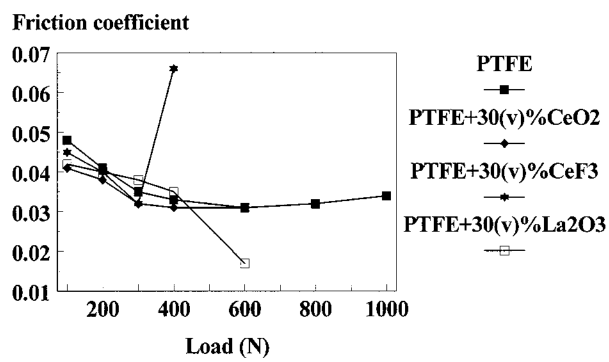

3(c)

Figure 3 Variations of the friction coefficients with load for the PTFE composites filled with CeO_2, CeF_3, and La_2O_3 with the addition content of (a) 5%, (b) 15%, and (c) 30% under lubrication of liquid paraffin (sliding speed, 2.5 m/s).

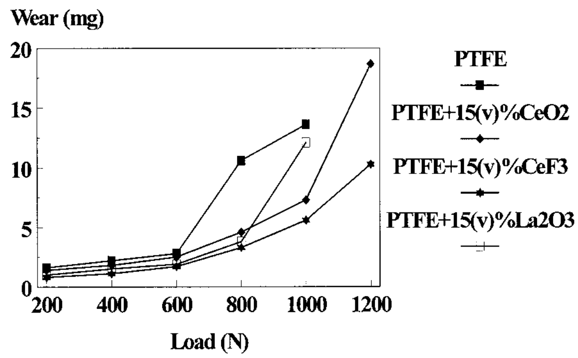

Figure 4 Variation of the wear with load for the PTFE composites filled with CeO_2, CeF_3, and La_2O_3 with the addition content of 15% under lubrication of liquid paraffin (sliding speed, 2.5 m/s).

load increases to the limit loads of the PTFE composites, the wear of the PTFE composites increases sharply. Under different loads in liquid paraffin lubrication, the antiwear properties of the CeO_2-, CeF_3-, and La_2O_3-filled PTFE composites are better than that of pure PTFE, and the antiwear property of the PTFE+15(v)%CeF_3 composite is the best.

When sliding speed is a constant, the variations of friction coefficients with load for the CeO_2-, CeF_3-, and La_2O_3-filled PTFE sliding against GCr15 bearing steel under lubrication of liquid paraffin can be described by the Stribeck's curves of friction coefficients against the Sommerfeld variable η**N/P**, where η is the viscosity of liquid paraffin; **N**, the rotation speed of GCr15 bearing steel ring; and **P**, the pressure applied.[16,17] At a given sliding speed in liquid paraffin lubrication, the temperature at frictional surfaces increases with increase of the load, while the viscosity of liquid paraffin decreases with increase of the temperature but increases with increase of the load. The variations of viscosity with temperature and load result in that the effect of viscosity on the Sommerfeld variable η**N/P** is so small compared to the effect of load on it that the η**N/P** can be simplified to **N/P**. Figure 5 gives the variation of the friction coefficient as a function of the simplified Sommerfeld variable **N/P** for pure PTFE sliding against GCr15 bearing steel under lubrication of liquid paraffin. The results in Figure 5 show that the friction coefficient of PTFE decreases with increase of the load at a given sliding speed under lubrication of liquid paraffin. Therefore, it can be deduced that the variations of the friction coefficients with load for the CeO_2-, CeF_3-, and La_2O_3-filled PTFE composites under lubrication of liquid paraffin can be described by the Stribeck's curve as given in Figure 5.

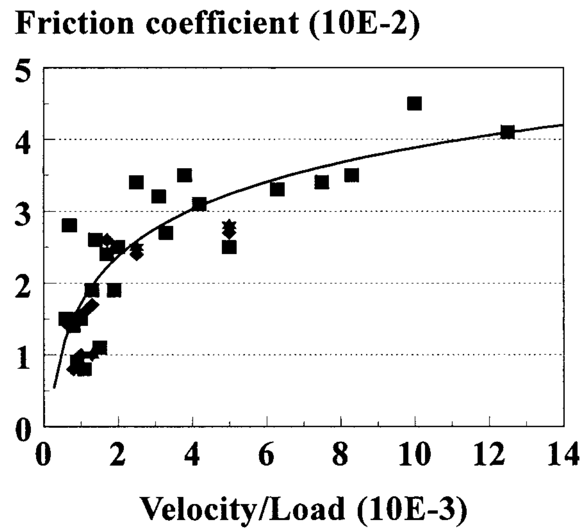

Figure 5 Variation of friction coefficient as a function of the simplified Sommerfeld variable (N/P) for pure PTFE sliding against GCr15 bearing steel under lubrication of liquid paraffin.

It was found in the experiments that, under lubrication of liquid paraffin, when the load increased to a certain value, some serious deformation or obvious cracks occurred on the worn surfaces of the CeO_2-, CeF_3-, and La_2O_3-filled PTFE composites. These loads under which serious deformation or obvious cracks occurred on the worn surfaces of the PTFE composites are considered as the limit loads of the PTFE composites under the given conditions. Figure 6 gives the limit loads of the CeO_2-, CeF_3-, and La_2O_3-filled PTFE composites sliding against GCr15 bearing steel under lubrication of liquid paraffin. The results in Figure 6 show that, at a given sliding speed of 2.5 m/s in liquid paraffin lubrication, the limit loads of the CeO_2-, CeF_3-, and La_2O_3-filled PTFE composites decrease with increase of the content of

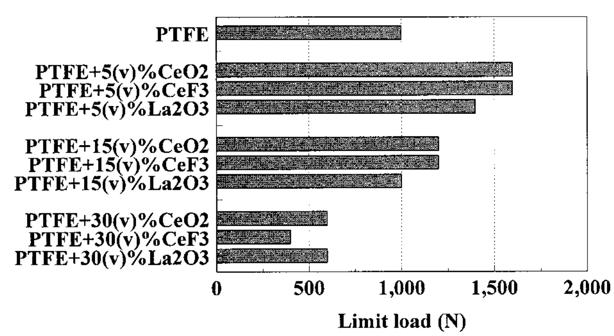

Figure 6 Limit loads of the PTFE composites filled with CeO_2, CeF_3, and La_2O_3 under lubrication of liquid paraffin (sliding speed, 2.5 m/s).

CeO_2, CeF_3, and La_2O_3 in PTFE. When the content of CeO_2, CeF_3, and La_2O_3 as fillers in PTFE is higher than 15(v)%, the limit loads of the CeO_2-, CeF_3-, and La_2O_3-filled PTFE composites are lower than that of pure PTFE. But when the content of CeO_2, CeF_3, and La_2O_3 in PTFE is lower than 15(v)%, the limit loads of the PTFE composites are much greater than that of pure PTFE. Therefore, it can be deduced that, under lubrication of liquid paraffin, with increase of the content of CeO_2, CeF_3, and La_2O_3 as fillers in PTFE (from 5 to 30%), the limit loads of the PTFE composites decrease; this would lead to the deterioration of the friction and wear properties of the PTFE composites under higher loads.

SEM Investigation of Worn Surfaces

The electron micrographs of the worn surfaces of CeO_2-, CeF_3-, and La_2O_3-filled PTFE composites sliding against GCr15 bearing steel under lubrication of liquid paraffin are shown in Figure 7. The results in Figure 7 show that there are still some obvious wear scars on the worn surface of pure PTFE under lubrication of liquid paraffin, but no obvious wear scars on the worn surfaces of the CeO_2-, CeF_3-, and La_2O_3-filled PTFE composites. However, there are some obvious cracks on the worn surfaces of the CeO_2-, CeF_3-, and La_2O_3-filled PTFE composites under the given conditions in this work. Comparison of the micrographs of Figure 7(b,c,d) with those of Figure 7(f,g,h) shows that, under lubrication of liquid paraffin, the number and the size of the cracks occurring on the worn surfaces of the CeO_2-, CeF_3-, and La_2O_3-filled PTFE composites increase with increase of the addition content of CeO_2, CeF_3, and La_2O_3 in PTFE. Meanwhile, comparison of the micrograph of Figure 7(e) with that of Figure 7(f) shows that the cracks occurring on the worn surfaces of the PTFE composites develop and become larger as the applied load increases under lubrication of liquid paraffin.

It is well known that filling CeO_2, CeF_3, and La_2O_3 into PTFE can produce some microdefects in the PTFE composites, and the microdefects in the PTFE composites increase with increase of the addition content of CeO_2, CeF_3, and La_2O_3 in PTFE. Therefore, it is believed that the interaction between liquid paraffin and the CeO_2-, CeF_3-, and La_2O_3-filled PTFE composites, especially the absorption of liquid paraffin into the microdefects of the PTFE composites under load, creates some cracks on the worn surfaces of the PTFE composites. The creation and development of the cracks under load reduces the mechanical strength and load-supporting capacity of the PTFE composites, which would lead to the deterioration of the friction and wear properties of the PTFE composites under higher loads in liquid paraffin lubrication.[18,19] Meanwhile, with increase of the addition content of CeO_2, CeF_3, and La_2O_3 in PTFE, the microdefects in the PTFE composites also increase; this would lead to increase of the cracks that occurred on the worn surfaces of the PTFE composites under load in liquid paraffin lubrication and, so, in turn, lead to the reduction of the limit loads of the PTFE composites. Therefore, the limit loads of CeO_2-, CeF_3-, and La_2O_3-filled PTFE composites decrease with increase of the addition content of CeO_2, CeF_3, and La_2O_3 in PTFE under lubrication of liquid paraffin.

Optical Microscope Examination of Transfer Films

The optical micrographs of the transfer films formed on the surface of GCr15 bearing steel for the CeO_2-, CeF_3-, and La_2O_3-filled PTFE composites under both dry and oil-lubricated conditions are shown in Figures 8 and 9, respectively. It can be seen from Figure 8 that there are some obvious transfer films formed on the surface of GCr15 bearing steel for the CeO_2-, CeF_3-, and La_2O_3-filled PTFE composites, but no obvious transfer films formed on the surface of GCr15 bearing steel for pure PTFE. This indicates that CeO_2, CeF_3, and La_2O_3 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, so they greatly reduce the wear of the PTFE composites.[20,21] However, the results in Figure 8 show that the transfer films of the CeO_2- and La_2O_3-filled PTFE composites formed on the surface of GCr15 bearing steel are thicker than those of the CeF_3-filled PTFE composite. This indicates that the formation ability of transfer films of the CeO_2- and La_2O_3-filled PTFE composites on the surface of GCr15 bearing steel is better than that of CeF_3-filled PTFE composite, so the PTFE composites filled with CeO_2 and La_2O_3 can easily form uniform transfer films on the surface of GCr15 bearing steel. Therefore, the friction and wear-reducing properties of the PTFE + 15(v)% CeO_2 and PTFE + 15(v)% La_2O_3 composites are much better than those of the PTFE + 15(v)% CeF_3 composite under the given conditions in this work.

Comparison of the results in Figure 9 with those in Figure 8 shows that the transfer of the CeO_2-, CeF_3-, and La_2O_3-filled PTFE composites onto the surface of GCr15 bearing steel can be

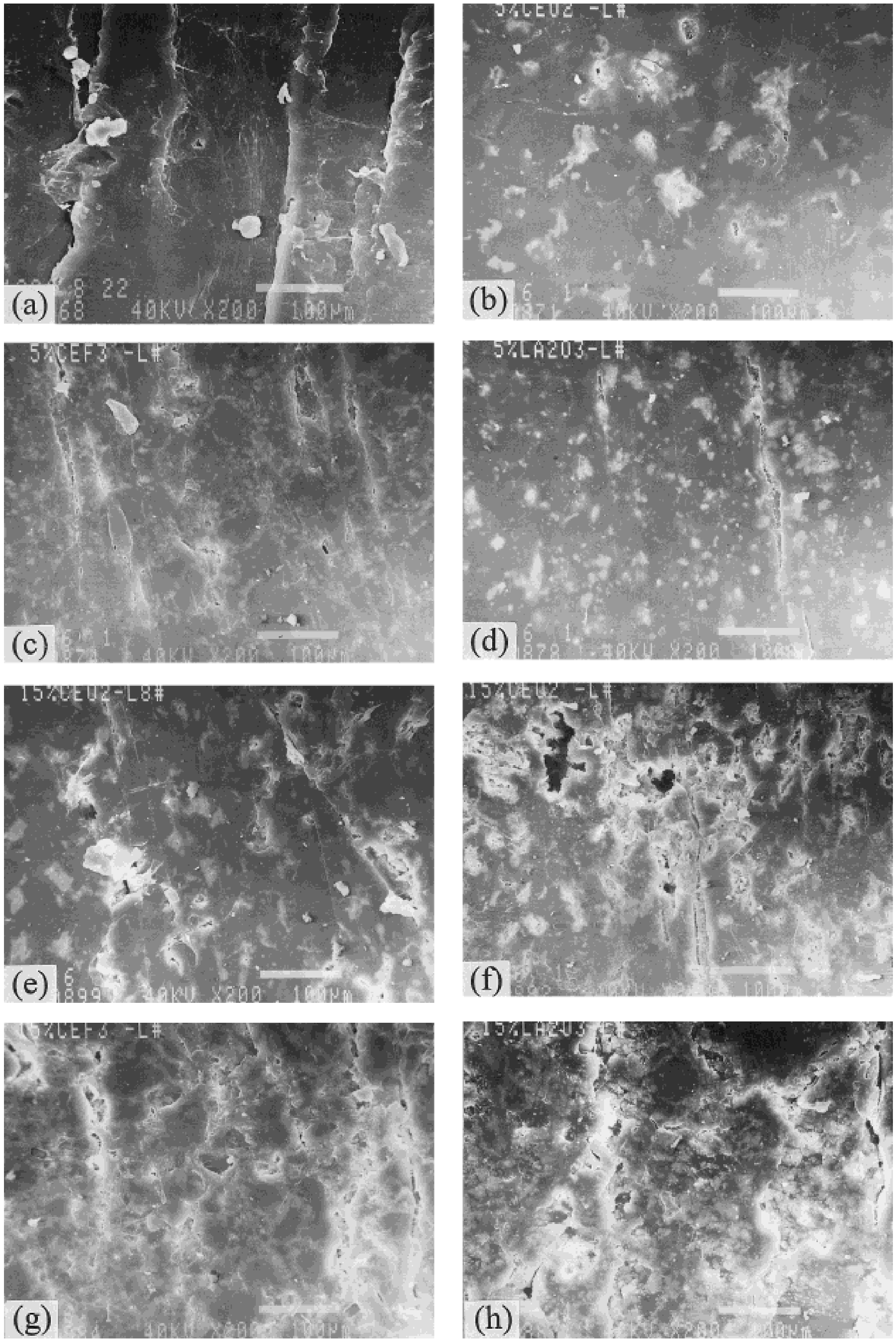

Figure 7 Electron micrographs of the worn surfaces of the CeO_2-, CeF_3-, and La_2O_3-filled PTFE composites under lubrication of liquid paraffin (sliding speed, 2.5 m/s): (a) PTFE, 1000 N; (b) PTFE + 5(v)% CeO_2, 1600 N; (c) PTFE + 5(v)% CeF_3, 1600 N; (d) PTFE + 5(v)% La_2O_3, 1400 N; (e) PTFE + 15(v)% CeO_2, 800 N; (f) PTFE + 15(v)% CeO_2, 1200 N; (g) PTFE + 15(v)% CeF_3, 1200 N; (h) PTFE + 15(v)% La_2O_3, 1000 N.

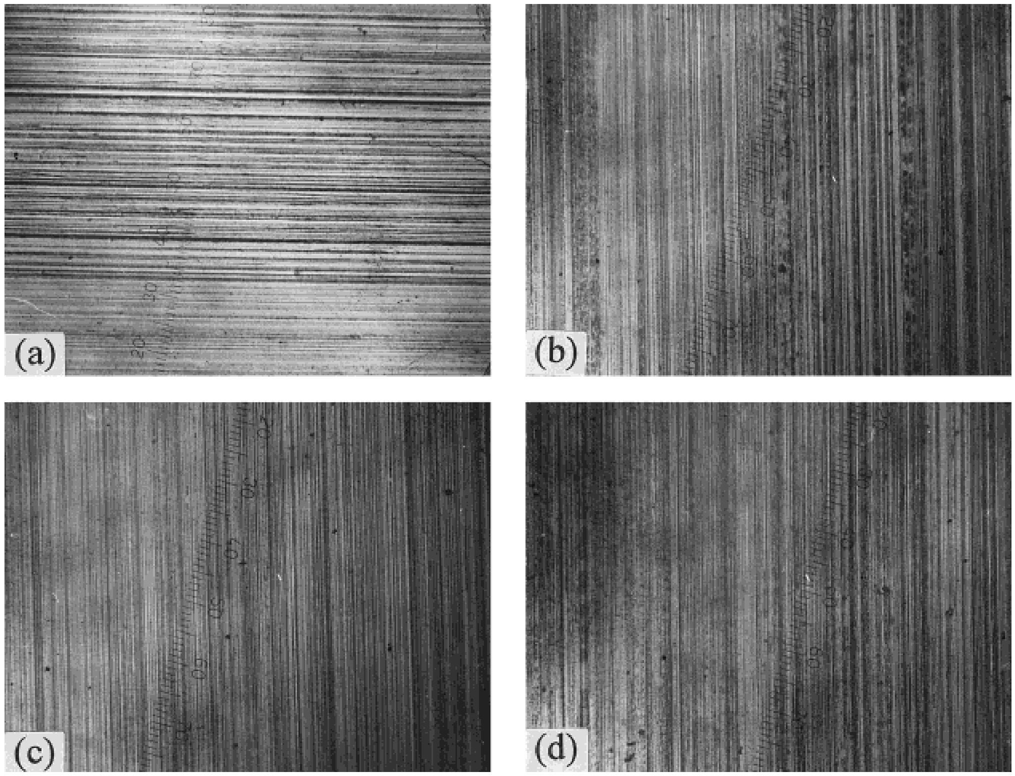

Figure 8 Optical micrographs of the transfer films formed on the surface of GCr15 bearing steel for the CeO_2-, CeF_3-, and La_2O_3-filled PTFE composites under dry friction conditions (128×; sliding speed, 1.5 m/s; load, 100 N): (a) PTFE; (b) PTFE + 15(v)% CeO_2; (c) PTFE + 15(v)% CeF_3; (d) PTFE + 15(v)% La_2O_3.

greatly reduced by lubrication with liquid paraffin, but the transfer still takes place.[22] This indicates that the formation of lubricating oil films on the frictional surfaces can greatly improve the lubrication condition of the friction pair, so the friction and wear as well as the transfer of the CeO_2-, CeF_3-, and La_2O_3-filled PTFE composites can be greatly reduced. The above analysis results are consistent with the results of the friction and wear tests.

CONCLUSIONS

1. The filling of CeO_2, CeF_3, and La_2O_3 into PTFE can reduce the wear of the PTFE com-

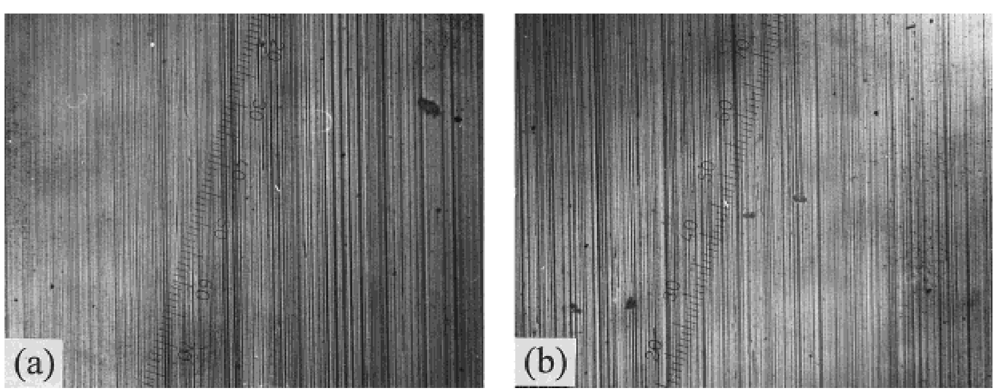

Figure 9 Optical micrographs of the transfer films formed on the surface of GCr15 bearing steel for the rare-earth-compound-filled PTFE composites under lubrication of liquid paraffin (128×; sliding speed, 2.5 m/s): (a) PTFE + 15(v)% CeO_2, 1200 N; (b) PTFE + 15(v)% La_2O_3, 1000 N.

posites by 1–2 orders of magnitude compared to that of pure PTFE under dry friction conditions. However, when the addition content of CeO_2, CeF_3, and La_2O_3 in PTFE is between 5 and 30%, the friction and wear properties of the CeO_2- and La_2O_3-filled PTFE composites are better than those of the CeF_3-filled PTFE composites.

2. When the content of CeO_2 in PTFE is 15%, the friction and wear properties of the CeO_2-filled PTFE composite are the best. Meanwhile, when the content of La_2O_3 in PTFE is between 15 and 20%, the La_2O_3-filled PTFE composite exhibits excellent friction and wear-reducing properties. However, the friction coefficient of the CeF_3-filled PTFE composite increases but its wear decreases with increase of the content of CeF_3 from 5 to 30% under dry friction conditions.
3. The friction and wear-reducing properties of the CeO_2-, CeF_3-, and La_2O_3-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 compared to those under dry friction conditions. Meanwhile, the friction coefficients of the CeO_2-, CeF_3-, and La_2O_3-filled PTFE composites decrease with increase of the load under lubrication of liquid paraffin, but the wear of these PTFE composites increases with increase of the load.
4. The interaction between liquid paraffin and the PTFE composites filled with CeO_2, CeF_3, and La_2O_3, especially the absorption of liquid paraffin into the microdefects of the PTFE composites under load, creates some cracks on the worn surfaces of the PTFE composites. The creation and development of the cracks under load reduces the mechanical strength and load-supporting capacity of the PTFE composites; this would lead to the deterioration of the friction and wear properties of the PTFE composites under higher loads in liquid paraffin lubrication.
5. With the increase of the addition content of CeO_2, CeF_3, and La_2O_3 in PTFE, the microdefects in the PTFE composites also increase; this would lead to increase of the cracks that occurred on the worn surfaces of the PTFE composites under load in liquid paraffin lubrication and, so, in turn, lead to the reduction of the limit loads of the PTFE composites under lubrication of liquid paraffin.
6. Rare earth compounds CeO_2, CeF_3, and La_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. Meanwhile, the excellent film formation actions of the CeO_2 and La_2O_3-filled PTFE composites on the surface of GCr15 bearing steel lead to the excellent friction and wear-reducing properties of the PTFE composites. However, the transfer of the CeO_2-, CeF_3-, and La_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.

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