Friction and Wear Behaviors of Several Polymers Under Oil-Lubricated Conditions

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ABSTRACT: The friction and wear properties of polytetrafluoroethylene (PTFE), polyimide (PI), and polyamide 66 (PA66) sliding against GCr15 bearing steel under both dry and oil-lubricated conditions were studied by using an MHK-500 ring-block wear tester (Timken wear tester), and then Stribeck's curves of PTFE, PI, and PA66 under lubrication of the oil were given out. The worn surfaces of these polymers and the transfer films formed on the counterfaces were examined by using a scanning electron microscope (SEM) and an optical microscope, respectively. Experimental results show that the friction and wear-reducing properties of PTFE, PI, and PA66 can be greatly improved by lubrication with liquid paraffin, and the friction coefficients can be decreased by 1 order of magnitude compared to those in dry friction condition. Under lubrication of liquid paraffin, the friction coefficients of PTFE, PI, and PA66 decrease with the increase of load, but the wear increases with the increase of load. The variations of friction coefficients with load for PTFE, PI, and PA66 under lubrication of liquid paraffin can be described properly by the Stribeck's curves, as given out in this article. Under higher loads and sliding speeds in liquid paraffin lubrication, the friction and wear reducing properties of PA66 are the best, and those of PTFE are the worst; therefore, PA66 is also very suitable for applications in oil-lubricated conditions. Meanwhile, SEM and optical microscope investigations show that the wear and transfer of PTFE, PI, and PA66 can be greatly reduced by lubrication of liquid paraffin, but they still take place. © 1998 John Wiley & Sons, Inc. J Appl Polym Sci 68: 2175–2182, 1998

INTRODUCTION

Polymers such as polytetrafluoroethylene (PTFE), polyamide 66 (PA66), and polyimide (PI) are important engineering materials. They have been widely used in practice as self-lubricating materials under dry friction conditions. However, it is known that the friction and wear behaviors of polymers in fluid environments differ greatly from those in the dry friction condition. The friction and wear behavior of polymers such as PTFE and PA66 in aqueous environments (water) have been studied by many coworkers.[1–4] It is found that many polymers wear much more in water than in air.[1,5] The wear of glass-fiber-reinforced PTFE composites is especially high in water,[6,7] but PA66 qualifies as material particularly suitable for the application in water.[4] However, up until now, much less information has been available about the oil-lubricated friction and wear properties of polymers such as PTFE, PA66, and PI.

With the enlargement of application fields of polymers, such as PTFE, PA66 and PI, in oil-lubricated conditions in recent years, it is essential to study the friction and wear behaviors as well as the mechanisms of these polymers in oil-lubricated conditions. However, until now, systematic studies on the friction and wear behaviors as well as the mechanisms of these polymers under oil-lubricated conditions have not been reported yet.

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Table I 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

The purpose of this work is to study the friction and wear behaviors of these polymers in oil-lubricated conditions and gain some insights into the friction and wear mechanisms of these polymers in oil lubrication. It is expected that this study may be helpful to the application of these polymers in oil-lubricated conditions in practice.

EXPERIMENTAL

In this experiment, 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 polymer block which is 12.3 × 12.3 × 18.9 mm in size. The steel ring, made of GCr15 bearing steel (SAE 52100 steel), was polished with number 900 grade SiC abrasive paper. Meanwhile, the surfaces of polymer blocks were polished with number 800 grade SiC abrasive paper, washed in acetone, and dried in air.

Three polymers, PTFE, PA66, and PI, were investigated in this experiment. PTFE samples were prepared by cold compression molding from PTFE powder (about 30 μm, produced by Jinan Chemical Factory, People's Republic of China) and then free sintering in air at the temperature of 380°C. PI samples were prepared by hot compression molding from PI powder (about 76 μm, produced by Shanghai No. 2 Smelter Factory, People's Republic of China) at the temperature of 375°C. Meanwhile, PA66 samples were processed by an extruded PA66 rod (produced by Shanghai No. 18 Plastic Factory). The lubricating oil used in this experiment was liquid paraffin (made by Tianjin No. 2 Chemical Reagent Factory, and its typical characteristics are listed in Table I), which was added to the rubbing surfaces at a rate of 30 drops per min during the tests.

The friction and wear tests were performed at room temperature in atmosphere with sliding speeds from 1.0 to 2.5 m/s and loads from 200 to 2000 N for oil-lubricated conditions while at the sliding speed of 1.0 m/s under the load of

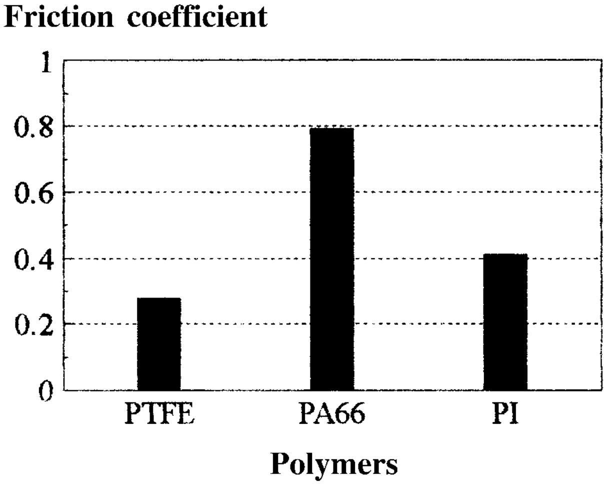


Figure 1 Friction coefficients of PTFE, PA66, and PI sliding against GCr15 bearing steel in the dry friction condition (sliding speed, 1.0 m/s; load, 100 N; time, 30 min).

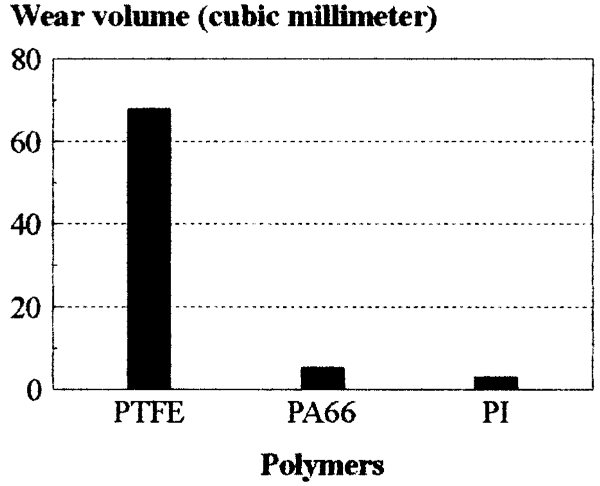
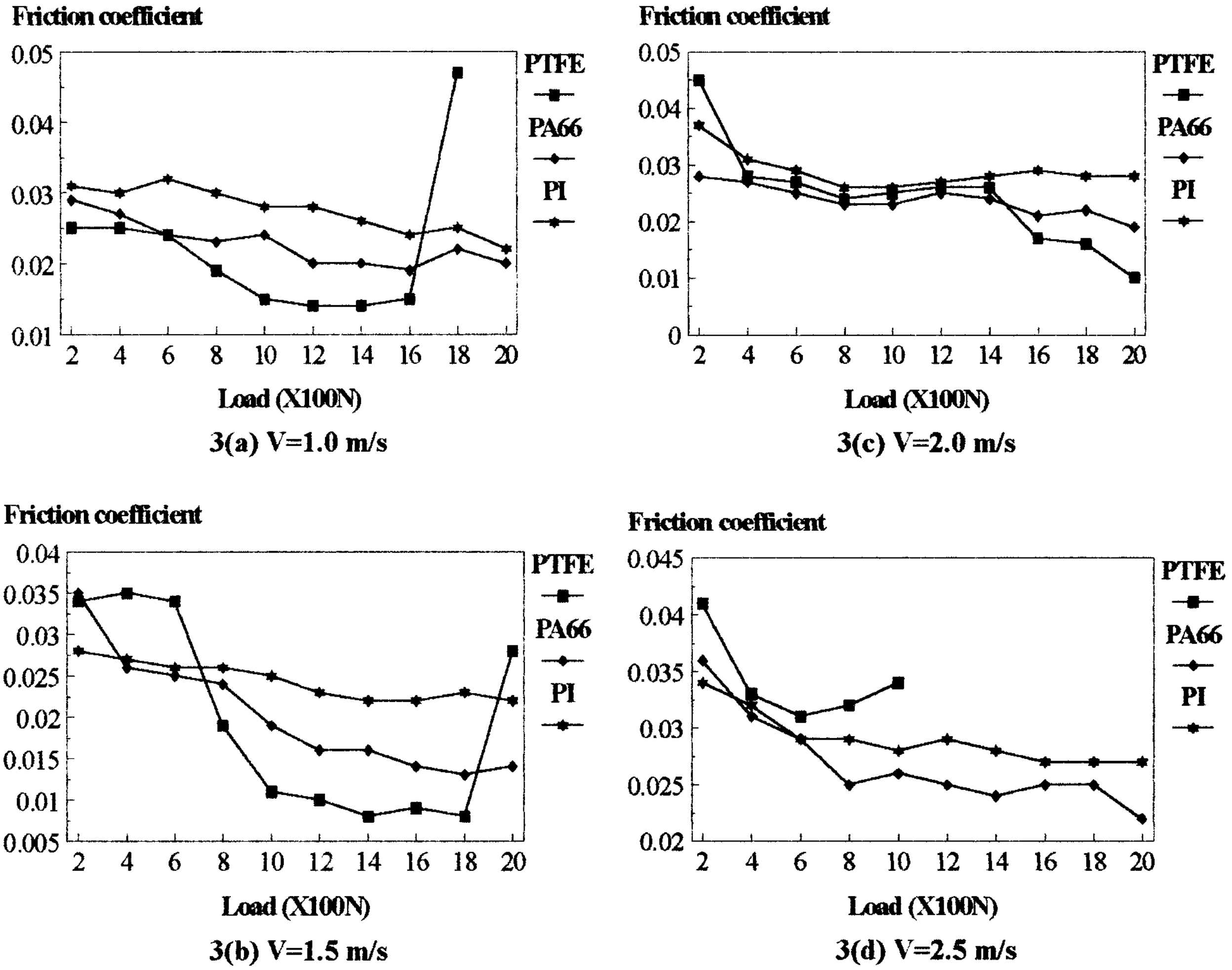


Figure 2 Wear volume of PTFE, PA66, and PI sliding against GCr15 bearing steel in the dry friction condition (sliding speed, 1.0 m/s; load, 100 N; time, 30 min).

Table II Comparison of the Results of the Friction Coefficients of PTFE, PA66, and PI Under Both Dry and Oil-Lubricated Conditions

	Friction Coefficient	
Polymer	Dry Friction Condition (1.0 m/s, 100 N)	Oil-Lubricated Condition (1.0 m/s, 200 N)
PTFE	0.276	0.025
PA66	0.792	0.029
PI	0.411	0.031

100 N for the dry friction condition. Before each test started, the surfaces of polymer blocks and GCr15 bearing steel ring were cleaned by rubbing with a soft cloth dipped in acetone and then dried in air. Each friction and wear test was performed for 30 min. The wear was detected by the weight loss of the polymer blocks after each test by an analytical scale (precision: 0.1 mg). The friction coefficient was determined by measuring the friction torque, while the friction torque was detected by a torque measuring 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. The worn surfaces of these polymers and the transfer films formed on the surface of GCr15 bearing steel ring were examined by using a JEM-1200EX/S scanning electron microscope and an optical microscope, respectively.



3(a) V=1.0 m/s

3(c) V=2.0 m/s

3(b) V=1.5 m/s

3(d) V=2.5 m/s

Figure 3 Variations of friction coefficients with load for PTFE, PA66, and PI sliding against GCr15 bearing steel at different sliding speeds under lubrication of liquid paraffin.

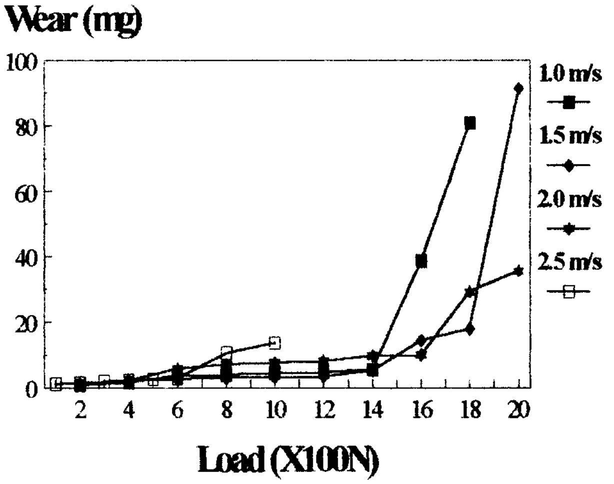


Figure 4 Variation of wear with load for PTFE sliding against GCr15 bearing steel under lubrication of liquid paraffin.

RESULTS AND DISCUSSION

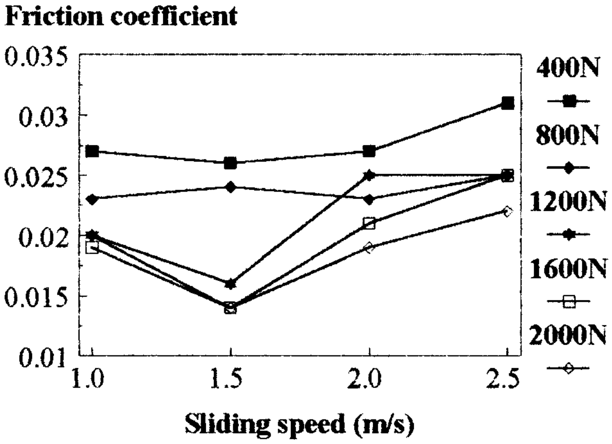
Friction and Wear Behaviors in the Dry Friction Condition

The friction coefficients and wear volume of PTFE, PA66, and PI sliding against GCr15 bearing steel in the dry friction condition are given out in Figures 1 and 2, respectively. The results in Figure 1 show that, to polymers PTFE, PA66, and PI in the dry friction condition, the friction-reducing property of PTFE is the best; that of PI is the second, and that of PA66 is the worst. The results in Figure 2 show that the antiwear properties of PI and PA66 are much better than that of PTFE, but the antiwear property of PI is the best of all in the dry friction conditions.

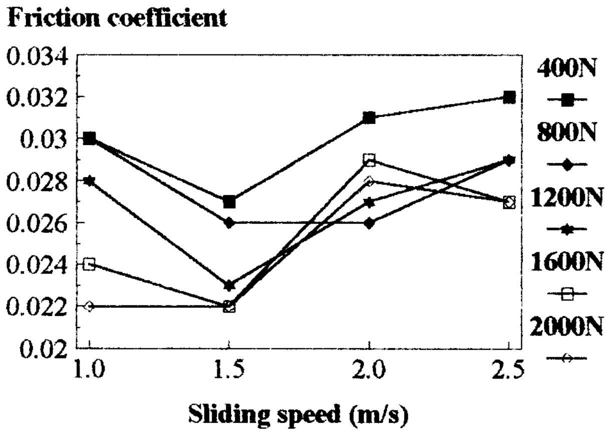
Friction and Wear Behaviors in Oil-Lubricated Conditions

Table II gives the comparison results of the friction coefficients of PTFE, PA66, and PI sliding against GCr15 bearing steel under both dry and oil-lubricated conditions. It can be seen from Table II that the friction properties of PTFE, PI, and PA66 can be greatly improved by lubrication with liquid paraffin, and the friction coefficients of these polymers can be reduced by 1 order of magnitude compared to those in the dry friction condition. Figure 3 gives the variations of friction coefficients with load for PTFE, PI, and PA66 sliding against GCr15 bearing steel under lubrication of liquid paraffin. The results in Figure 3 show that the friction coefficients of PTFE, PI, and PA66 decrease with the increase of load under lubrication of liquid paraffin, and the friction property of PA66 is better than that of PI at a different sliding speed. Meanwhile, at the sliding speed of 2.5 m/s, the friction properties of PA66 and PI are better than that of PTFE, but the friction property of PA66 is best of all. Therefore, it can be deduced that PA66 is much suitable for application under higher load and sliding speed in oil lubricated conditions.

The variation of wear with load for PTFE sliding against GCr15 bearing steel under lubrication of liquid paraffin is shown in Figure 4. Comparison of the wear results to those in dry friction condition indicates that the antiwear property of PTFE can be greatly improved by lubrication with liquid paraffin. Meanwhile, the wear of PTFE in-



5(a) PA66



5(b) PI

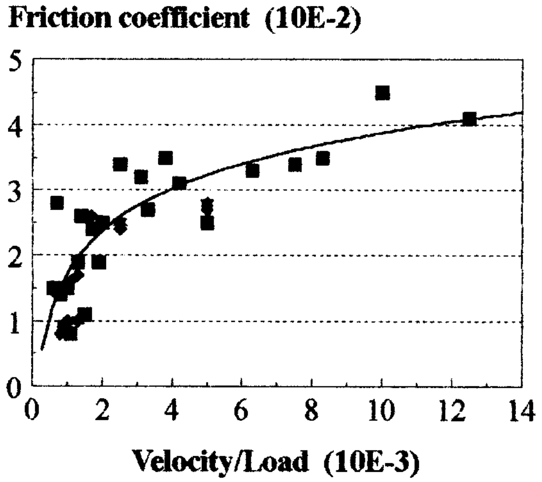
Figure 5 Variations of friction coefficients with sliding speed for PA66 and PI sliding against GCr15 bearing steel under lubrication of liquid paraffin.

creases with the increase of load under lubrication of liquid paraffin, but the wear increases sharply when the load increases to the load limit of the PTFE.

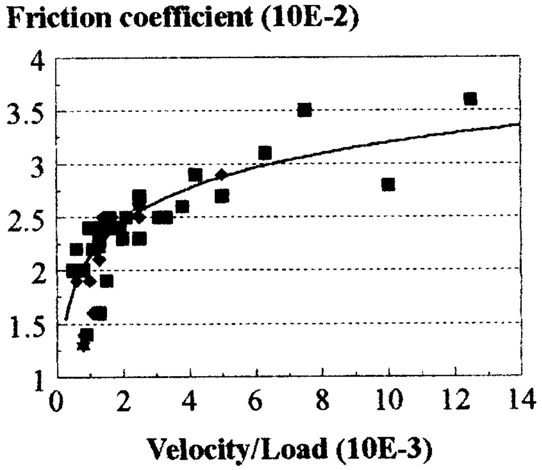
Figure 5 gives out the variations of friction coefficients with sliding speed for PA66 and PI sliding against GCr15 bearing steel under lubrication of liquid paraffin. It can be seen from Figure 5 that the friction coefficients of PA66 and PI first decrease with the increase of sliding speed and then increase with the sliding speed increase. It is known that the thermal conductivity of polymers such as PTFE, PA66, and PI is very poor, and their physical and mechanical properties can be influenced greatly by temperature. It is believed that with the increase of sliding speed under constant loads, a layer of lubricating oil film can be more easily formed on the frictional surfaces, then the lubrication condition of the frictional surfaces can be greatly improved. This would lead to the decrease of the friction coefficient. However, with a further increase of the sliding speed, the temperature of frictional surface increases. The temperature increase of frictional surface would result in the reduction of mechanical strength and load carrying capacity of the polymers. This would lead to the increase of friction coefficients. When the load increases to the load limits of the polymers, their friction coefficients increase sharply.

When sliding speed is constant, the variations of friction coefficients with load for PTFE, PA66, and PI under lubrication of liquid paraffin 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 applied pressure.[8–10] At a constant sliding speed, the temperature at frictional surface increases with the increase of load, while 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 influence of viscosity on the Sommerfeld variable $\eta N/P$ is so small that $\eta N/P$ can be approximated by N/P.

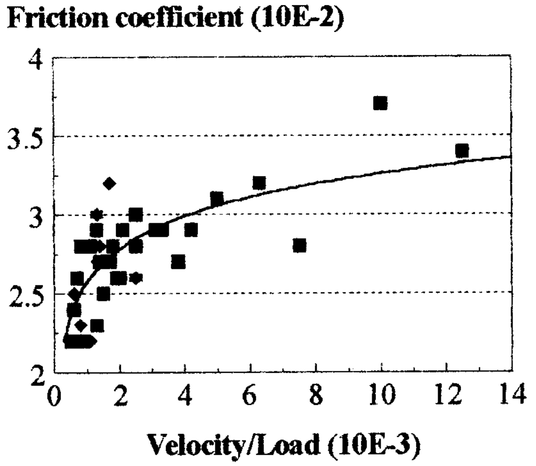
Based on the above analyses, the Sommerfeld variable $\eta N/P$ can be approximated to N/P under the conditions in this experiment. Figure 6 gives out the relationships between friction coefficients and velocity/load (N/P) for PTFE, PA66, and PI sliding against GCr15 bearing steel under lubrication of liquid paraffin. The results in Figure 6 show that the variation curves of friction coefficients with velocity/load for PTFE, PA66, and PI



6(a) PTFE



6(b) PA66



6(c) PI

Figure 6 Relationships between friction coefficients and velocity/load for PTFE, PA66, and PI sliding against GCr15 bearing steel under lubrication of liquid paraffin.

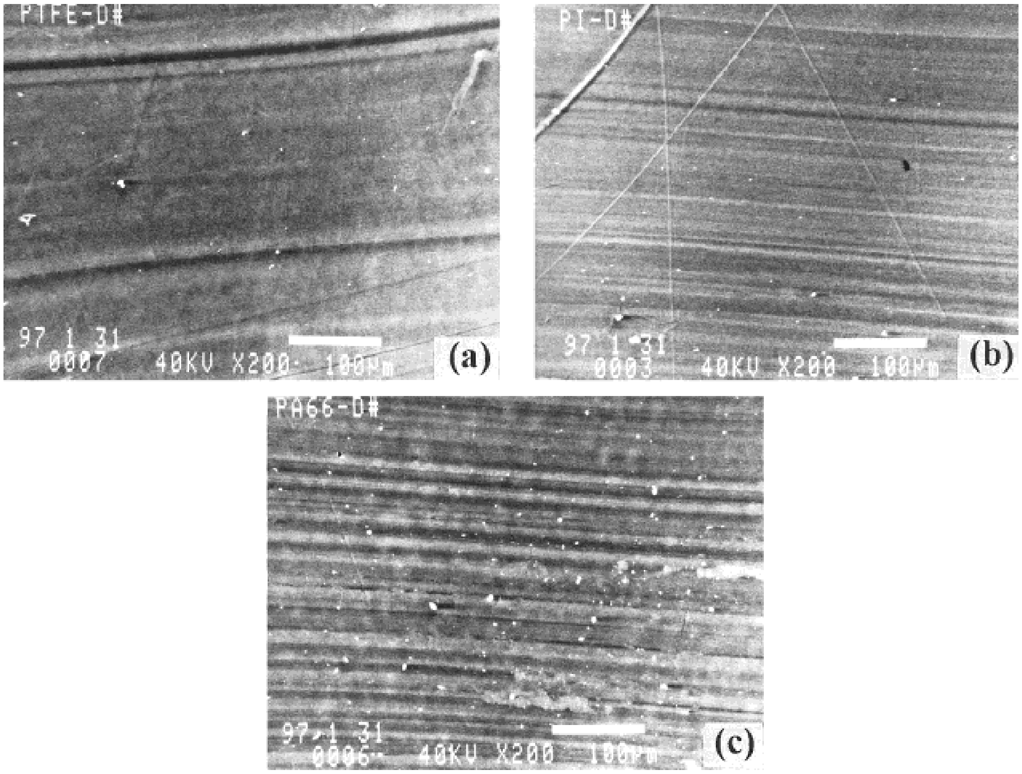


Figure 7 Electron micrographs of the worn surfaces of PTFE, PA66, and PI in the dry friction condition (sliding speed, 1.0 m/s; load, 100 N): (a) PTFE, (b) PI, and (c) PA66.

sliding against GCr15 bearing steel under lubrication of liquid paraffin are similar to each other. This indicates that the variation lows of friction coefficients with velocity/load are the same for PTFE, PA66, and PI under the conditions in this experiment. Meanwhile, it can be seen from Figure 6 that, at a constant sliding speed, the friction coefficients of PTFE, PA66, and PI sliding against GCr15 bearing steel under lubrication of liquid paraffin decrease with the increase of load. Therefore, the variations of friction coefficients with load for PTFE, PA66, and PI under lubrication of liquid paraffin can be described properly by the Stribeck's curves, as given out in Figure 6. However, under higher loads in liquid paraffin lubrication, the temperature increase of frictional surface can result in the reduction of mechanical strength and load-carrying capacity of the polymer, and this can lead to the increase of friction and wear. When the load increases to the load limit of the polymer, its friction and wear increase sharply.

SEM Investigations of Worn Surfaces

It was found in the experiments that, under dry friction conditions, the width of the wear scar on the worn surface of PTFE was about 10 mm, but the wear scars on the worn surfaces of PI and PA66 were much smaller than that of PTFE. Figure 7 gives out the electron micrographs of the worn surfaces of PTFE, PI, and PA66 in dry friction condition. It can be seen from Figure 7 that there are still some obvious wear scars in the large wear scar of PTFE. Meanwhile, the worn surface of PI is smoother than that of PA66, and the wear scars on the worn surface of PI are smaller than those of PA66. Therefore, it can be deduced from the above investigation results that the wear of PI and PA66 is much lower than that of PTFE, and the wear of PI is the lowest of all in dry friction conditions.

Figure 8 gives out the electron micrographs of the worn surfaces of PTFE, PI, and PA66 under lubrication of liquid paraffin. It can be seen from Figure 8 that there are wide and deep wear scars on the worn surface of PTFE in liquid paraffin lubrication, but the wear scars on the worn surfaces of PI and PA66 are much smaller than those of PTFE. This indicates that the antiwear properties of PI and PA66 are much better than that of PTFE in liquid paraffin lubrication. Meanwhile,

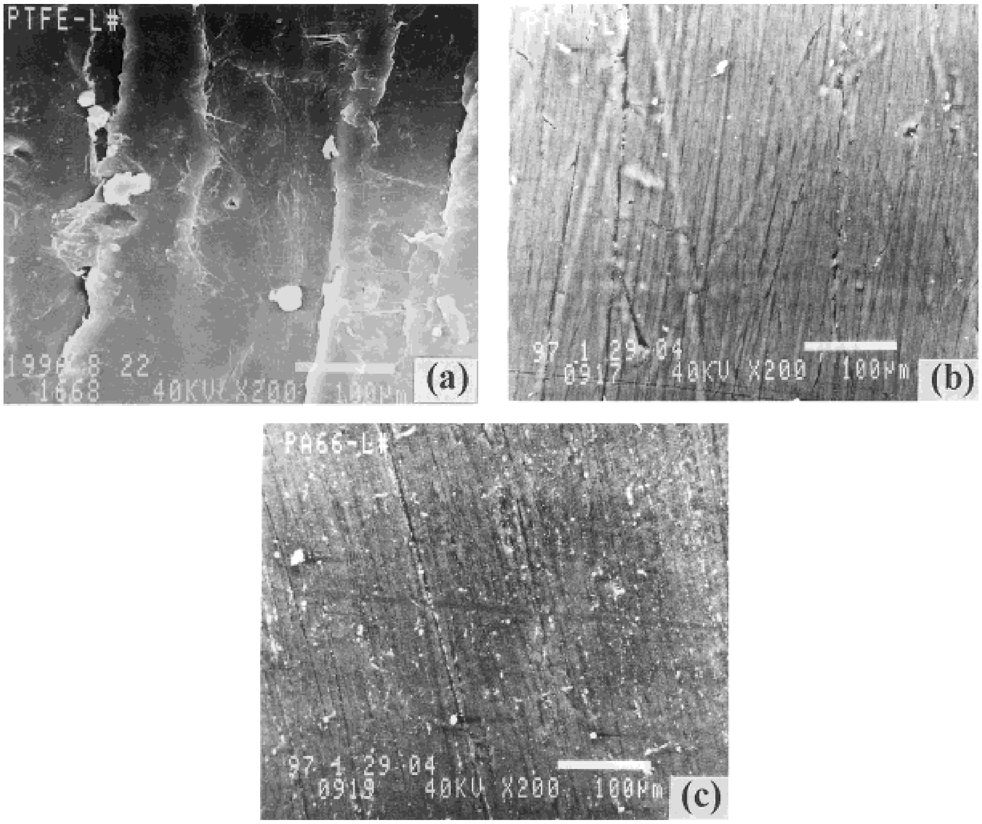


Figure 8 Electron micrographs of the worn surfaces of PTFE, PA66, and PI in liquid paraffin lubrication (sliding speed: 2.5 m/s): (a) PTFE, 1000 N; (b) PI, 2000 N; (c) PA66, 2000 N.

comparison the results in Figure 8 to those in Figure 7 shows that the wear scars on the worn surfaces of PTFE, PI, and PA66 in liquid paraffin lubrication are much smaller than those in dry friction condition. This indicates that the wear of PTFE, PI, and PA66 can be greatly reduced by liquid paraffin lubrication. All of the above investigation and analysis results are consistent with the data of wear.

Optical Microscope Investigations of Transfer Films

It was found in the experiments that there were some obvious transfer films formed on the counterface for PA66 in dry friction condition, but no obvious transfer films formed on the counterfaces for PTFE and PI in dry friction condition while for PTFE, PA66, and PI in liquid-paraffin-lubricated conditions. Figure 9 gives out the optical micrographs of the transfer films of PA66 formed on the surface of GCr15 bearing steel under both dry and lubricated conditions. The results in Figure 9 show that PA66 can easily form transfer films on the surface of GCr15 bearing steel in dry friction condition, so the friction between PA66 and the counterface can be transformed to the friction between PA66 and the transfer films of PA66 formed on the counterface, then adhesive friction occurs to PA66. Therefore, the friction coefficient of PA66 sliding against GCr15 bearing steel is very high in dry friction. Meanwhile, the results in Figure 9 also show that the transfer of the polymer onto the counterface can be greatly reduced by lubrication of liquid paraffin, but the transfer still takes place.[11–12] This indicates that a layer of lubricating oil film was formed on the frictional surfaces. Therefore, the friction and wear of the polymer were greatly reduced. All of the above investigation and analysis results are consistent with the results of the friction and wear tests.

CONCLUSIONS

1. For polymers PTFE, PA66, and PI sliding against GCr15 bearing steel in the dry fric-

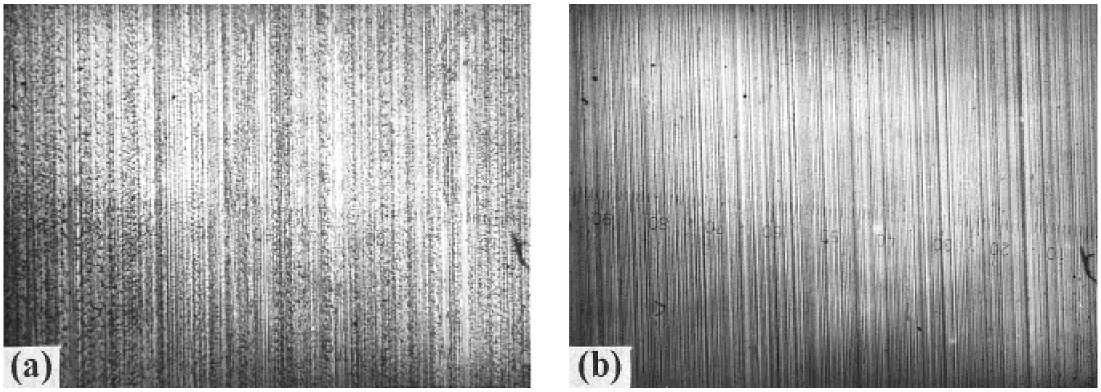


Figure 9 Optical micrographs of the transfer films of PA66 formed on the surface of GCr15 bearing steel (128×): (a) sliding speed, 1.0 m/s; load, 100 N; dry friction condition; and (b) sliding speed, 2.5 m/s; load, 2000 N; liquid paraffin lubrication.

tion condition, the friction coefficient of PTFE is the lowest and that of PA66 is the highest. However, the antiwear property of PTFE is the worst, and that of PI is the best.

2. The friction and wear-reducing properties of PTFE, PA66, and PI can be greatly improved by lubrication of liquid paraffin, and the friction coefficients of PTFE, PA66, and PI can be decreased by at least 1 order of magnitude compared to those in the dry friction condition.
3. Under lubrication of liquid paraffin, the wear of PTFE, PA66, and PI increases with the increase of load, but the friction coefficients decrease with the increase of load. When the load increases to the load limits of the polymers, their friction and wear increase sharply.
4. Under higher loads and sliding speeds in liquid paraffin lubrication, the friction and wear-reducing properties of PA66 and PI are much better than those of PTFE, while the friction reducing property of PA66 is the best of all. Therefore, PA66 is very suitable for application in oil-lubricated conditions.
5. Under the conditions in this experiment, the variations of friction coefficients with load for PTFE, PA66, and PI sliding against GCr15 bearing steel in liquid paraffin lubrication can be described properly by the Stribeck's curves, as given out in this article.
6. The wear and transfer of PTFE, PA66, and PI can be greatly reduced by lubrication of liquid paraffin, but they still take place.

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