Tribological Behavior of Micrometer- and Nanometer-Al₂O₃-Particle-Filled Poly(phthalazine ether sulfone ketone) Copolymer Composites Used as Frictional Materials

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ABSTRACT: Micrometer- and nanometer-Al₂O₃-particle-filled poly(phthalazine ether sulfone ketone) (PPESK) composites with filler volume fractions ranging from 1 to 12.5 vol % were prepared by hot compression molding. We evaluated the tribological behaviors of the PPESK composites with the block-on-ring test rig by sliding PPESK-based composite blocks against a mild carbon steel ring under dry-friction conditions. The effects of different temperatures on the wear rate of the PPESK composites were also investigated with a ball-on-disc test rig. The wear debris and the worn surfaces of the PPESK composites were investigated with scanning electron microscopy, and the structures of the PPESK composites were analyzed with IR spectra. The lowest wear rate, 7.31×10^{-6} mm³ N⁻¹ m⁻¹, was obtained for the composite filled with 1 vol %-nanometer Al₂O₃ particles.

The composite with nanometer particles exhibited a higher friction coefficient (0.58–0.64) than unfilled PPESK (0.55). The wear rate of 1 vol %-nanometer-Al₂O₃-particle-filled PPESK was stable and was lower than that of unfilled PPESK from the ambient temperature to 270°C. We anticipate that 1 vol %-nanometer-Al₂O₃-particle-filled PPESK can be used as a good frictional material. We also found that micrometer-Al₂O₃-particle-filled PPESK had a lower friction coefficient at a filler volume fraction below 5%. The filling of micrometer Al₂O₃ particles greatly increased the wear resistance of PPESK under filler volume fractions from 1 to 12.5%. © 2005 Wiley Periodicals, Inc. J Appl Polym Sci 95: 993–1001, 2005

Key words: fillers; composites; nanometer

INTRODUCTION

The formulation and production of frictional materials for the braking systems of automobiles, trucks, airplanes, racing cars, and frictional slides for vibration–reduction have undergone major changes in the last 2 decades. Since 1980, efforts to develop nonasbestos friction materials have been initiated primarily for health and environmental safety considerations.[1] There has been a shift in the direction of better heat resistance, more stable coefficients of friction, and extended durability.[2] In general, polymers and polymer-based composites have found numerous applications in the reduction of friction and the improvement of wear resistance.[3] The majority of polymer-based materials used in industry as bearing materials commonly incorporate fillers and reinforcements, not only to improve the tribological, mechanical, and thermal properties but also to reduce the materials cost and improve the processability of the polymers.[4–6] When a polymer composite is used in sliding friction, the filler particle size; its aspect ratio, hardness, and concentration; and the nature of the interface between the polymer and the particles are all important.[4,7]

It is now widely recognized that one can significantly improve the friction and wear properties of some polymers by filling them with organic and inorganic compounds, and several mechanisms have been suggested to demonstrate the action mechanisms of fillers.[8,9] Until now, some attention has been paid to nanoparticle-filled polymers for tribological applications, and what has been reported seems to show promise.[10–14] To our knowledge, very little work has been done on nanometer-particle-filled polymer composites for frictional materials. Thermosetting phenol–formaldehyde resins reinforced with asbestos of different fiber lengths has formed the basis for the development of frictional materials in the automotive industry.[15]

Recently, to keep up with modern technological innovations, ever-increasing demands have been placed on tribomaterials for enhanced performance for operation under stringent conditions of load,

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speed, and temperature and in hazardous environments. Poly(phthalazine ether sulfone ketone) (PPESK) copolymer with an equivalent molar ratio of sulfone to ketone is an attractive matrix material because of its high-temperature stability, its excellent mechanical properties, its radiation and hydrolytic resistance, and its easy processing.[16] Because of these advantages, it has received considerable attention in tribological research.[17,18] It has been found that unfilled PPESK possesses a higher friction coefficient and wear rate. The ideas proposed here led us to study polymer composites made with nanometer particles as fillers for frictional materials.

In this study, we examined the tribological behaviors of nanometer- and micrometer-Al_2O_3-particle-filled PPESK composites. We investigated the different effects of micrometer and nanometer Al_2O_3 particles on the tribological behaviors of PPESK composites under identical experimental conditions.

EXPERIMENTAL

In this study, the material used to prepare the experimental specimens consisted of a matrix of PPESK filled with Al_2O_3 particles. The pure PPESK powders were provided by Dalian University of Technology (Liaoning Province, China); the average diameter was 40 μm, and the density was 1.35 g/cm^3. This material had a glass-transition temperature of 284°C.[16] The micrometer Al_2O_3 particles (<75 μm) were supplied by Shanghai Jinshan Chemical Factory, Shanghai, China. The nanometer Al_2O_3 particles, with a grit size of 40 nm, were produced by Zhengyuan Nanomaterial Corp. (Shandong Province, China). Fillers with volume fractions from 1 to 12.5% were used in this study. The wear specimens were prepared by hot compression molding. PPESK and the fillers were fully mixed by ultrasonic dispersion in acetone for about 20 min; the samples were then dried at 100°C for 120 min to remove the acetone and moisture. The mixture was then compressed in a mold at a pressure of 30 MPa, a temperature of 340°C, and a rate of 5°C/min and was held at 340°C for 20 min. Finally, the mold was cooled

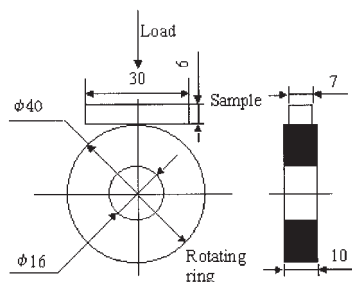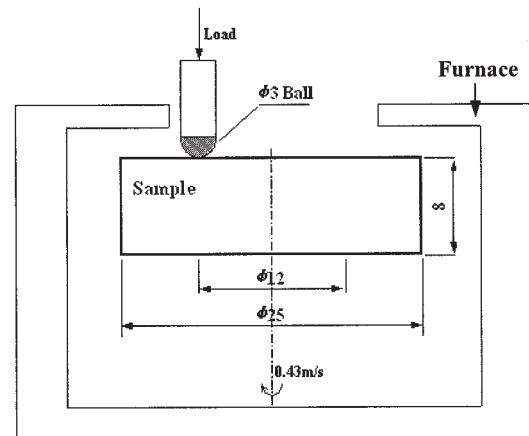**Figure 2** Contact schematic diagram of the frictional couple for the THT07-135 tester (unit: millimeters).

to room temperature in air. After the mold was released, resultant composite blocks 30 × 7 × 6 mm or 25 × 8 mm were obtained. An MH-5 microhardness tester (Tokyo, Japan) was used to measure the microhardness of PPESK and its composites filled with Al_2O_3. A load of 50 g and a loading time of 5 s were used to measure the microhardness. In this study, five replicate microhardness measurements were carried out to minimize data scattering, and the average of the five replicate test results is reported. The relative bending strengths of the PPESK composites were determined on an AG-10TA universal materials tester (Shimadzu, Japan). A velocity of 0.5 mm/min was used for the measurement of the bending strength.

The friction and wear tests were conducted on an MM-2000 friction and wear tester made by the Xuanhua Tester Factory (Hebei Province, China). The contact schematic diagram of the frictional pairs is shown in Figure 1. A mild carbon steel (AISI 1045 steel, Beijing, China) ring with a diameter of 40 mm was used as the counterpart. In this study, sliding was performed under ambient conditions (temperature = 18–20°C, humidity = 50 ± 5%) at a sliding velocity of 0.43 m/s and a normal load of 200 N. The friction coefficients were recorded with a computer connected to the tester by a sensor. We investigated the effects of different temperatures on the tribological behaviors of PPESK composites on a THT07-135 (CSEM Instrument Ltd., Swiss) high-temperature tribotester by sliding a Si_3N_4 ball on the PPESK composite disks. The contact schematic diagram of the frictional pairs is shown in Figure 2. Before each test, the surfaces of the specimen and the counterpart ring were polished with No.-900-grade SiC abrasive paper to a surface roughness of 0.52–0.88 μm. Both the blocks and the rings were cleaned with acetone and then dried; then, they were used for friction and wear tests. At the end of each test, the widths of the wear scars were measured to an accuracy of 0.01 mm on a digital-reading microscope;

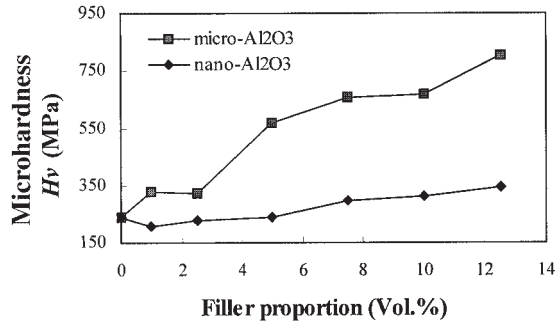**Figure 1** Contact schematic diagram of the frictional couple for the MM-2000 tester (unit: millimeters).

Figure 3 Effect of the filler volume fraction on the microhardness of the PPESK composites filled with Al$_2$O$_3$.

then, the wear rate of each specimen was calculated.[17] Three replicate tests were carried out for each specimen, and the average of the three replicates is reported in this article. The deviation of the friction and wear test data was 10%.

The morphologies of the wear traces of micrometer- and nanometer-Al$_2$O$_3$-particle-filled PPESK composites and the wear debris were observed with a JSM-5600LV scanning electron microscope, Jeol, Japan. IR spectra were taken on a Bio-Rad FTS-165 IR spectrometer, Philadelphia, PA, USA, which operated from 4000 to 500 cm^{-1}, to characterize the structure of PPESK and its composites with Al$_2$O$_3$ particles.

RESULTS AND DISCUSSION

The microhardness values of PPESK and its composites filled with Al$_2$O$_3$ are given in Figure 3. The nanometer Al$_2$O$_3$ as the filler between 1 and 12.5% volume fractions caused very little variation in the microhardness of the PPESK composite. In the meantime, micrometer-Al$_2$O$_3$-particle-filled PPESK composites exhibited a higher microhardness than PPESK. Further, the microhardness of micrometer-Al$_2$O$_3$-filled PPESK composites increased as the filler volume fraction increased. We attributed this to an effective increase in the load-carrying capacity of the micrometer-Al$_2$O$_3$-particle-filled PPESK composites. The bending strengths of the PPESK composites are given in Table I. As seen in Table I, the bending strength of nanometer-Al$_2$O$_3$-particle-filled PPESK was higher that that of

TABLE I
Bending Strength of 10 vol % Al$_2$O$_3$-Particle-Filled PPESK Composites

Specimen	PPESK	PPESK–nanometer Al$_2$O$_3$	PPESK–micrometer Al$_2$O$_3$
Bending strength (%)	100	117	56

An AG-10TA universal materials tester was with the bending strength of unfilled PPESK at 100%.

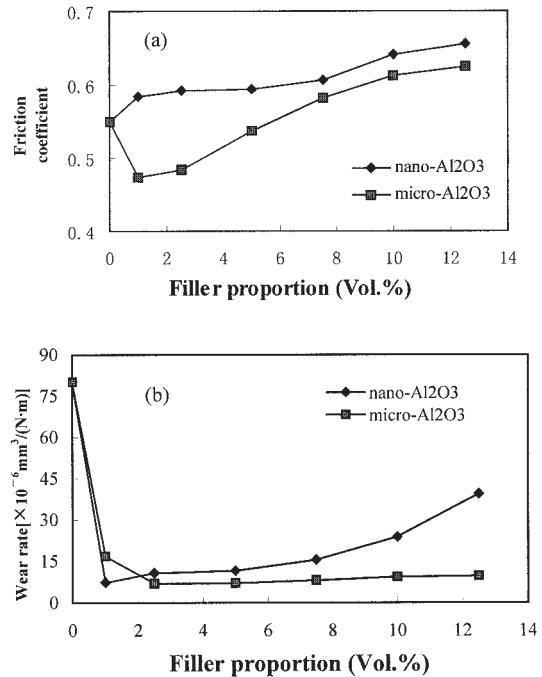**Figure 4** (a) Friction coefficient and (b) wear rate of Al$_2$O$_3$-particle-filled PPESK composites as a function of filler proportion (sliding velocity = 0.43 m/s; load = 200 N).

pure PPESK, but the bending strength of micrometer-Al$_2$O$_3$-particle-filled PPESK was lower than that of pure PPESK. We suggest that the improved interface bonding between the nanometer Al$_2$O$_3$ filler and the PPESK matrix was responsible for the increase in bending strength in this case. In other words, the toughness of nanometer-Al$_2$O$_3$-filled PPESK was higher than that of pure PPESK. Meanwhile, the decrease in the bending strength of micrometer-Al$_2$O$_3$-particle-filled PPESK was mainly due to a weakened interfacial layer between the micrometer Al$_2$O$_3$ particles and the PPESK chain.

Figure 4(a) shows plots of the friction coefficient versus the filler volume fraction for micrometer- and nanometer-Al$_2$O$_3$-particle-filled PPESK composites in dry sliding friction. Sliding wear tests were performed over a period of 90 min, which resulted in a sliding distance of 2330 m. As shown in Figure 4(a), a higher friction coefficient was always obtained with nanometer-Al$_2$O$_3$-particle-filled PPESK composites. Namely, the friction coefficient of the nanometer-Al$_2$O$_3$-particle-filled PPESK composites was higher than that of unfilled PPESK (ca. 0.55) at filler volume fractions between 1 and 12.5%. When the filler volume fraction of nanometer Al$_2$O$_3$ particles in PPESK was 1%, the friction coefficient was about 0.58, and when the volume fraction was 10%, the friction coefficient was about 0.64. Contrary to the previous case, the friction coefficient of micrometer-Al$_2$O$_3$-particle-filled PPESK composites first decreased with the filling of microme-

ter Al_2O_3 and then increased as the filler volume fraction increased, as shown in Figure 4(a). Further, when the volume fraction was above 5%, the friction coefficient was higher than that of unfilled PPESK. This indicated that the micrometer Al_2O_3 particles were beneficial in reducing the friction of the PPESK when the filler volume fraction was below 5%. It was apparent that in all of the filler fractions, the friction coefficients of the nanometer-Al_2O_3-particle-filled PPESK composites were higher than that of the unfilled PPESK composite under the same test conditions.

The wear rates of the nanometer- and micrometer-Al_2O_3-particle-filled PPESK composites against the filler volume fractions are plotted in Figure 4(b). In both filled PPESK composites, the wear rate of the composite fell greatly with small additions of nanometer or micrometer Al_2O_3 in PPESK. For the nanometer-Al_2O_3-filled PPESK, the wear rate reached its lowest value (7.31×10^{-6} mm N^{-1} m^{-1}) at an Al_2O_3 fraction of 1%, which was one order of magnitude lower than that of unfilled PPESK (80.12×10^{-6} mm N^{-1} m^{-1}) under identical test conditions. The wear rate then increased slightly with the increasing filler fraction of nanometer Al_2O_3. In the case of micrometer-Al_2O_3-filled PPESK, the flattening of the curve between 1 and 12.5% indicated that most of the beneficial wear-reducing effect had been achieved with these volume fractions. As shown in Figure 4(a,b), interestingly, the nanometer-Al_2O_3-particle-filled PPESK had a higher friction coefficient and a lower wear rate than that of unfilled PPESK, whereas micrometer-Al_2O_3-particle-filled PPESK exhibited a lower friction coefficient and wear rate than nanometer-Al_2O_3-particle-filled PPESK. Such a difference could be attributed to the different specific surface areas and surface reactivities of the nanometer and micrometer fillers and, thereby, the different wear mechanisms between the nanometer- and micrometer-particle-filled PPESKs.
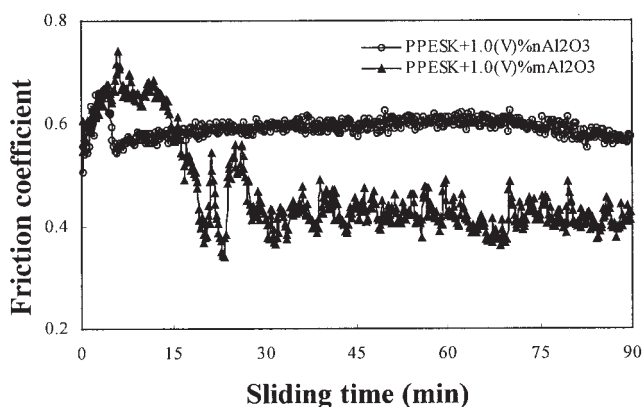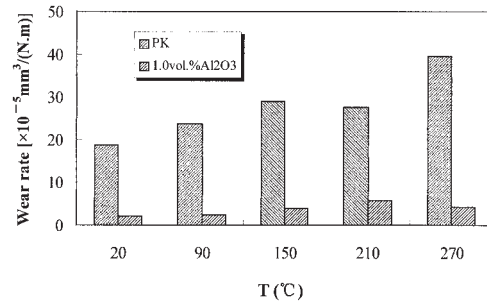

Figure 6 Wear rate of 1 vol %-nanoparticle-Al_2O_3-filled PPESK composites as a function of the ambient temperature. PK = PPESK; T = temperature.

Because automotive brake materials must satisfy adequate and stable friction-level requirements, we decided to study the variation of the friction coefficient as a function of sliding time for micrometer- and nanometer-Al_2O_3-particle-filled PPESK composites. Figure 5 gives the variation of the friction coefficient with sliding time for the PPESK composites filled with 1 vol % micrometer Al_2O_3 and 1 vol %-nanometer Al_2O_3 particles. As shown in Figure 5, for the 1 vol %-nanometer-Al_2O_3-particle-filled PPESK, the friction coefficient was stable during the test. In contrast, the friction coefficient of the 1 vol %-micrometer-Al_2O_3-particle-filled PPESK fluctuated.

High-temperature resistance is an important index for frictional materials. So the effect of different temperatures on the wear rate of nanometer-Al_2O_3-particle-filled PPESK was investigated with a high-temperature tester. For comparison, the wear rate of unfilled PPESK is also shown in Figure 6. As shown in this figure, the higher wear rate was always obtained for unfilled PPESK specimens under all temperatures, and the wear rate increased as the temperature increased, whereas the wear rate of 1 vol %-nanometer-Al_2O_3-particle-filled PPESK was lower than of unfilled PPESK under identical test conditions. Meanwhile, the wear rate of the nanometer-Al_2O_3-particle-filled PPESK was stable in the range of the ambient temperature to 270°C. In other words, increasing the temperature had little effect on the wear rate of nanometer-Al_2O_3-particle-filled PPESK.

To explore the different effects of micrometer and nanometer Al_2O_3 particles on the tribological behaviors of PPESK under identical experimental conditions, the wear traces and wear debris were observed with scanning electron microscopy (SEM). For comparison, the SEM micrographs of the wear traces and wear debris of unfilled PPESK are shown in Figure 7. Severe adhesion and cutting were the dominant wear mechanisms for unfilled PPESK [Fig. 7(b,c)]. The wear debris of unfilled PPESK were large flakes, and many granules adhered to the large flakes [Fig. 7(d)]. These factors contributed to the high wear rate of unfilled PPESK.

Figure 5 Variation of the friction coefficient with sliding time for PPESK composites filled with micrometer and nanometer Al_2O_3 particles (sliding velocity = 0.43 m/s; load = 200 N).
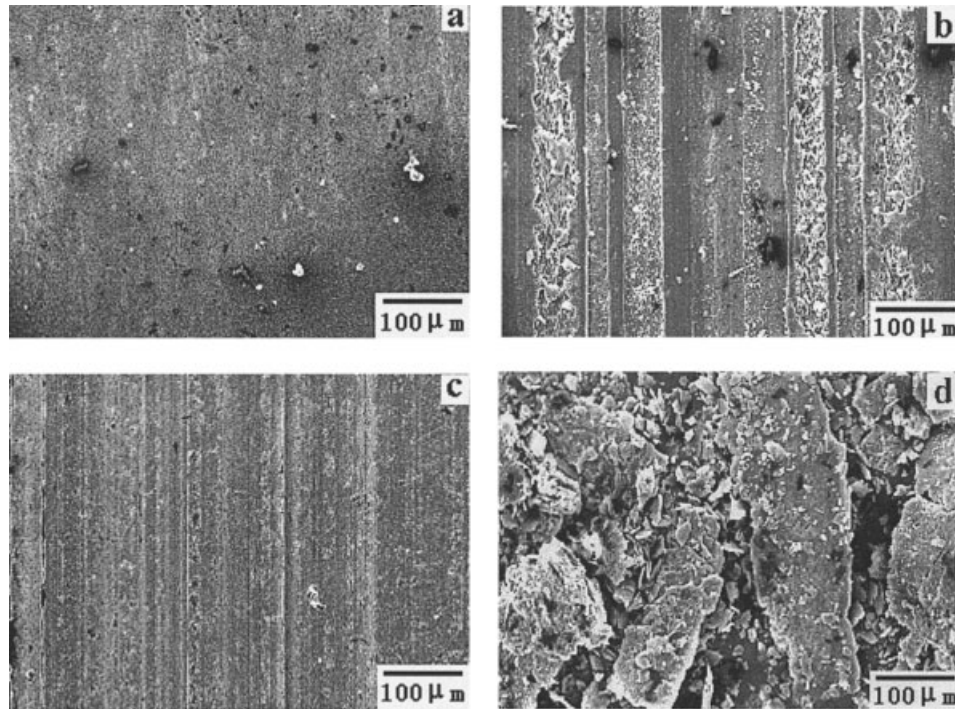
Figure 7 SEM micrographs of (a) the original surface of unfilled PPESK, (b) the worn surface of unfilled PPESK, (c) the surface of the steel ring sliding against unfilled PPESK, and (d) the wear debris of unfilled PPESK (sliding velocity = 0.43 m/s; load = 200 N).

The SEM micrographs for the worn surfaces of nanometer-Al$_2$O$_3$-particle-filled PPESK composites before and after friction, the surfaces of the steel ring sliding against the composites, and the wear debris of the composites are shown in Figure 8. The worn surface of 1%-nanometer-Al$_2$O$_3$-filled PPESK was smooth, and there were some bright zones, as shown in Figure 8(c). This was probably caused by the polishing action of nanometer Al$_2$O$_3$ particles. As is well known, the nanoparticle has a much smaller particle diameter, a much greater surface-area-to-volume ratio, and more physical and chemical defects on its surface, which can easily lead to a combination of particles with the polymer by a chemical pattern. This may have been important for increasing the binding of the particles to the polymer matrix at the polymer active position in the composite material. Thus, we concluded that nanometer particles have the capability of blending well with the polymer and, hence, increasing the bond strength between the filler and the polymer. Thus, the composite was difficult to transfer from the composite to the surface of the steel ring, and the surface of the steel ring was naked, as shown in Figure 8(e). So the wear debris, as shown in Figure 8(g), was much smaller than that of unfilled PPESK [Fig. 7(d)]. This probably accounted for the better wear resistance and higher friction coefficient of the 1%-nanometer-Al$_2$O$_3$-filled PPESK. Similarly, there

was hardly any transfer film on the surface of the steel ring, as shown in Figure 8(e,f), which revealed that the surface of the steel ring was polished by this nanoabrasive powder. We thus inferred that the wear mechanism of the micrometer-Al$_2$O$_3$-particle-filled PPESK was mainly slight abrasive wear. Contrary to those of the 1%-nanometer-Al$_2$O$_3$-filled PPESK composite, the micrographs of the worn surface of the 10%-nanometer-Al$_2$O$_3$-filled PPESK composite showed obvious scuffing and adhesion [Fig. 8(d)]. The examination of the wear debris, shown in Figure 8(h), for 10%-nanometer-Al$_2$O$_3$-filled PPESK tests also showed obvious signs of scuffing and adhesion. This may have been caused by a rigidity effect of the nanoparticles when the volume fraction of the nanometer Al$_2$O$_3$ was higher. In this case, the interface between the filler and the polymer became weaker, so the wear rate became higher. Therefore, the wear mechanism of the nanometer-Al$_2$O$_3$-filled PPESK was mainly slight abrasive wear when the filler proportion was 1% (the lower filler proportion), and the wear mechanism was mainly abrasive wear when the filler proportion was 10% (the higher filler proportion).

Figure 9 shows the SEM micrographs for the worn surfaces of the micrometer-Al$_2$O$_3$-particle-filled PPESK composites and the steel ring sliding against the composites before and after friction and the wear debris of the composites. As shown in Figure 9(a,b), for microme-
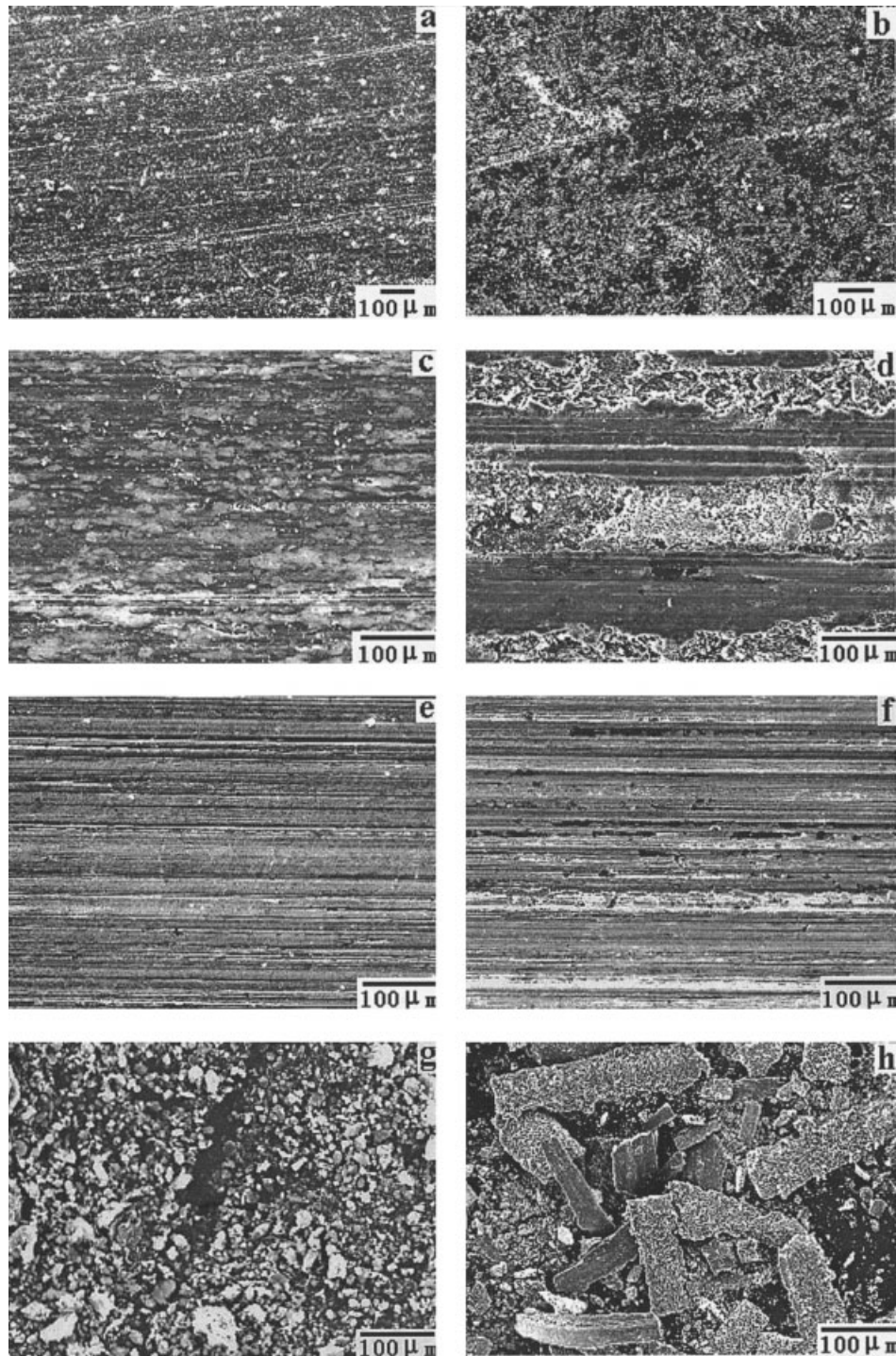
Figure 8 SEM micrographs of the original surface of (a) 1 and (b) 10% nanometer Al_2O_3–PPESK, the worn surface of (c) 1 and (d) 10% nanometer Al_2O_3–PPESK, the surface of the steel ring sliding against (e) 1 and (f) 10% nanometer Al_2O_3–PPESK, and the wear debris of (g) 1 and (h) 10% nanometer Al_2O_3–PPESK (sliding velocity = 0.43 m/s; load = 200 N).

ter-Al_2O_3-particle-filled PPESK, the distribution of filler was not uniform. As shown in Figure 9(c), the worn surface of 1%-micrometer-Al_2O_3-filled PPESK was relatively smooth and showed only slight signs of scuffing and plastic deformation. At the same time, the wear debris of the micrometer-Al_2O_3-filled PPESK composite

was smaller than that of unfilled PPESK [see Fig. 9(g,h)]. On the contrary, as shown in Figure 9(d), the morphology of the worn surface of the 10%-nanometer-Al_2O_3-filled PPESK showed obvious signs of plastic deformation. For micrometer-Al_2O_3-filled PPESK, the increasing wear resistance (see Fig. 4) was related to the load-
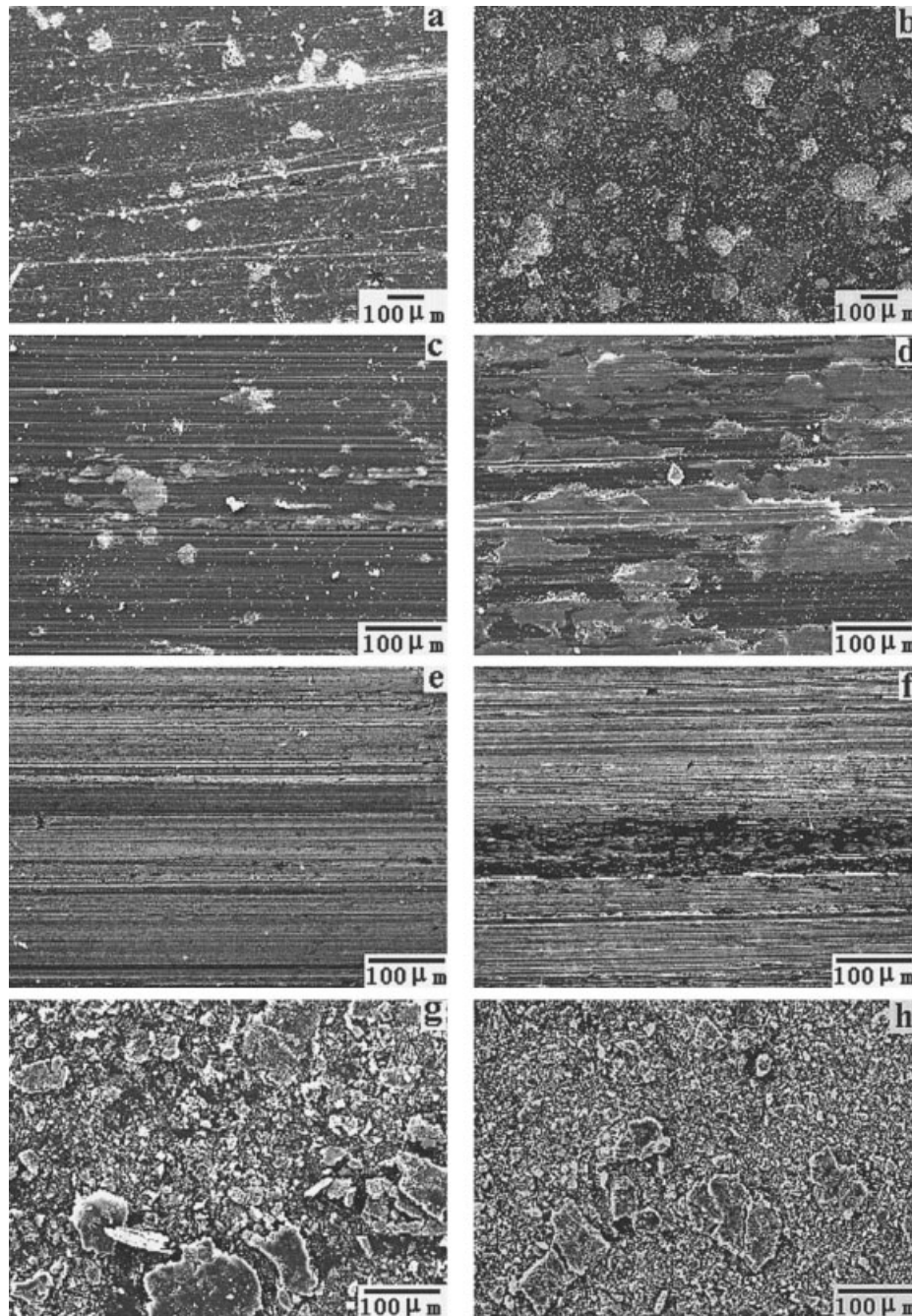
Figure 9 SEM micrographs of the original surface of (a) 1 and (b) 10% micrometer Al$_2$O$_3$–PPESK, the worn surface of (c) 1 and (d) 10% micrometer Al$_2$O$_3$–PPESK, the surface of the steel ring sliding against (e) 1 and (f) 10% micrometer Al$_2$O$_3$–PPESK, and the wear debris of (g) 1 and (h) 10% micrometer Al$_2$O$_3$–PPESK (sliding velocity = 0.43 m/s; load = 200 N).

carrying action of the micrometer Al$_2$O$_3$ and the modification of the counterface by abrasion because the micrometer Al$_2$O$_3$ particles were hard. This can be better understood through consideration of the microhardness of Al$_2$O$_3$-filled PPESK (see Fig. 3).

It is well known that as a consequence of the crosslinking of the polymer, a crosslinked polymer cannot be dissolved in a solvent in which the uncrosslinked polymer can dissolve, but it can swell, and the higher the crosslinking is in the polymer, the lower the ratio

of the equilibrium swelling (Q) is. The properties of the dissolution and swelling of the micrometer- and nanometer-Al$_2$O$_3$-particle-filled PPESK are shown in Table II. As shown in Table II, the pure PPESK and the micrometer-Al$_2$O$_3$-particle-filled PPESK both dissolved in CHCl$_3$. Contrary to what was observed for micrometer-Al$_2$O$_3$-particle-filled PPESK, the composites filled with nanometer particles dissolved in CHCl$_3$ when the volume fraction was below 5%, but when the volume fraction was above this value, the compos-

	Proportion of filler (vol %)						
	0	1	2.5	5	7.5	10	12.5
Nanometer filled	√	√	√	12.89	10.07	9.55	8.61
Micrometer filled	√	√	√	√	√	√	√

A numeral refers to the Q value of the PPESK composite. A check indicates that the composite was soluable (in CHCl$_3$).

ites did not dissolve in CHCl$_3$. Further, the Q value of the PPESK composites decreased as the filler volume fraction increased, as shown in Table II. We thus concluded that the addition of nanometer Al$_2$O$_3$ to PPESK led to the crosslinking of the PPESK [as shown in Fig. 10(a)] and increased the roughness of the composite. In this case, the chains of PPESK were difficult to slip. Consequently, the strength of the composites filled with nanometer Al$_2$O$_3$ was high. So the friction coefficient of nanometer-Al$_2$O$_3$-particle-filled PPESK was higher and the wear rate was lower than that of unfilled PPESK. From these results, we concluded that the nanometer-Al$_2$O$_3$-particle-filled PPESK composites met with the demands of frictional materials. Contrary to the previous results, the chains of the micrometer-Al$_2$O$_3$-particle-filled PPESK composites retained the uncrosslinked structure [as shown in Fig. 10(b)]. The lower friction coefficient and wear rate were related to the load-carrying action of the micrometer filler, and the higher friction coefficient and wear rate were related to the contact between the filler and the frictional couple.

To explain the different effects of the nanometer and micrometer Al$_2$O$_3$ particles on the wear mechanisms of the PPESK composites, it is necessary to emphasize again that there existed obvious differences among the nanometer and micrometer Al$_2$O$_3$ particles. The nanoparticles had the capability of blending well with the polymer. We believe that the nanometer Al$_2$O$_3$ particles in the PPESK provided a stronger connection among the chains of the PPESK molecules and, hence, obviously decreased the wear rates of the PPESK. However, when the nanometer Al$_2$O$_3$ particle volume fraction was higher, this connecting action was largely absent because of the aggregate action of the nanoparticles. Subsequently, a higher wear rate was achieved.

Another difference between the nanoscale and microscale particles of the same material is that the nanoparticle has a much higher surface-area-to-volume ratio. Figure 11 shows the Fourier transform infrared transmission spectra of PPESK and its composites with Al$_2$O$_3$. In combination with the strength of the C—O—C stretching vibration peak at 1240 cm^{-1} and the Ar—C=O peak at 1666 cm^{-1} for unfilled PPESK and the nanometer-Al$_2$O$_3$-particle-filled and micrometer-Al$_2$O$_3$-particle-filled PPESK composites, as shown in Figure 11, the Ar—C=O peak for the nanometer-Al$_2$O$_3$-particle-filled PPESK composite became weak [Fig. 11(b)]. This indicated that the double bond in Ar—C=O was active and reacted with the nanometer Al$_2$O$_3$ particles during heating compression. Therefore, the binding strength of the nanometer Al$_2$O$_3$ particles was high. Consequently, the friction coefficient of nanometer-particle-filled PPESK was higher than that of unfilled PPESK, and the wear rate was lower than that of unfilled PPESK. This also indicated that the 1%-nanometer-Al$_2$O$_3$-particle-filled PPESK could be used as a frictional material.

CONCLUSIONS

1. The nanometer-Al$_2$O$_3$-particle-filled PPESK composites always exhibited a higher friction coefficient than that of unfilled PPESK, although small additions of nanometer Al$_2$O$_3$ could greatly increase the wear resistance of PPESK. The wear rate of nanometer-Al$_2$O$_3$-filled PPESK was at its lowest value (7.31×10^{-6} mm^3 N^{-1} m^{-1}) at an Al$_2$O$_3$ fraction of 1%; we found that nanometer-
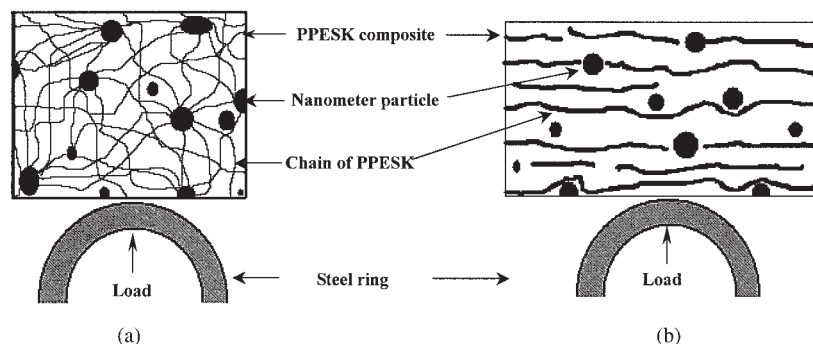

Figure 10 Schematic illustration of the wear model of (a) nanometer- and (b) micrometer-Al$_2$O$_3$-particle-filled PPESK. The length scales in this figure are not represented correctly.
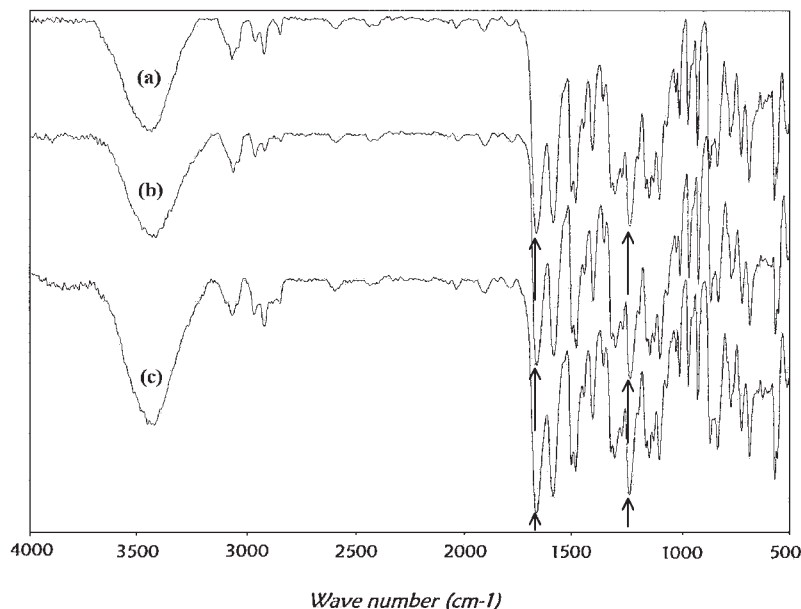
Figure 11 IR spectra of (a) pure PPESK, (b) nanometer-Al$_2$O$_3$-filled PPESK, and (c) micrometer-Al$_2$O$_3$-filled PPESK.

Al$_2$O$_3$-particle-filled PPESK could be used as a good frictional material at a 1% volume fraction. At higher volume fractions, the wear rate of the composites with nanometer Al$_2$O$_3$ particles became higher.

2. In contrast, micrometer Al$_2$O$_3$ had a lower friction coefficients at filler volume fractions below 5%. The filling of micrometer Al$_2$O$_3$ particles greatly increased the wear resistance of PPESK at filler volume fractions of 1–12.5%

3. The wear rate of 1 vol % nanometer-Al$_2$O$_3$-particle-filled PPESK was lower than that of unfilled PPESK and was stable from the ambient temperature to 270°C.

4. The results from the bending strength and solubility tests of the PPESK composites indicated that the nanometer Al$_2$O$_3$ particles led to crosslinking of the PPESK. In contrast, the PPESK filled with micrometer Al$_2$O$_3$ particles retained an uncrosslinked structure. So the friction coefficient of nanometer-Al$_2$O$_3$-particle-filled PPESK was higher and the wear rate was lower than those of unfilled PPESK.

5. The wear mechanism of nanometer-Al$_2$O$_3$-particle-filled PPESK was characteristic of slight abrasive wear, whereas that of micrometer-Al$_2$O$_3$-particle-filled PPESK was characteristic of plastic deformation.

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