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Key Laboratory of Molecular Engineering of Polymers of Ministry of Education, Department of Macromolecular Science, Fudan University, Shanghai, China

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Study on the Friction and Sliding Wear Behavior of Hybrid Polytetrafluoroethylene/Kevlar Fabric Composites Filled with Polyphenylene Sulfide

TING HUANG, RENGUO LU, YUNING MA, PEI LIU, AND TONGSHENG LI

Key Laboratory of Molecular Engineering of Polymers of Ministry of Education, Department of Macromolecular Science, Fudan University, Shanghai, China

Hybrid fabric/polyphenylene sulfide (PPS) composites filled with the particulates of PPS were prepared by dip coating the polystyrene (PS)/poly(p-phenylene terephthalamide) (Kevlar) hybrid fabric in a PPS suspension solution containing the particulates to be incorporated. The friction coefficient and wear rate of the hybrid fabric/PPS composites were evaluated on a MPX-2000A friction and wear tester with an end-face contact mode in a dry sliding condition. The results showed the hybrid PTFE/Kevlar fabric composites filled with 40 wt% PPS had the best tribological behavior. The friction coefficient and wear rate decreased with an increase in sliding speed, and they reached the lowest value when the load was 1000 N. The Rockwell hardness affected the wear rate to some degree. Scanning electron microscopy (SEM) micrographs revealed that even, smooth, and coherent transfer films, formed on the counterface, played an important role in the friction process. They were effective in improving the tribological properties. The surface appearances and cross sections of the hybrid fabric composites were examined through SEM. They showed that the PPS held the hybrid fabric together and adhered it to the wear tester surface, accounting for the improvement of the tribological properties of the hybrid fabric/PPS composites.

Keywords fixation effect, hybrid fabric composites, PPS, transfer films, tribological properties

1. Introduction

With the development of aviation and aerospace, as well as automotive needs, bearing materials made of fabric composites cohering onto a metal surface are being used in many high-tech areas. In addition, fiber reinforced polymeric composites are known to have improved mechanical properties, and also improved friction and wear performance. They are extensively used in sliding wear applications such as bearings, slides, gears, and seals. In previous studies, the fabric composites, composed of fabric as the matrix, and adhesive resin as the binder, cohered onto the metal surface in the presence of the adhesive resin. However, to our knowledge, there is no reported research that thermostable...
engineering plastics improved the tribological characteristics of fabric composites, acting as the fixing agent, holding the fabric together, instead of just as an adhesive resin.

PPS has a high melting point and excellent adhesiveness with inorganic substances at high temperature, as well as high hardness and good wear resistance at room temperature\[13,14\]. As the fixing agent, it cannot only be used to fix fabric composites onto the metal surface, but also can hold the PTFE and Kevlar fibers in place. In addition, it was reported by Duan et al. that PPS showed high load-carrying capacity and wear resistance in previous reports from our group.\[15,16\] Consequently, one of the effective methods for the improvement of the tribological properties of the hybrid fabric might be introducing PPS into the composites.\[17\]

Early studies were mainly focused on the tribological behavior of only one type of fiber.\[18–20\] The advantage of hybrid fabric composites is that one type of the fabric can complement what is lacking in another.\[21–23\] Hybrid PTFE/Kevlar fabric is woven out of PTFE and Kevlar fibers. When the selected weaving process is finished, the hybrid PTFE/Kevlar fabric exhibits two types of surfaces with different proportions between PTFE and Kevlar. The one rich in PTFE fiber was used as a friction surface while the other, rich in Kevlar fiber, was used as a binding surface. However, the PTFE fibers had a high wear rate and poor adhesion to other materials.\[24\] In order to increase the applicability of hybrid PTFE/Kevlar fabric composites in the bearing industries where the integration and multifunction of bearings made of various composites are of particular interest, a modification is thus necessary to improve the tribological properties of hybrid PTFE/Kevlar fabric composites.

The objective of this paper was to investigate the friction and wear behavior of hybrid fabric/PPS composites. The experiments were carried out by studying the effect of concentration of fillers, sliding speed, load, etc. In addition, Rockwell hardness was also tested. The morphologies of the surface appearances of hybrid fabric composites, cross sections, worn surfaces, wear debris, and transfer films were characterized by scanning electron microscopy (SEM) and were used to understand the related mechanisms.

2. Experimental Details

2.1. Materials

The twill-woven hybrid PTFE/Kevlar fabric was composed of low-friction PTFE fiber and high-strength Kevlar fiber with an area density of 310 gm$^{-2}$ (the volume ratio of the PTFE/Kevlar fibers was about 35:65). A photograph of the hybrid fabric is shown in Fig. 1. PPS resin was purchased from Sichuan Deyang Chemical Co., Ltd., Chengdu, China. The properties of the PPS resin are listed in Table 1. The steel substrate was coated with a sintered porous bronze layer with a thickness of 0.5 mm, and the surface roughness was controlled to be between $R_a$ 0.30 and 0.45 $\mu$m. Absolute ethanol was purchased from Shanghai Zhenxing NO.1 Chemical Plant, Shanghai, China.

2.2. Preparation of Hybrid Fabric/PPS Composites

A mixed solution (absolute ethanol:distilled water = 1:6) was prepared uniformly at room temperature. PPS resin was added into this mixed solution, forming a PPS suspension by dispersing in an ultrasonic bath. The hybrid PTFE/Kevlar fabric was dipped in acetone for 24 h, followed by boiling in distilled water for 15 min and cleaning with acetone in
an ultrasonic bath. Then the pretreated hybrid fabric was immersed in the PPS suspension with a chosen mass fraction. The hybrid PTFE/Kevlar fabric was coated with different amounts of PPS by means of successive immersion, brushing, and drying around 110°C. The process was repeated until the mass fraction of PPS reached the desired value. In order to fix the hybrid fabric/PPS composites onto the steel substrate (the surface was coated with a sintered porous bronze layer), they were brushed with a PPS suspension, followed by drying. Finally, the hybrid PTFE/Kevlar fabric composites filled with PPS were affixed onto the porous bronze substrate by a hot pressing process. The hot pressing process was conducted at 295°C and 3 MPa for 5 min with several intermittent pressure releases (3 seconds each time), then cooled at a rate of 1°C/min after holding at constant temperature and pressure for 10 min. A schematic diagram of the preparation of the hybrid fabric/PPS composites from the PPS suspension is shown in Fig. 2.

In the following work, N-HF composites stand for the composites without added PPS and any adhesive resin, while U-HF composites stand for the composites that only contained the proper amount of PPS resin between the hybrid fabric composites, unfilled with PPS, and the steel substrate. HF-PX composites stand for the composites filled with different

<table>
<thead>
<tr>
<th>Table 1</th>
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<tbody>
<tr>
<td>The properties of the PPS resin</td>
</tr>
<tr>
<td>Test value</td>
</tr>
<tr>
<td>Weight average molecular weight</td>
</tr>
<tr>
<td>Melt flow rate (1.18 mm, 315°C, 5 kg)</td>
</tr>
<tr>
<td>Ash content</td>
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<tr>
<td>Moisture content</td>
</tr>
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mass fractions of PPS (0 < X < 100). They were prepared and evaluated for tribological properties. The compositional variation and the designation of the composites are given in Table 2.

### 2.3. Friction and Wear Test

Sliding experiments were conducted on a MPX-2000A friction and wear tester (Xuanhua Testing Machine Factory, Lanzhou, China) with an end-face contact mode. Figure 3 shows the schematic diagram of the contact couples. The prepared sample (35 mm × 7 mm) was sliding against a 440C steel ring (Φ 23 mm × Φ 20 mm), which was ground with abrasive paper of various grit sizes in sequence. Prior to each test, the specimens and steel rings were ultrasonically cleaned in acetone, and then, dried thoroughly. The sliding was performed at varied loads from 600 to 1400 N, sliding velocity of 0.2 – 0.4 m/s and over a period of 2 h under ambient conditions (temperature: 23°C ± 2°C, relative humidity: 50% ± 10%).

The friction coefficient was calculated by the computer automatically through measuring the frictional torque gained from the load cell sensor. The wear volume loss (∆V, mm³) of the specimen was obtained by measuring the depth (mm) of the wear track with a micrometer, and calculated according to Equation (1):

\[ \Delta V = 2d \left[ R^2 \sin^{-1} \frac{b}{2R} - r^2 \sin^{-1} \frac{b}{2r} + \frac{b}{4} \left( \sqrt{4R^2 - b^2} - \sqrt{4r^2 - b^2} \right) \right]. \] (1)

### Table 2

<table>
<thead>
<tr>
<th>Composite designations</th>
<th>N-HF</th>
<th>U-HF</th>
<th>HF-P</th>
<th>HF-30P</th>
<th>HF-40P</th>
<th>HF-50P</th>
<th>HF-60P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hybrid fabric</td>
<td>100</td>
<td>100</td>
<td>100-X</td>
<td>70</td>
<td>60</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>PPS resin</td>
<td>0</td>
<td>0</td>
<td>X</td>
<td>30</td>
<td>40</td>
<td>50</td>
<td>60</td>
</tr>
</tbody>
</table>
Here, $d$, $b$, $R$, and $r$ refer to the average depth (mm) of the wear track, the width (mm) of the specimen, and the exterior radius (mm) and interior radius (mm) of the steel ring, respectively.

Then, the wear rate $[K$ (mm$^3$/Nm)] was calculated according to Equation (2):

$$K = \frac{\Delta V}{PL}.$$  \hspace{1cm} (2)

Here, $P$ and $L$ refer to the load (N) and the sliding distance (m), respectively.

In this work, the average results of five repeated friction and wear tests were reported to minimize data scatter.

2.4. Mechanical Tests

The Rockwell hardness was tested with an XHR-150 Rockwell hardness tester (Shanghai Material Testing Machine Factory, Shanghai, China). The test was conducted according to the standard ISO2039-2:1987 and the S scale was used.

Each experiment was carried out three times and the average value is used.

2.5. Analysis Methods

A TS 5136MM SEM (Tescan Co., Brno, Czech) was used to observe the surface, cross sections, worn surfaces, wear debris (collected during the friction tests), and transfer films of the hybrid fabric composites. All specimens were sputtered with gold for conductivity before SEM observation.
3. Results and Discussion

3.1. Fixation Effect of PPS on the Tribological Properties

The variation of friction coefficient of the N-HF, U-HF, and HF-P composites with sliding time is presented in Fig. 4. N-HF composites sliding against the steel ring wore out after only 4 min at 0.2 m/s, 1000 N, and room temperature, while U-HF composites did not wear out after 33 min sliding time for the same test conditions. The best tribological properties were obtained for the HF-P composites (taking the HF-40P composite as an example). Compared with N-HF composites and U-HF composites, the HF-P composites did not wear out in the whole process. Furthermore, they had the most stable friction coefficient and the lowest wear rate ($1.09 \times 10^{-6} \text{ mm}^3/\text{Nm}$).

A fixation effect of PPS occurred, which not only can fix the hybrid fabric composites onto the steel substrate, but also can maintain the integrity of the hybrid fabric without pull-out fibers. Consequently, the differences between the N-HF, U-HF, and HF-P composites might be explained by the fixation effect of PPS, which can improve abrasion resistance. The results indicate that it is crucial to add PPS resin to the hybrid fabric to improve the tribological properties of HF-P composites.

3.2. Rockwell Hardness

Figure 5 shows the influence of the concentration of PPS on the Rockwell hardness of HF-P composites. The Rockwell hardness of the HF-40P composites was slightly higher than that of the HF-30P composites. However, there existed a sharp drop in the average value of the Rockwell hardness when the mass fraction of PPS was above 40 wt%. As a result, it suggests that the optimum content of PPS was 40 wt%.

3.3. Friction and Wear Behaviors

Figure 6 shows the variations of friction coefficient and wear rate of HF-P composites with the mass fraction of PPS. Compared with the HF-30P, HF-50P, and HF-60P composites,
Figure 5. Effect of concentration of PPS on the Rockwell hardness of hybrid fabric/PPS composites.

the HF-40P composites had the lowest friction coefficient (0.08) and wear rate ($1.33 \times 10^{-6} \text{ mm}^3/\text{Nm}$) at 0.2 m/s and 600 N. When the mass fraction of PPS was below or above 40 wt%, the friction coefficient and wear rate increased. This phenomenon suggested that the proper mass fraction of PPS could favorably improve the tribological properties, while excessive PPS worsened the wear-resisting properties and increased the friction coefficient. In other words, the optimal addition of PPS was 40%. Thus, the HF-40P composites were chosen to investigate the influence of load and sliding speed.

In addition, combined with the above analysis of Rockwell hardness, the higher the Rockwell hardness is, the lower the wear rate is, suggesting that the Rockwell hardness was a significant factor in the wear rate of the HF-P composites.

Figure 6. Effect of concentration of PPS on friction coefficient and wear rate of hybrid fabric/PPS composites (load: 600 N, sliding speed: 0.2 m/s).
Figure 7. Effect of (a) load and (b) sliding speed on friction coefficient and wear rate of HF-40P composites.

Figure 7 shows the influence of the sliding speed and load on the friction and wear behavior of the HF-40P composites. It can be seen from Fig. 7(a) that the friction coefficient of HF-40P composites was at its lowest value when the applied load was 1000 N, and then, went up with increasing applied load. The wear rate and friction coefficient of the HF-40P composites had similar trends compared with each other. Under lower applied loads (below 1000 N), such behavior may be explained by the influence of contact pressure and a gradual increase of the real contact area through elastic deformation of the surface asperities.\textsuperscript{25} Under the higher loads (above 1000 N), the increase of friction coefficient was due to the first law of friction (the friction force is proportional to the applied normal load).\textsuperscript{26} Kragelskii has reported that the friction coefficient for thermoplastic polymers
and rubbers went through a minimum that corresponded to the transition from elastic to plastic contact.\textsuperscript{[27]} As to the wear rate of the HF-40P composites, it decreased linearly up to 1000N, and then, increased linearly with higher loads (above 1000 N). This phenomenon has been reported often for the tribological properties of polymer composites.\textsuperscript{[28–30]} The effect of excessive loads can be partially accounted for by a large amount of friction heat, which could result in damaging the HF-P composites severely. In addition, the overload led to a high contact stress exceeding the polymer compressive strength.

As shown in Fig. 7(b), the increase of sliding speed (from 0.2 to 0.4 m/s) decreased the wear rate to a certain extent. The friction coefficient of the HF-40P composites was also reduced with increasing velocity. It was reported by Fort that the duration of contact

![Figure 8. SEM micrographs of surface appearances and cross sections of (a) and (b) HF-30P composites; (c) and (d) HF-40P composites; (e) and (f) HF-50P composites; (g) and (h) HF-60P composites (load: 1000N, sliding speed: 0.2 m/s) (Continued).](image-url)
shortened and the contact area decreased at a higher sliding velocity with a further decrease in the friction force,\(^{[31]}\) which might account for the lower friction coefficient at higher sliding velocities (below the critical speed). Some research papers have shown that high sliding velocities produce high temperatures, which might cause polymers to soften or to degrade. In some cases, however, high temperatures might be beneficial to the lubricating process. It can favor molecular relaxation and formation of a transfer film.\(^{[32]}\) Therefore, a high sliding velocity might cause a decrease of wear rate in some case.

3.4. Surface Appearances, Cross Sections, Worn Surfaces, Wear Debris, and Transfer Films Observations

Figure 8 shows SEM micrographs of the surface appearances and cross sections of the HF-P composites. For the HF-30P composites, there existed a great many voids between
the warps and wefts due to the shortage of PPS [Fig. 8(a)]. In addition, there were obvious
voids and gaps between the individual fibrils in the HF-30P composites [Fig. 8(b)], which
might adversely affect the tribological behavior. Excessive PPS was also disadvantageous
for the friction and sliding wear behavior because of the resulting uneven and lumpy
surface appearance [Figs. 8(e) and 8(g)] as compared to the smoother surface in Fig. 8(c).
Figure 8(c) shows that the HF-40P composites have an even and smooth surface appearance.
In addition, the cross section of the HF-40P composites indicated that the PPS resin adhered
to the hybrid fabric well without any voids, compared with the other HF-P composites [Figs.
8(d), 8(f), and 8(h)]. This further confirmed that the optimum content of PPS was 40%.
Figure 9 shows SEM micrographs of the worn surfaces and wear debris of the HF-P
composites. Some fibers were pulled out of the substrate and the worn surface showed some

Figure 9. SEM micrographs of worn surfaces and wear debris of (a) and (b) HF-30P composites;
(c) and (d) HF-40P composites; (e) and (f) HF-50P composites; (g) and (h) HF-60P composites (load:
1000 N, sliding speed: 0.2 m/s) (Continued).
scuffed grooves and wear cracks in the case of the HF-30P composites [Fig. 9(a)]. This phenomenon was indicative of severe wear. The wear debris of the HF-30P composites presented irregular long strips and, rarely, flake-like sheets [Fig. 9(b)]. For the HF-50P and HF-60P composites, there existed a large number of crevasses and asperities on the worn surface. Moreover, plastic deformation and melting phenomena could be observed visibly [Figs. 9(e) and 9(g)]. In addition, large and thick flakes were clearly present [Figs. 9(f) and 9(h)]. In agreement with their excellent antiwear ability, a smooth and flat worn surface [Fig. 9(c)] occurred for the HF-40P composites, resulting in mild wear, which was beneficial for improvement of the tribological behavior of the HF-40P composites. Furthermore, less serious damage was observed on the worn surface of HF-40P composites, compared with other HF-P composites. In addition, the wear debris consisted of relatively small sheets
From the above observations, it can be concluded that the tribological wear mechanism of the HF-P composites was mainly adhesive wear.

Representative SEM micrographs of the counterpart steel ring prior to the tests and the transfer films formed by the HF-P composites are shown in Fig. 10. It can be seen from Fig. 10(c) that for the HF-30P composites a small and discontinuous transfer film formed on the surface of counterpart steel ring, which provided no protection for the friction pair. This behavior explained why the HF-30P composites had poor antiwear ability. With respect to the HF-60P composites, the transfer film on the counterface was thick, rough, and incoherent [Fig. 10(d)], which was likely to be rubbed off the counterface and formed the large sheet debris observed in Fig. 9(h) under the 1000 N load. The debris was transferred to the interface between the counterface and hybrid fabric composites and presumably

![Figure 10. SEM micrographs of (a) the counterpart steel ring and the transfer films formed by (b) HF-40P composites, (c) HF-30P composites, (d) HF-60P composites (load: 1000 N, sliding speed: 0.2 m/s).](image-url)
led to the high wear due to a three-body abrasive wear. Obviously, this behavior would be unfavorable to provide an excellent antiwear property for the corresponding composite. Contrary to the above, the transfer film of the HF-40P composites appeared to be continuous, smooth, and adhesive [Fig. 10(b)]. This suggested that the adhesion between transfer film and the counterpart steel ring was strong and the film was not easy to be rubbed off during the friction process. The tenacious transfer film can prevent direct contact between the steel ring and hybrid fabric composites and prevent severe wear of the HF-P composites even at high load. Zhang and Zhang have reported that a thin and coherent transfer film on the counterface could hinder the abrasion of the matrix surface that would be due to asperities on the steel ring.\(^{[33]}\) This resulted in a low wear rate. Samyn found that the self-lubricating ability of most polymers depends on the formation of a transfer film on the sliding counterface.\(^{[31]}\) In a word, the hybrid fabric composite filled with 40% PPS tended to form a thin, smooth, and adhesive transfer film, which was related to the tribological properties discussed above.

4. Conclusions

Studies on the friction and sliding wear behavior of hybrid PTFE/Kevlar fabric composites filled with PPS led to the following conclusions:

1. N-HF, U-HF, and HF-P composites were prepared to study the friction and sliding wear. The most significant improvement of the antiwear ability was obtained with the incorporation of PPS in comparison with the others. This can be attributed to the fixation effect of PPS, which not only can fix the hybrid fabric composites onto the steel substrate, but also maintain the integrity of the hybrid fabric without pull-out fibers.

2. The friction and wear properties of the HF-P composites were strongly influenced by the content of PPS. An optimum PPS content was found to be 40%. At lower or higher concentration, the transfer films of the HF-P composites were discontinuous and rough, which were not favorable for the tribological properties of HF-P composites.

3. Load and sliding speed played an important role in the tribological properties of the HF-P composites. For the HF-40P composites chosen to study, the best tribological properties were at 0.4 m/s and 1000 N.

4. The Rockwell hardness of the HF-P composites depended on the content of PPS. A higher Rockwell hardness corresponded to a lower wear rate.

Acknowledgement

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