Tribological behavior of hybrid PTFE/Kevlar fabric composites with different weave densities

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Abstract
Purpose – The purpose of this paper is to achieve attractive fabric composites with excellent tribological performance and investigate the wear mechanisms of these fabric composites sliding against bearing steel pins under dry sliding process.
Design/methodology/approach – Five different weave density composites were prepared, and the tribological behaviors of these composites were studied at different testing conditions. Scanning electron microscopy, laser microscopy (three-dimensional profile measurements) and energy-dispersive X-ray spectrometry were used to analyze the worn surface morphology, wear volume and elemental content of the transfer films, respectively.
Findings – The composite weave density serves an important influence on tribological behavior. Generally, the wear rate of each composite increased with increasing weave density, and the friction coefficient of each composite decreased with increasing weave density.
Originality/value – Nanoparticle-filled hybrid polytetrafluoroethylene/Kevlar fabric composites with proper weave density have exhibited superior tribological properties in dry sliding conditions. The results that obtained in this paper may offer a reference for others who intend to achieve attractive fabric composites with excellent tribological performance.

Keywords Polymers, Bearings, Tribology, Wear resistance, Solid lubricants

Paper type Research paper

1. Introduction
Hybrid polytetrafluoroethylene (PTFE)/Kevlar fabric composites are potentially excellent tribological performance materials for use as advanced bearing liner materials in aerospace, aviation and automobile industries (Biswas and Vijayan, 1992). The PTFE fiber side is used as the friction surface due to its good lubrication, and the Kevlar fiber side, with its good mechanical properties, is used as the binding surface (Penn and Larsen, 1979; Zhang et al., 2009). However, PTFE exhibits a high wear rate in its pristine form (Tanaka et al., 1973); as a result, hybrid PTFE/Kevlar fabric composites do not satisfy most tribological requirements.

Many researchers have shown that one or two or even more kinds of reinforcement filler materials were complemented to improve the tribological behaviors of polymer-matrix composites. The addition of micro- and nano-sized fillers into the polymer could significantly reduce wear rate (Burriss and Sawyer, 2006; Han et al., 2001; Yang et al., 2009). One example is the wear rates of alpha-alumina-filled PTFE composites nearly five orders of magnitude less than that of virgin PTFE (Burriss and Sawyer, 2006; Krick et al., 2012). These significant decreases in wear rate and friction coefficient might be attributed to the following reasons. First, adding fillers to polymer composites could shorten the time of formation of transfer film, due to the rapid formation of a groove-filling transfer film on the counterpart, the composites exhibited excellent tribological properties (Sebastian et al., 2013). Second, adding fillers to polymer composites could significantly improve the characteristics of the transfer film (Goyal and Yadav, 2013). Third, using nanometer fillers in polymer composites changed the microstructure of polymer and prevented the destruction of this kind of materials and restrain formation of larger debris during the friction process (Li et al., 2002). Wear debris composed of tiny flakes is easily trapped in the gap of a worn surface and can repair the damaged surface, and this trapped debris can be considered as a secondary source of lubricant that permeates to the surface to reduce the friction and retard the galling during sliding (Li et al., 2014). Finally, the positive rolling effect of nanoparticles between the material pairs is also a reason that effectively reduces the frictional coefficient and wear rate (Chang and Friedrich, 2010; Chang et al., 2006).

Similar investigations can be found in nanoparticle-filled fabric composites (Li et al., 2014; Su et al., 2007; Zhang et al., 2005, 2009). Recently, many researchers have reported that weave structures exhibit an important influence on the
tribological properties of hybrid fabric composites (Bijwe and Rattan, 2007; Gu et al., 2012; Rattan and Bijwe, 2006; Rattan et al., 2007, 2008). The retention capability of pulverized fiber debris in the composite surfaces dominated the wear resistance of the fabric composites. A plain weave was the most effective in retaining debris, so it has the highest wear resistance, while satin was the least effective in this aspect, so it has the poorest performance (Rattan et al., 2007). The seepage capability and resin retention significantly influence the strength and tribological properties of fabric composites (Rattan and Bijwe, 2006). In adhesive wear mode, twill weave has proven to be the most suitable for the optimal combination of strength, modulus and tribo-performance (Rattan et al., 2008). In general, weave structure determines the strength, seepage capability and resin retention of the composites; thus, weave structures greatly influence the tribological properties of fabric composites. Similarly, with the change of weave density, the strength, capability of seepage and retention of resin of the composites will change. Therefore, weave density might also have an effect on the tribology properties of the composites. Unfortunately, few studies have been performed to investigate this topic. Therefore, this work examines the tribological behavior of hybrid PTFE/Kevlar fabric composites with different weave densities.

2. Experimental details

2.1 Materials and specimen preparation

The PTFE/Kevlar fabric used in this study was woven from PTFE and Kevlar fibers, and the weave density was varied between 50 and 65 threads per inch. A photograph of the fabric is presented in Figure 1. As shown, the two sides of the fabric possess different proportions of PTFE and Kevlar. The front face is rich in PTFE fiber and is always used as the friction surface. The back face is rich in Kevlar fiber and is used as a binding surface. In this way, the low friction of PTFE and the high strength of Kevlar are combined to a great extent (Zhang et al., 2009). The fillers used in this study are commercially available, and the material properties are listed in Table I.

The hybrid PTFE/Kevlar fabrics were ultrasonically cleaned for 1 h, boiled for 30 min in distilled water and dried in an oven at 150°C for 3 h; the dried hybrid PTFE/Kevlar fabrics were then weighed on a precision balance (accuracy, 0.1 mg). The fillers were mixed uniformly with modified polyimide adhesive resin at the proper mass fractions (7.5 wt.% WS2 and 12.5 wt.% Si3N4) (Li et al., 2014) with the assistance of ultrasonic stirring. Afterwards, the hybrid PTFE/ Kevlar fabrics were immersed in mixed adhesive containing filler. Subsequently, the immersed PTFE/Kevlar fabrics were dried in a nitrogen-purged environment at a rate of 50°C/h to 130°C, where they were maintained for 1 h. The specimens were then cooled at a rate of 50°C/h back to room temperature. Afterwards, the specimens were weighed, and the relative mass fraction of the fabrics was calculated. The immersion was repeated several times until the relative mass fraction of fabrics was 70 ± 5 per cent. A laboratory press was then used to consolidate the fabrics under a pressure of 5 MPa at 210°C for 30 min. Finally, the filled PTFE/Kevlar fabric composites were affixed onto ASTM A 959-04 stainless steel 440C (C 0.95-1.20 per cent, Si 1.00 per cent, Mn 1.00 per cent, S 0.030 per cent, P 0.040 per cent, Cr 16.00-18.00 per cent and Mo 0.75 per cent) using the modified polyimide adhesive resin and cured at 210°C for 15 min under a pressure of 0.2-0.3 MPa.

2.2 Tribological test

Tribological tests were performed using a pin-on-disc tribometer (RTEC MFT-5000, USA) as described elsewhere (Li et al., 2014, 2015). All of the experiments were performed under laboratory conditions (25°C, relative humidity of approximately 50 per cent). Figure 2 illustrates the test assembly schematics. In the pin-on-disc tester, a stationary steel pin was slid against a rotating steel disc that was affixed with PTFE/Kevlar fabric composite specimens. A flat-ended bearing steel pin (diameter of 4 mm) was secured to the load arm with a chuck. The distance between the center of the pin and the center of the disc was 16 mm. The pin remained over the disc with two degrees of freedom: vertical, for normal load application by direct contact with the disc, and horizontal, for friction measurements.

Sliding was performed under dry friction conditions at varied sliding speeds that ranged between 0.6 and 1.0 m/s, normal load that ranged between 377 and 628 N and a sliding distance of 3.6 km. The normal load and friction force were measured using a normal force sensor (range, 50 to 5,000 N;
resolution, 0.25 N) and a friction force sensor (range, 1 to 100 N; resolution, 0.005 N), and the sampling frequency was 1,000 Hz. The friction coefficients ($\mu$) of the specimens were calculated by the relationship $\mu = F/P$, where $F$ is the friction force (N) and $P$ represents the normal load (N). At the end of each test, the wear volume loss of the PTFE/Kevlar fabric composites was obtained by measuring the cross-sectional area of the wear scar using three-dimensional (3D) profile measurement laser microscope (accuracy, 0.012 µm; KEYENCE VK-X200, Japan). To ensure statistically relevant results, three measurement zones, equispaced along the wear scar, were collected for each sample, and each measurement zone was divided into 12 cross-sectional measurements to determine the general average of volume loss. Meanwhile, to reduce the influence of the initial surface characteristics on the measurement accuracy, the average height of initial surface was used as the measuring datum (baseline). The wear data were finally presented as the wear rate in well-known units (m$^3$/Nm). The uncertainty of volume loss ($u_v$) was determined using Equation (1) (Colbert et al., 2011):

$$u_v = \frac{2\pi R}{\sqrt{N\sigma_A}}$$  (1)

Here, $R$ is the nominal radius of the wear scar, $N$ represents the number of scans and $\sigma_A$ denotes the standard deviation of the measured areas. The schematic diagram of the measurement technique is shown in Figure 3.

Figure 3 A schematic diagram of the measurement technique

Notes: (a) A photo of measuring device; (b) a schematic diagram of measurement results

Prior to testing, the pins were polished using 1,000 grit paper to an average roughness of 0.1-0.2 µm (Ra), and the pins were then cleaned with acetone and dried with a laboratory wipe. Each experiment used a new pin and PTFE/Kevlar fabric sample. To ensure statistically relevant results, each experiment was repeated three times. Thus, every data point in the diagrams represents an average of three repeated tests.

After the experiments, all of the samples (the surface of the pins and the wear scar of the PTFE/Kevlar fabrics) were examined by scanning electron microscopy (SEM). The images shown exemplify representative of the general samples. Some operating parameters of the SEM are as follows: beam accelerating voltage, 20 kV; the vacuum in the specimen chamber, $6 \times 10^{-4}$ Pa; magnification, 200/600; and working distance, 11.6 mm.

In addition, energy dispersive X-ray spectroscopy (EDS) was used to determine the elemental distribution and content of the transfer films. Some operating parameters of the EDS are as follows: beam accelerating voltage, 5 kV; the vacuum in the specimen chamber, $6 \times 10^{-4}$ Pa; magnification, 1,000; and working distance, 15.0 mm.

3. Results and discussion

3.1 Friction and wear properties

The friction coefficients and wear rates of the hybrid PTFE/Kevlar fabric composites with different weave densities are comparatively shown in Figure 4. The fabric weave density greatly influences the wear rate of the hybrid PTFE/Kevlar fabric composites. Generally, the wear rates of the hybrid PTFE/Kevlar fabric composites decrease with decreasing weave density, and the friction coefficient of the hybrid PTFE/Kevlar fabric composites increased with decreasing weave density. When the weave density of the composites decreased from 65 to 50 threads per inch, the wear rate of the composites decreased from $0.631 \times 10^{-14}$ m$^3$/Nm to $0.540 \times 10^{-14}$ m$^3$/Nm, decreased about 14.4 per cent. As mentioned above, the retention capability of pulverized fiber debris in the composite surfaces dominated the wear resistance of the fabric composites. Compared with those of high weave density fabric composites, the low weave density fabric composite was the most effective in capturing larger debris, so it has the better...
wear resistance. In contrast, when the weave density of the composites decreased from 65 to 50 threads per inch, the friction coefficient of the composites increased from 0.046 to 0.049, increased about 6.1 per cent. As mentioned, when the weave density of the composites was 50 threads per inch, the composites exhibited the lowest wear rate. Meanwhile, the friction coefficient was only increased to approximately 0.03 when compared with that of the 65 threads per inch fabric composites. Therefore, this weave density was selected to investigate the effects of different loads and speeds on the tribological properties of hybrid PTFE/Kevlar fabric composites. Figure 5 shows the variation of the friction coefficient and the wear rate of the PTFE/Kevlar fabric composites with different normal loads. The composite weave density was 50 threads per inch; the other friction conditions were the same as that mentioned above. Generally, the wear rate was found to decrease with increasing normal load, and the friction coefficient also decreased with increasing normal load. Figure 6 shows the variations of the friction coefficient and the wear rate of the PTFE/Kevlar fabric composites with different sliding speeds. From Figure 6, the wear rates of the composites increased with increasing speed. However, the friction coefficients of the composites decreased with increasing speeds, except for those with a sliding speed at 1.0 m/s. A decrease in coefficient of friction and the increase in wear rate are often believed that with the increase of speed, the temperature at the friction interface between composite and counterpart pin increased. Additionally, the adhesive resins become soft with increasing temperature. Accordingly, the surfaces of the composites were polished rapidly, finally leading to a decrease in the friction coefficient. However, increasing temperature increased the degradation, decomposition and the breakage of the composites, which might result in higher composite wear rate.

Figure 7(a-c) shows the mean friction coefficients vs sliding distance of hybrid PTFE/Kevlar fabric composites under different weave densities, loads and speeds. It can be seen from Figure 7(a) that for all the weave densities of fabric, the friction coefficients increased at first and then decreased and stabilized at an approximately constant value until the end of the test. Similar to Figure 7(a), for all the speeds, the friction coefficients increased at first and then decreased and stabilized at an approximately constant value until the end of the test, except for a speed of 0.6 m/s. However, it can be seen from Figure 7(b), that for all the loads, only the friction coefficient under 628 N and 503 N stabilized at an approximately constant value until the end of the test.

3.2 Laser microscopy observations of the worn surfaces

The 3D profile measurement laser microscopy was used to analyze the worn surface morphologies of hybrid PTFE/Kevlar composites at different weave densities and different friction conditions. Figure 8(a and b) present the laser microscopy images of the worn surface of 50 and 65 threads per inch composites sliding against steel pins at 628 N and 1.0 m/s. The wear scar surface of the 50 threads per inch composites are smoother than that of the 65 threads per inch composites, and some of the PTFE and Kevlar fibers are cut off and peeled out from the matrix of the 65 threads per inch composites. This observation indicates that the composites with low weave densities result in strong fiber adhesion to the matrix, resulting in the strengthening of the fabric composite mechanical properties and improving the wear resistance. From Figure 8(c and d), in contrast to high
speed and high load, the worn surfaces of samples sliding under low speeds and low loads are smooth, and barely any fabric is cut off and peeled out from the matrix, suggesting the wear processes in those composites are dominated by polishing.

3.3 Scanning electron microscopy observations of the worn surfaces

Figure 9(a-d) shows the SEM images of worn surfaces of 50 and 65 threads per inch composites sliding against steel pins at 628 N and 1.0 m/s. The wear scars of the 50 threads per inch composites are smoother than that of the 65 threads per inch composites, and no significant fiber stripping and matrix cracking phenomena were observed. Contrary, in the worn surface of the 65 threads per inch composites, some of the PTFE and Kevlar fibers are cut off and peeled out from the matrix, and many long and deep cracks on the worn surface were observed, which are indicative of poor wear resistance. Reasons for these phenomena are that as weave density increases, nanoparticle and resin penetration into the fiber become more difficult, especially in the crossover points of the fabrics. Meanwhile, the adhesion and wear resistance of PTFE is very poor, so with increasing weave density, the fiber-matrix interfacial adhesive strength and the composites wear resistance worsens.

Figure 10(a-d) shows SEM images of the worn surfaces of 50 threads per inch composites sliding against steel pins at 628 N-0.6 m/s and 377 N-1.0m/s. The worn surfaces of the 50 threads per inch composites under a low load and low speed are smooth, and the fibers are completely wrapped in resin matrix, indicating that at lower loads and speeds, the worn surfaces of the 50 threads per inch composites were still in the well-lubricated stage. In the lubricated stage, Kevlar fibers remain intact, and the wear debris that includes the PTFE fibers, resin and nanoparticles are trapped in the gap and concaves of the composite surface, which reduces surface roughness. In addition, the trapped debris could be considered a secondary source of lubrication.
3.4 Scanning electron microscopy and energy dispersive X-ray spectroscopy analyses of the transfer films

The results of EDS elemental analyses of the transfer films are shown in Figure 11. F, O, N, Si, W and Fe were detected in the transfer films of all samples. These findings indicate that the transfer of PTFE, resin and filler occurred during sliding (Lai et al., 2004; Li et al., 2014; Yamane et al., 2008). From Figure 11, the F and O content in the transfer film for composite with 65 threads per inch weaves were higher, and the Fe content was lower than that of the composites with 50 threads per inch weaves. These observations might suggest that the transfer film for 65 threads per inch composites formed on the steel pin is thicker than that for the 50 threads.
per inch hybrid PTFE/Kevlar fabric composites formed on the steel pin surface. According to previous research, under the same counterface morphology, thick transfer films are easily scaled off of the counterface and form debris during the wear process, which results in poor wear resistance.

SEM images of transfer films formed on pin surfaces are shown in Figure 12. Under low speed and low load, the transfer films formed on pin surfaces are smooth and even. In the case of the same experimental conditions, the transfer films formed under steel pin sliding on the 50 threads per inch composites are smoother than those formed under steel pin sliding on the 65 threads per inch composites. Thin and smooth transfer films strongly bond to the counterface and provide better protection to the surface, therefore reducing the wear.

4. Conclusions

This work presents research concerning the tribological behaviors of hybrid PTFE/Kevlar fabric composites with different weave densities against bearing steel at dry friction conditions. Meanwhile, for a particular weave density, the tribological behaviors of hybrid PTFE/Kevlar fabric composites under different loads and speeds were also investigated. The following conclusions can be drawn from the current study:

- Reducing the weave density of the composites can reduce the wear rate of the fabric; when the weave density decreased from 65 to 50 threads per inch, the wear rate of the composites decreased about 14.4 per cent. Compared with the high weave density fabric composites, the low weave density fabric composite were the most effective in capturing larger debris. The debris gets trapped in the gap of a worn surface and can repair the damaged surface. Maybe this is the main reason that with the decrease of the weave density, the wear resistance increased.
- Reduced weave density will result in increased friction coefficient, when the weave density decreased from 65 to 50 threads per inch, the friction coefficient of the composites increased about 6.1 per cent.
- Sliding speed has a significant effect on the wear rate and friction coefficient of the composites. Generally, the higher the speed is, the higher the wear rate is and the lower the friction coefficient is. A decrease in coefficient of friction and the increase in wear rate are often believed that with the increase of speed, the temperature at the friction interface increased. Then, the adhesive
resins become soft, and the surfaces of the composites were polished rapidly, finally leading to a decrease in the friction coefficient. However, increasing temperature increased the degradation, decomposition and the breakage of the composites, which might result in higher composite wear rate.

- Contact pressure also has a highly important effect on the wear rate and friction coefficient of the composites. Generally, the higher the contact pressure is, the lower the wear rate and friction coefficient will be.

References


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