WEAR PROCESS ANALYSIS OF THE POLYTETRAFLUOROETHYLENE/KEVLAR TWILL FABRIC BASED ON THE COMPONENTS' DISTRIBUTION CHARACTERISTICS

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Abstract:

Polytetrafluoroethylene (PTFE)/Kevlar fabric or fabric composites with excellent tribological properties have been considered as important materials used in bearings and bushing, for years. The components' (PTFE, Kevlar, and the gap between PTFE and Kevlar) distribution of the PTFE/Kevlar fabric is uneven due to the textile structure controlling the wear process and behavior. The components' area ratio on the worn surface varying with the wear depth was analyzed not only by the wear experiment, but also by the theoretical calculations with our previous wear geometry model. The wear process and behavior of the PTFE/Kevlar twill fabric were investigated under dry sliding conditions against AISI 1045 steel by using a ring-on-plate tribometer. The morphologies of the worn surface were observed by the confocal laser scanning microscopy (CLSM). The wear process of the PTFE/Kevlar twill fabric was divided into five layers according to the distribution characteristics of Kevlar. It showed that the friction coefficients and wear rates changed with the wear depth, the order of the antiwear performance of the previous three layers was Layer III>Layer II>Layer I due to the area ratio variation of PTFE and Kevlar with the wear depth.

Keywords:

Fabric, polytetrafluoroethylene (PTFE), Kevlar, wear process, confocal laser scanning microscopy (CLSM)

1. Introduction

In the aviation industry, non-metal materials are just beginning to be used alternatively instead of metals and alloys. High-performance fibers, fabrics, and their composites have been increasingly applied in some important parts as a class of triboengineering materials for their excellent load-carrying capacity, friction reduction, antiwear properties, and light quality [1,2]. As one of the high-performance fibers, Polytetrafluoroethylene (PTFE) fibers exhibit ultra-low friction coefficient and excellent chemical resistance, but poor wear resistance, whereas Kevlar fibers are characterized by high modulus, high strength, and excellent wear resistance. Combining the benefits of the PTFE fibers and Kevlar fibers into a single composite, The PTFE/Kevlar fabrics are woven out and usually used as frictional materials in aviation bearings and bushings [3,4]. The antiwear performance is one of the important indexes for the life evaluation of such fabrics. Many researchers have made numerous attempts to enhance the antiwear performance of such fabrics. Such fabrics being immersed in a resin matrix is a usual method; thus, it becomes a multiple composite system composed of the fabric and resin matrix. However, the interfacial adhesion between the fibers and the resin matrix is proved to be an important factor in the antiwear performance [5-6]. Therefore, various surface treatment methods, such as plasma treatment [7-9], strong HNO₃ oxidation [10], and silane coupling agent modification [11], were applied to increase the quantity of the surface functional groups on the surface of the fibers, and thus,

improve the interfacial bonding. Moreover, some researchers have reported that a variety of micro- or nano-particles [12,13], which dispersed uniformly in the resin matrix, could improve the antiwear performance of the fabric composites. In general, there are various factors controlling the antiwear performance of such fabric composites. By contrast, hybrid fabrics are interwoven with warp yarns and weft yarns together. Thousands of textile structures can be obtained by changing the textile process parameters. Recently, it has been demonstrated that the textile structures, such as weaves [14,15] and weft densities [16], showed an important impact on the wear performance of such materials. However, even without considering the influence of the resin matrix, surface treatment, filling of particles, weaves, and so on, just for a specific structure fabric, which we could consider as a two-component (weft and warp) material system, textile structures will make the components' distribution of such materials uneven [17]. As shown in Figure 1, by taking a horizontal section, the wear geometry of warp and weft changes with the section height, which can be equivalently expressed as the wear depth (To distinguish clearly, the color of the wear geometry is different from the yarns intentionally). As we all know, the components' distribution area ratios at the wear interface have an important influence on the antiwear properties. So, the wear behavior changes with the wear geometry variation caused by the textile structure during the wear process [17,18].

However, hardly any literature is available on the study of the fabric wear process and behavior based on the components'

Figure 1. Schematic showing the variation of the components' area ratio on the worn surface

area ratio on the worn surface. Hence, in this paper, the components' area ratio on the worn surface of the PTFE/Kevlar twill fabric was analyzed by the wear experiment and by the theoretical calculations with our previous wear geometry model [17]. The wear process and behavior of the PTFE/Kevlar twill fabric were investigated under dry sliding conditions against AISI 1045 steel by using a ring-on-plate tribometer. The morphologies of the worn surface were observed using a confocal laser scanning microscopy (CLSM). The relationship between the antiwear performance and the components' area ratios on the worn surface was analyzed.

2. Experimental

2.1. Materials

The Kevlar fiber (density 1.44 g/cm³, tensile modulus 123 GPa, and tensile strength 3.4 GPa) was provided by Du Pont Corporation, USA. The PTFE fiber (linear density 500 den, break force 20 N, and tensile strength 4.0 g/den) was provided by Shanghai Lingqiao Environmental Protection Equipment Works Co., Ltd., China. The phenolic-acetal resin adhesive was provided by Shanghai Xinguang Chemical Plant, China.

2.2. Fabric

The PTFE/Kevlar fabric was woven by a rapier loom. The weave was twill, as shown in Figure 1. The warp density and the weft density were, respectively, 185 ends/10 cm and 323 picks/10 cm. The thickness was 0.46 mm. The PTFE/Kevlar fabrics were dipped in acetone for 12 h, cleaned in the acetone solution, boiled for 20 min in distilled water, and then dried in an oven at 80°C for 1 h.

2.3. Wear test and method

The wear test of the PTFE/Kevlar twill fabrics was done on the MMU-5G wear testing apparatus. As shown in Figure 2, a ring-on-plate contact form was utilized. An ASTM 1045 steel ring, outer diameter 26 mm, inner diameter 20 mm, and chamfer 0.5 mm, was used as the upper specimen, and an ASTM 1045 steel plate, diameter 43 mm and thickness 3 mm, was used as the lower specimen. The pre-treatment approaches of the upper and lower metal specimens were listed as follows. The lower specimen was polished with 150# and 400# water sandpapers. The upper specimen was polished with 600#, 800#, and 1200# water sandpapers. Moreover, both of the lower and upper specimens were cleaned for 15 min in alcohol by ultrasonic waves. Then, the PTFE/Kevlar fabric was bonded on the surface of the lower specimen with a small amount of the phenolic-acetal resin adhesive and cured at 180°C for 2 h under the contact pressure of 0.2 MPa. When the test started, the load was applied downward through the upper specimen against the lower specimen, on which the PTFE/Kevlar fabric was bonded. The lower specimen was kept stationary and the upper specimen was rotated for a certain period of time under a prescribed set of working conditions. Then, the wear depth of the lower specimen was measured and the worn surface appearance was observed using a CLSM. Two different working conditions (load 0.7 MPa, velocity 0.12 m/s, load 2.1 MPa, and velocity 0.36 m/s) were chosen for each test. Five samples were repeated.

The specific wear rates were calculated using the following equation:

$$\omega = \Delta V / FL \quad (1)$$

Test set up

Figure 2. Test setup and schematic diagram of the ring-on-plate contact form

where, ω is the specific wear rate in $\text{m}^3/(\text{N}\cdot\text{m})$, ΔV is the volume loss in m^3 , F is the applied normal load in N, and L is the total sliding distance in m.

3. Results and discussion

3.1 Tribological performance

Figure 3 shows the relationship of the friction coefficients and wear depths, and the wear rates changing with the wear time under two different working conditions. Figure 3(a) shows that the friction coefficients of all the five samples have a running-in process, first increasing to a peak at about 3200 s, and then decreasing under load 0.7 MPa and velocity 0.12 m/s. After the running-in process, the friction coefficients of all the five samples fluctuate with time whether under the working condition load 0.7 MPa and velocity 0.12 m/s or load 2.1 MPa and velocity

0.36 m/s. In Figure 3(b), the wear depths of all the five samples rise rapidly in the beginning and then rise slowly. The increase of load from 0.7 MPa to 2.1 MPa and velocity from 0.12 m/s to 0.36 m/s have a small effect on the wear depth. From Figure 3(c), it can be seen that the wear rates of five samples drop fast, after keeping around a certain value under 0.7 MPa and 0.12 m/s. When the working conditions change to 2.1 MPa and 0.36 m/s, the wear rates of five samples drop markedly. This is because the wear depth increment is less than the increment of load and velocity; from equation (1), the wear rates decrease with the increase in load and velocity.

3.2 Wear process analysis

In order to investigate the wear behavior and variation of the components' area ratio in the wear process, the worn surface topographies of the PTFE/Kevlar fabric by CLSM are shown in Figure 4. Figure 4(a) shows the PTFE/Kevlar twill fabric before

Figure 3. Friction coefficient, wear depth, and wear rate changing with the wear time

wear. Figures 4(b)–(k) show the worn surface morphologies under the working conditions 0.7 MPa and 0.12m/s. Figures 4(l)–(n) are the worn surface morphologies under 2.1 MPa and 0.36 m/s. From Figure 4(a), it is seen that the surface

morphology of the PTFE/Kevlar fabric is rough. The rough fabric surface is slightly larger than the initial wear depth of 0.025 mm, resulting in the surface of the PTFE/Kevlar fabric seem like little abrasion at the wear depth 0.025 mm, as shown

Figure 4. Morphology of the worn surface of the PTFE/Kevlar fabric

(i) $\Delta h = 0.120$ mm (j) $\Delta h = 0.138$ mm (k) $\Delta h = 0.158$ mm (l) $\Delta h = 0.185$ mm (m) $\Delta h = 0.198$ mm (n) $\Delta h = 0.201$ mm**Figure 4.** Morphology of the worn surface of the PTFE/Kevlar fabric

in Figure 4(b). Due to the peculiar molecular structure, PTFE could be easily worn out. These gaps between PTFE and Kevlar are just like pockets, as seen in the rectangular box of Figures 4(b) and 4(c), which can collect the PTFE wear debris. The light scratches and plough grooves on the worn surface of PTFE, observed since the beginning of the wear test, are a typical phenomenon of abrasive wear, as seen in Figures 4(c) and 4(d). The light scratches were thought to be caused mainly by the surface roughness of the upper specimen. By contrast, the plough grooves should be caused by some “hard particles” with respect to PTFE. These “hard particles” are thought to be mainly from the separated micro-cut Kevlar fiber, as evidenced in the rectangular box of Figure 4(e). From the comparisons of Figures 4(e) and 4(f) with Figures 4(a) and 4(b), obvious plastic deformations of PTFE are observed, for the gaps between PTFE and Kevlar are getting smaller. In Figure 4(g), most of the gaps are filled with the PTFE wear debris and plastic-

deformed PTFE. In Figure 4(h), Kevlar fibers begin to appear on the wear surface and share friction and wear. The time is about 3090 s from the beginning to the Kevlar fibers appearing on the wear surface. Correspondingly, the wear depth is about 0.103 mm, while the wear depth increment from Figure 4(h) to Figure 4(k) is 0.055 mm, which is smaller than 0.103 mm from Figure 4(a) to Figure 4(h). However, the wear time of Figure 4(h) to Figure 4(k) is about 25200 s, which is more than 8 times of the wear time 3090 s of Figure 4(a) to Figure 4(h). It is shown that the components' area ratio has an important influence on the antiwear performance. In Figures 4(l)–(n), with the working conditions changing to 2.1 MPa and 0.36 m/s, Kevlar is worn badly by abrasive wear.

In our previous studies, the geometrical description of the textile structure of the twill fabric was obtained by Peirce's model [17]. The cross sections of warp and weft yarns are assumed

to be circular, and the flexion shapes of warp and weft yarns are described by arcs and tangent lines, respectively. Based on the geometric characteristics of the twill fabric, a numerical analysis stratified method was presented to determine the components' area ratio on the worn surface. For the PTFE/Kevlar fabric used in the following test, the measured radii of the PTFE and Kevlar yarns are, respectively, 0.092 mm and 0.136 mm. The measured yarn-to-yarn distances of two adjacent PTFE and Kevlar are, respectively, 0.322 mm and 0.542 mm. The measured flexion height hw of PTFE is 0.329 mm (as shown in Figure 5). Figures 6(a) and (b) show, respectively, the theoretical values and measured values of the area ratios of PTFE and Kevlar the and gap between PTFE and Kevlar varying with the wear depth.

Figure 5. The weft section of the PTFE/Kevlar fabric

Based on the preceding study, the wear process and behavior of the PTFE/Kevlar twill fabric are summarized. Considering the influence of the textile structure, the PTFE/Kevlar twill fabric is divided into five layers along the thickness by four lines tangent to the outer diameter of Kevlar, denoted as Layer I, Layer II, Layer III, Layer IV, and Layer V, as shown in Figures 6(b)–(f). For these classification methodologies, Figures 4(a)–(g) show the worn surface of Layer I (the wear depth range is 0–0.103 mm). Figures 4(h)–(k) show the worn surface of Layer II (the wear depth range is 0.103–0.158 mm). Figures 4(l)–(n) show the worn surface of Layer III (the wear depth range is from 0.158 to a certain value larger than 0.201 mm). As the worn surfaces were undistinguishable and a small amount of the phenolic-acetal resin adhesive could exist in Layer IV and Layer V, the wear experiment had to stop in Layer III, and no experimental results of Layer IV and Layer V were obtained. The relationship of the friction coefficients and wear rates with the wear depth was further considered in Figure 7. Figure 7(a) shows obviously that the friction coefficients of all five samples increase first, then decrease and fluctuate irregularly. Figure 7(b) shows that the wear rates of all five samples decrease first, then keep around a certain value whether under 0.7 MPa and 0.12 m/s or under 2.1 MPa and 0.36 m/s.

From the calculated and experimental results in Figures 6 (a) and (b), Layer I is mainly made up of a gap and PTFE (also proved by Figures 4(a) and (b)). As seen in Figure 6(d), in Layer I, the variation and shear effect of the friction shearing

force, as a result of the extruding force of the vertical load and the relative sliding of steel and PTFE, have a significant damage effect on PTFE. A great deal of lamellar PTFE wear debris is quickly produced. Some PTFE wear debris escape from the friction interface, and others are retained in the gaps. Moreover, plastic deformation of PTFE is observed, which plays an important role in the filling of gaps (as shown in Figures 4(g) and (h)). Thus, Layer I exhibits poor antiwear performance, showing the larger wear depth (0.103 mm) with the shorter enduring wear time (3090 s).

As seen from Figures 6 (a) and (b), the PTFE area ratio increases with the wear depth, but the friction coefficient increases with the wear depth increasing in Layer I (as seen in Figure 7 (a)). It is seen that the friction coefficient and wear state are unstable and still in the running-in stage, for that the surface morphology in Layer I is uneven with a large number of "convexes" and "concaves." Layer II is mainly made up of a gap, PTFE, and Kevlar in theory (as seen in Figure 6(a)). However, in the wear experiment, the worn surface of Layer II is mainly composed of PTFE and Kevlar (as seen in Figure 6(b) and Figures 4(h)–(k)), for that the gap is fully filled by the plastic deformation PTFE and PTFE wear debris. As seen in Figure 6(e), when the wear depth is reached in the range of Layer II, a small amount of Kevlar is involved in friction and wear. And, the area ratio of Kevlar on the worn surface increases with the increase in the wear depth. Compared with the friction coefficient and wear rates of the PTFE/Kevlar fabric in Layer I, the wear rates become smaller obviously in Layer II. It is shown that Layer II of the PTFE/Kevlar fabric has a better antiwear performance than Layer I; thus, the smaller wear depth (0.055 mm) of Layer II endures with the longer wear time (25,200 s). Moreover, the friction coefficient decreases with the wear depth increasing in Layer II, which is contrary in Layer I. In all, the antifriction performance in Layer II is a bit better than that in Layer I. As seen in Figure 6(a), Layer III is mainly composed of Kevlar (the average area ratio is 3 times larger than that of the PTFE), PTFE, and gap in theory. However, in fact, the worn surface is only composed of PTFE and Kevlar due to the plastic deformation of PTFE and the twist loosed of Kevlar, as shown in Figure 4(l). Though the working conditions are changed from 0.7 MPa and 0.12 m/s in Layer II to 2.1 MPa and 0.36 m/s in Layer III, compared with Layer II, the wear depth increment from Figure 4(k) to Figure 4(n) in Layer III is 0.043 mm (the wear time is 28,800 s), which is smaller than Layer II with 0.055 mm (25200 s). It is shown that Layer III of the PTFE/Kevlar fabric has better antiwear performance than Layer II. It is mainly attributed to the area ratio of Kevlar in Layer III, which is larger than in Layer II.

4. Conclusions

The wear process and behavior of the PTFE/Kevlar twill fabric were investigated under dry sliding conditions. Due to the textile structure, the components' area ratio of the PTFE/Kevlar fabric changed with the wear depth. The components' area ratios were analyzed both theoretically and experimentally. The friction coefficient and wear rate were varied with the wear depth. The wear process of the PTFE/Kevlar twill fabric was divided into

Figure 6. Schematic showing a stratified method and wear process of the PTFE/Kevlar fabric

Figure 7. Friction coefficient and wear rate changing with the wear depth

five layers along the thickness, according to the distribution characteristics of Kevlar. For the first three layers, Layer I, Layer II, and Layer III, it is shown that Layer III exhibited the best antiwear performance, while Layer I performed the worst. Analyses show that the antiwear performance is associated with the distribution characteristics of Kevlar. The study will be valuable for the textile structure design of a fabric and fabric composites used as tribo-engineering materials.

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