Materials Research Express

OPEN ACCESS

PAPER

Effects of PTFE coating modification on tribological properties of PTFE/aramid self-lubricating fabric composite

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Keywords: textile composites, solid lubricant, surface modification, friction and wear

Abstract

Polytetrafluoroethylene (PTFE)/aramid fabric composites are currently widely used as self-lubricating bearing liners. In this study, a PTFE composite coating was performed to improve the friction stability of the PTFE/aramid fabric composite in long-term friction. Effects of the surface modification on the composite tribological properties were studied using ball-on-disk friction tests. Results showed that under different sliding condition, the friction coefficient of the modified and unmodified fabric composite were similar after sliding of 240 min. However, the friction coefficient curves of the unmodified fabric composite increased first, then decreased, and then increased, while that of the modified fabric composite increased first and then stabilized. At a sliding speed of 4.5 m min⁻¹ and load of 50 N, the unmodified fabric composite worn out at ~200 min, but the modified fabric composite was still stable after 240 min. SEM results confirmed that the PTFE composite coating had a good film forming property, which improved the wear resistance and friction stability of the composite in long-term friction especially under high sliding speed. These results give a reference for the development of self-lubricating plain bearing liners with long lifespans.

1. Introduction

Polytetrafluoroethylene (PTFE) is an ideal lubricating material due to its low friction coefficient, excellent chemical resistance, and high-temperature stability [1, 2]. However, its poor wear resistance and high creep rate greatly limit its applications [3]. Aramid, glass, or carbon fibers are usually woven with PTFE fibers as reinforcement to fabricate hybrid fabric composites [4, 5]. Recently, hybrid PTFE/aramid fabric composites, which are prepared with PTFE fibers, aramid fibers and matrix resin, are one of the most popularly self-lubricating bearing liner materials in industries such as electric power, aerospace, and etc [6–9].

Due to the high strength, modulus, and temperature resistance of aramid fibers, the hybrid PTFE/aramid fabric composites have enhanced wear resistance, mechanical properties, and dimensional stability. Wang et al [10] studied the tribological properties of PTFE/Kevlar fabric composites under overloading conditions (240–330 MPa) whose frictional coefficient and wear rate were approximately 0.086 and 0.1 mm h⁻¹ respectively. Qiu et al [11] investigated the tribological properties of self-lubricating radial spherical plain bearings with PTFE/aramid fabric woven liners under step loads. In most cases, PTFE/aramid fabric composite liners are developed for harsh service environments, especially heavy load condition.

Many researches have studied its wear mechanism [12–15]. When the hybrid PTFE/aramid fabric composites are working, the PTFE fibers in the fabric forms a lubrication film on the contact surface of the friction pair through plastic deformation and ‘cold flow’. The tribological properties are greatly determined by the characteristics of the formed lubrication film. The additives and surface treatments changed the properties of the lubrication film, thus improving the tribological properties. Submicron WS₂ [16], Mo₂C/graphene nanocomposites [17], and
multi-walled carbon nanotubes [18] were added to the matrix resin to reduce the friction coefficient of the fabric composites. Plasma treatments [19, 20], ultrasonic treatments [21], and other surface treatments were used to improve interfacial adhesion between the fabrics and adhesive resins. The braided modes of the fabric composites were also studied and optimized [22, 23]. However, when the friction time increases, the wear loss increases, more aramid fibers participated in the friction, and the lubrication properties often decrease.

With the development of equipment in aerospace and rail transit, such as helicopter and high-speed rail, the demand for service stability of self-lubricating liner is increasing. To promote the wear resistance of PTFE/aramid fabric composites, this study considered adding a surface modification layer on the fabric composites [24, 25]. A PTFE particle/resin composite coating was used as surface modifier to improve the tribological properties of a PTFE/aramid fabric composite. Ball-on-disk friction tests were used to investigate the tribological behaviors of the modified fabric composites. The influence mechanism of the PTFE composite coating on the friction and wear process was discussed in detail, which give a reference for the development of self-lubricating plain bearing liners with long lifespans.

2. Materials and methods

2.1. Materials and specimen preparation
The PTFE/aramid fabric composites used in this study was provided by Shanghai Bearing Technology Research Institute. Two types of fabric composites were studied for comparison. One was unmodified composite (Sample UF#), the other was modified composite (Sample MF#). The surface morphology of the composites was detected by an optical microscope (Serein SVM2515II, China). The results are shown in figure 1. The fabrics and resins in the two samples are the same. They are both woven with two types of yarns. One was twisting the PTFE fibers and aramid fibers together (plied yarn), and the other was the aramid fiber single yarn. The friction surface was rich in the PTFE fibers (figure 1(a)) and the bonding surface was rich in the aramid fibers (figure 1(b)). There was no difference in the bonding surface (figures 1(b) and (d)). The surface modification was performed by coating the friction surface with a white paste. The white paste was a mixture of PTFE particles and phenolic resin as shown in figure 1(c). In order to compare their tribological properties, the samples were cured on an aluminum substrate using 204 phenolic resin with a pressure of 2 MPa at 175 °C for 2 h.

2.2. Tribological test and characterizations
Friction and wear tests of the fabric composites were performed using a CETR UMT-2 tribometer at room temperature. Ball-on-disk friction tests were applied, and figure 2 shows the schematic diagram of the testing
system. The ball pair was made of bearing steel with a diameter of 10 mm and the linear reciprocating distance was 15 mm. To investigate the effects of the applied load on composite tribological properties, the applied loading conditions were set to 10 N, 30 N and 50 N with a sliding speed of 1 m min$^{-1}$. To test the effects of the sliding speed, the sliding speed was set to 1 m min$^{-1}$, 3 m min$^{-1}$ and 4.5 m min$^{-1}$ under a load of 50 N. The sliding time was 240 min.

Scanning electron microscopy (SEM, Fei Helios Nanolab G3 UC, America) and super depth of field microscope (Leica DVM6, Germany) were used to measure the morphology and contour curves of the friction surface of the cured samples. To analyse the influence mechanism of surface modification on the composite tribological properties, the wear morphology of all samples was observed using SEM. The element distributions and contents in the friction surface were determined by energy dispersive spectroscopy (EDS). The average contents of F element were calculated from three surface scanning results.

3. Results and discussion

3.1. Microstructure of the fabric composites before sliding

The surface morphology of UF# and MF# after curing were tested and analysed. Figure 3 displays SEM images and element distributions of the cured fabric composites. The surface of UF# was obvious braided structure, and the surface elements are not evenly distributed. The areas mostly composed of C and O element conformed to the aramid fibers and resin matrix, and the distribution regions of F element were PTFE fibers. The surface of the modified fabric composite was more flat than that of unmodified sample. The braided morphology was not observed. The distribution of F element was more dispersed and uniform in figure 3(d). At the same time, the element distribution shows that the content of F element on the surface of MF# increased to $\sim 39\%$. This indicates that the PTFE particles with the resin formed a relatively smooth film layer after the curing process, and the modified layer greatly increased the content of F element on the composite surface.

Figure 4 shows the three-dimensional images and the corresponding surface contour curves of the composites. It can be seen that the surface of UF# was uneven and obvious braided, and the surface undulation was $\sim 37\ \mu \text{m}$. After modification (figure 4(b)), the surface grooves were filled, the surface flatness was significantly improved, and the surface undulation was only $\sim 15\ \mu \text{m}$. The surface flatness is obviously improved.

3.2. Tribological behavior of the fabric composites under different loads

Figure 5 shows the friction coefficient curves of the two samples under different applied loads (with a sliding speed of 1 m min$^{-1}$). It is found that the friction coefficient curve of MF# are obviously different from that of UF#. The friction coefficient curves of UF# showed a trend of first increasing, then decreasing, and then increasing again. The friction coefficient curves of MF# showed a characteristic of first increasing and then stabilizing with a slight increase to 240 min. Meanwhile, under the load of 10 N and 30 N, the friction coefficients of MF# are a little higher than that of UF#, but when the loading increased to 50 N, the friction coefficient of MF# and UF# are similar at the sliding time of 240 min.

Figure 6 shows the wear morphology and the corresponding element distributions of UF# under different loads. The sliding speed was 1 m min$^{-1}$ and sliding time was 240 min. When the load was 10 N, only PTFE yarns
deformed, the furrows between the yarns were not filled, and the wear loss of UF was small. As the sliding load increased to 30 N, the plastic deformation of the composite increased, the PTFE transferred to the gaps between the yarns. As more aramid fibers were exposed, the friction coefficient increased. With increasing the load to 50 N, the PTFE filled some gaps between the yarns. This indicates that due to the increase of load, plastic deformation of the fabric composite was more severe. At the same time, the content of F increased, which means PTFE tried to deform a film for lubrication. However, due to the aramid yarns, the lubricating film was not complete at 50 N with sliding time of 240 min.

The wear morphology and the corresponding element distributions of MF under different loads are shown in figure 7. When the load was 10 N, the modification layer changed little and only a few holes disappeared. With increasing the load to 30 N, the worn areas were covered by a smooth film with uniform distribution of F element. This film was deformed by the PTFE particle modified layer. When increased further to 50 N, the wear
of the surface modified layer was more serious and original fabric surface morphology was observed in the worn area. At this time, the furrows between the yarns were still filled with the modified layer and the wear surface remained relatively smooth state. Compared figure 6 with figure 7, the contents of F element of MF# were all higher than that of UF#. Meanwhile, the distributions of F element in MF# were more uniform. This indicates
that the modified sample formed more continuous and uniform lubrication film under different loads. Benefit from the formed lubrication film, the friction coefficient were roughly stable during sliding from 80 min to 240 min, which means the composite friction stability was improved. However, compared with UF#, the friction coefficient of MF# increased, especially under low load. This may be related to the higher friction coefficient of the resin used in the PTFE composite coating.

Figure 7. SEM images and the corresponding element distributions of MF# under different loads (with a sliding speed of 1 m min\(^{-1}\) and a sliding time of 240 min): (a) and (b) 10 N; (c) and (d) 30 N; (e) and (f) 50 N.

Figure 8. Friction coefficient curves of the composite under different sliding speeds (with a load of 50 N): (a) UF# and (b) MF#.
3.3. Tribological behavior of the fabric composites under different sliding speeds

Figure 8 shows the friction coefficient curves under different sliding speed (with a load of 50 N and a sliding time of 240 min): (a) and (b) 3 m min$^{-1}$ of UF#; (c) and (d) 4.5 m min$^{-1}$ of UF#; (e) and (f) 3 m min$^{-1}$ of MF#; (g) and (h) 4.5 m min$^{-1}$ of MF#.

![Figure 9. SEM images and the corresponding element distributions of the samples under different sliding speeds (with a load of 50 N and a sliding time of 240 min): (a) and (b) 3 m min$^{-1}$ of UF#; (c) and (d) 4.5 m min$^{-1}$ of UF#; (e) and (f) 3 m min$^{-1}$ of MF#; (g) and (h) 4.5 m min$^{-1}$ of MF#.

The wear morphology and the corresponding element distributions of the samples under different sliding speeds with a load of 50 N and a sliding time of 240 min are shown in Figure 9. With the increase of sliding speed from 1 m min$^{-1}$ to 3 m min$^{-1}$, the PTFE film layer on the surface of UF# obviously fell off, and a number of aramid fibers were exposed and fractured. When increased to 4.5 m min$^{-1}$, UF# worn completely and the aluminium substrate was damaged, which was the main reason for the increase of friction coefficient at the end.
of sliding. However, under sliding speeds of 3 m min$^{-1}$ and 5 m min$^{-1}$, the surface morphology of MF# was similar. The number of aramid fibers appeared on the surface increased, but F element content on the worn surface still remained at a high level. It concluded that with the increase of sliding speed at a high load of 50 N, the wear loss of UF# increased significantly. After the consumption of the fabric composite, UF# failed at 200 min. Due to the PTFE surface coat, MF# still worked at 4.5 m min$^{-1}$ for 240 min. The high-speed wear resistance of the fabric composite was improved by the surface coating modification.

### 3.4. Wear mechanism and Influence mechanism of the PTFE composite coating modification

To explore the wear mechanism of the PTFE composite coating modification, the variation of F element content on worn surfaces under different friction conditions is shown in figure 10. When the sliding speed was 1 m min$^{-1}$, the F contents of UF# and MF# were both increased with the increase of the sliding loads. It indicated that at this speed, the wear was not serious, more PTFE deformed and covered the worn surface with the increase of load, resulting in the increase of F content. When continuous increasing the sliding speed at 50 N, the F contents began to decreased, which was resulted from the wear loss of PTFE fibers or powders. With the consumption of the lubricating materials, the content of F element decreased obviously. However, under different conditions, the F contents in the wear areas were largely increased by the surface modification. The F element represented the presence of PTFE, which was the main material for lubrication, so that MF# had a better friction stability and wear lifespan.

![Schematic diagram of the wear process of the two samples](figure_11)

**Figure 11.** Schematic diagram of the wear process of the composites: (a) the unmodified composite and (b) the modified composite.

Schematic diagram of the wear process of the two samples was drawn (as shown in figure 11). At the beginning of sliding, the PTFE/resin layer quickly formed a complete film at the modified fabric composite surface, which had an effect on reduce wear. In the long time sliding, the PTFE/resin layer continually filled the original defects to form uniform lubrication layers on the surface of the fabric composite, which led to a stable
sliding stage. Therefore, the PTFE/resin composite coating significantly improved the wear-resisting performance of the PTFE/aramid fabric composite especially under high speed.

4. Conclusion

The effects of the PTFE composite coating modification on the tribological behavior of a PTFE/aramid fabric composite were investigated.

(1) Under different sliding conditions, the friction coefficients of unmodified and modified samples are similar. The friction coefficient curves with time of the unmodified composite increased first, then decreased, and then increased again, while the curves of the modified composite increased first and then stabilized.

(2) When the sliding speed increased to 4.5 m min\(^{-1}\) at 50 N, the unmodified composite worn out at 200 min, while the modified composite still worked after 240 min. The wear resistance of the composite was improved more than 20% by the surface coating modification.

(3) The wear morphology confirmed that complete lubrication films formed on the worn surface of the unmodified composite, which played an obvious protective role on the composite surface and leading to the higher wear resistance and friction stability.

(4) The PTFE composite coating has broad application prospects as a reference for the development of self-lubricating plain bearing liners with long lifespans.

Acknowledgments

This research was sponsored by Shanghai Sailing Program (No. 20YF1400900). The authors are grateful to the support.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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