Fibers and Polymers 2022, Vol.23, No.4, 1111-1118
DOI 10.1007/s12221-022-4421-8

ISSN 1229-9197 (print version)
ISSN 1875-0052 (electronic version)

Comparative Study on the Tribological Properties of PTFE Coated Kevlar Fabric and Hybrid PTFE/Kevlar Fabric

Junzhu Zhao and Pibo Ma*

Engineering Research Center of Knitting Technology, Ministry of Education, College of Textile Science and Engineering, Jiangnan University, Wuxi 214122, China

(Received April 29, 2021; Revised August 8, 2021; Accepted August 10, 2021)

Abstract: Polytetrafluoroethylene (PTFE)/Kevlar fabric has been widely used in functional fabric composites applied to wear-resistant lining. In this study, the fabric sprayed PTFE and paste a PTFE film have been compared, the scheme for PTFE coating has been optimized showing the friction coefficient of 0.091. The tribological properties of hybrid PTFE/Kevlar fabric were studied, showing that the best blending ratio of 1:3, weave structure of twill 2/1, and present outstanding wear resistance at loads of 7350 Pa by fabric abrasion tester. Besides, scanning electron microscopy (SEM) was conduct to reveal the wear mechanism. The results show that the wear process of PTFE/Kevlar fabric can be divided into two stages: bond wear and fatigue wear. The investigation of the tribological properties of fabric has significant impact on the application of anti-friction and wearable materials in heavy loading machinery equipment and aerospace industry.

Keywords: Fricition coefficient, Wear performance, Hybrid PTFE/ Kevlar fabric, Coat of PTFE, Wear mechanism

Introduction

Functional fabric composites can achieve high strength, light weight, excellent chemical stability and superior tribological performance. Various kinds of fabric composites combine their own advantages obtain various properties to fulfill different requirements and fit different occasions [1]. A type of functional fabric composites is applied to require anti-friction and wearable materials; they are widely employed in engineering applications such as heavy loading machinery equipment and aerospace industry [2-4]. The composite material usually be considered as wear-resistant linings or bushings, and can also be used for parachute canvas. Polytetrafluoroethylene (PTFE), carbon fiber, glass fiber and aramid fiber fabrics are the mainstream trends in the research of tribological properties of various fiber fabric reinforced polymer materials. Aramid is a kind of fiber with high strength and high elastic modulus, PTFE exhibits low friction coefficient, high temperature resistance but poor abrasion resistance and used to be solid lubricant [5-7], carbon fiber has advantages of high strength, high modulus and light weight, could carry part of applied load, is a good kind of reinforcing materials [8,9], glass fiber exhibits the advantages of high strength and heat resistance, but has the characteristic restrictions on brittleness, rigidity and wear resistance [10,11], hence it is not suitable for use singly. Besides, as the lubricating material, PTFE has been employed typically due to these advantages such as self-lubricating ability, light weight and antiwear performance [12].

The hybrid systems of functional fabric composites can not only be composed of two or more fibers but also composed of fabrics and polymers. As for composite materials, Wang *et al*. [13] reported that the PTFE/aramid and phenolic resin served as low-speed heavy-load sliding bearing linings, and explored the effect of high temperature on tribological properties. Zhou *et al*. [14] suggested that tribological lining prepared by carbon/polytetrafluorethylene (CF/PTFE) hybrid fabric had better friction and wear property than prepared by carbon fabric. Among them, blend weaving of aramid and PTFE provide the possibility to obtain fabrics with low friction coefficient and high mechanical strength, and the tribological performance have comprehensively on drying sliding. Besides, introduction of PTFE coating is able to improve the tribological properties of fabric composites [15]. Yuan *et al*. [16] studied sliding against steel ball significantly improved the friction and wear mechanism of PTFE coatings. However, high ambient temperature or the generation of friction heat result in the softness of PTFE film and it adhere to the contact surface of soft fabric matrix [17], therefore it is necessary to consider the effect of temperature on tribological properties. For fabric, the matrix of composites, Gu *et al*. [18] investigated the tribology properties of hybrid PTFE/kevlar fabric composite with broken twill weave under different vacuum conditions, and they found the worn extend is closely related to the sliding speed during the friction process. Yang *et al*. [19] used satin weave which volume fraction of PTFE to Nomex is 1:3 to be the substrate. Moreover, Qi *et al*. [20] investigate the influence of weft density and weave structure on the friction and wear properties of the liner under heavy load conditions, it is proved that within a certain range, the friction coefficient first decreases and then increases with the elevation of weft density. In summary, the tribological properties of the Kevlar/PTFE fabrics is closely related to the blending ratio, yarn count, warp and weft density, and weave structure of the fabric. The above factors affect the applied stress and the friction force between yarns.

*Corresponding author: mapibo@jiangnan.edu.cn

However, the studies are more from the perspective of composite matrix, about the matrix properties of composite materials and the bonding properties of resins and fabrics. The research is implemented from the perspective of fabrics reinforcement and explored the relationship between blending ratio, weave structure and tribological performance of PTFE/Kevlar fabric are still insufficient.

In this paper, the friction coefficient of Kevlar covered with PTFE coatings was investigated under high and low temperature conditions, and explored the effect of blending ratio of PTFE/aramid fabric and weave structure on the friction properties of the hybrid fabric. Besides, the wear resistance performance of PTFE coated fabric and hybrid fabric has also been compared. It is expected that this study may be helpful to extend the application of hybrid PTFE/Kevlar fabric composite in aerospace fields.

Experimental

Material and Sample Preparation

The Kevlar fabric, textile structure of plain weave, was provided by Tekailun New Material Co., Ltd, China. The Kevlar fabric was sprayed with PTFE emulsion, and dried at an ambient temperature of 150 °C. According to the required coating thickness, the PTFE emulsion can be sprayed and dried again. The Kevlar fabric sprayed with PTFE was then pasted a PTFE film at 370 °C, the PTFE film started to melt at 330-360 °C and adhered to the sprayed PTFE as shown in Figure 1. The samples are shown in Figure 2. The Kevlar yarn linear density 210 den, the coefficient of static friction 0.327, the coefficient of kinetic friction 0.271. The other four different hybrid PTFE/Kevlar fabrics viz. plain, twill (as shown in Figure 3) were produced by Y200S Electronic Sample Loom of Changzhou Tiantian Co., Ltd., China. The Kevlar fiber is the same as mentioned above. The PTFE yarn linear density 390 den, the coefficient of static friction 0.067, the coefficient of kinetic friction 0.041. The specific structures of sample are shown in Table 1.

Peeling Test

Peeling strength tests of the fabric covered with PTFE film were measured with the HD026N+ Electronic Fabric Strength Tester as per GB/T 8808-1988 in order to examine the adhesion of PTFE film under high and low temperature to evaluate its reliability. The PTFE film was stripped in advance from the sample size of 30 mm×150 mm. The upper jaw clamped the pre-peeled PTFE film, and the lower jaw clamped the composite material. Examined the peel

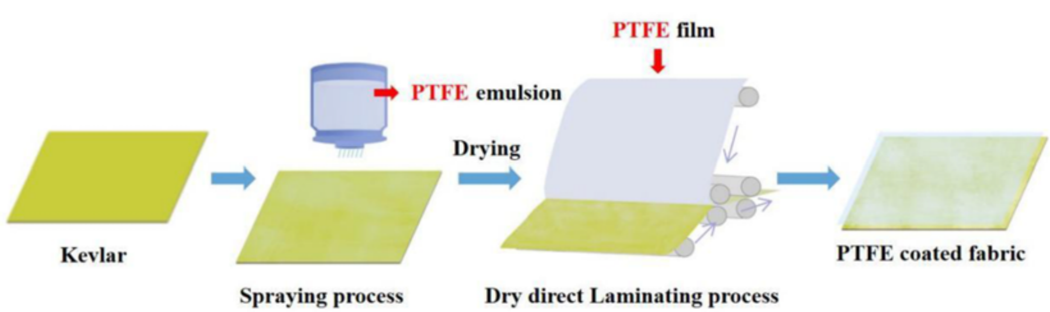

Figure 1. Process of PTFE coated fabric.

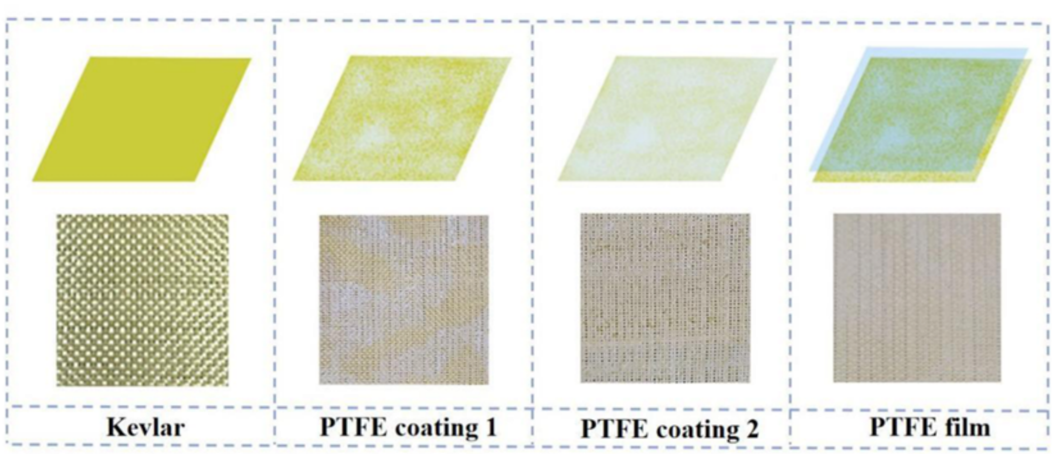

Figure 2. Organization of specimens.

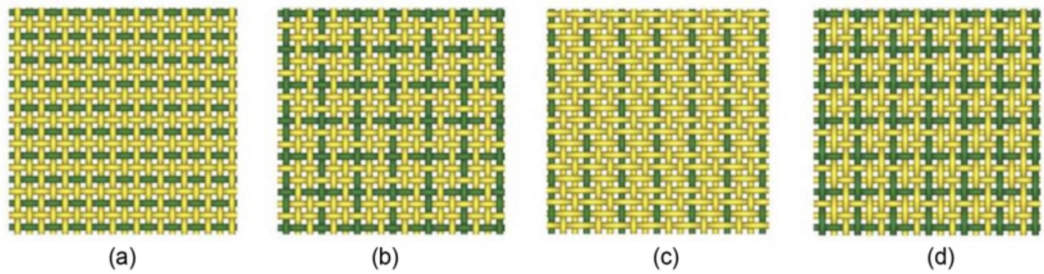

Figure 3. Schematic showing different weave patterns; (a) plain 1, (b) plain 2, (c) twill 1/2, and (d) twill 2/1.

Table 1. Experimental specimens and characteristics

Group	Sample	Characteristic
1#	Kevlar	Face fabric (Kevlar 100 %, plain, 210 denier)
2#	PTFE coating 1	Face fabric PTFE coating 100 m/min
3#	PTFE coating 2	Face fabric + PTFE coating100 m/min + PTFE coating 100 m/min
4#	PTFE film	Face fabric + PTFE coating 100 m/min + PTFE film
5#	Hybrid system A	PTFE/Kevlar fabric(Kevlar 75 %, PTFE 25 %, plain)
6#	Hybrid system B	PTFE/Kevlar fabric(Kevlar 67 %, PTFE 33 %, plain)
7#	Hybrid system C	PTFE/Kevlar fabric(Kevlar 83 %, PTFE 17 %, twill 1/2)
8#	Hybrid system D	PTFE/Kevlar fabric(Kevlar 67 %, PTFE 33 %, twill 2/1)

strength of the Kevlar fabric covered with PTFE film after high and low temperature conditions. The peeling length was 50 mm and the peeling width was 30 mm. The peeling speed was 100 mm/min.

Tribological Properties Test

The coefficient of kinetic friction and the deviation of the friction coefficient were measured with a KES-F4 System (Kato Tech Co. Ltd., Japan), the test of the coefficient of kinetic friction was realized by the movement of the metal probe, as shown in Figure 4. Each sample was required to examine three positions to test the coefficient of kinetic friction along the warp direction, each test was repeated 3 times, and was carried out at an ambient temperature of 23 ^{o}C, an ambient humidity of 50 %. The wear resistance is evaluated by the surface abrasion morphology and the weight loss rate of the hybrid systems. Both them were investigated by YG522N Fabric Abrasion Tester (as shown in Figure 5), used 150-mesh grinding wheels as the abrasive parts. Each sample was subjected to abrasion test under different pressure conditions. The worn surface appearances were observed by Scanning Electron Microscope. The weight wear rate was calculated according to the following equation:

$$R = \frac{W_0 - W_1}{S} \tag{1}$$

where R is the weight wear rate (g/cm^2), W_0 is the weight before the test (g), W_1 is the weight after the test (g), S is the area of friction test (cm^2).

Figure 4. (a) Machine of KES-F4 System and (b) test process of friction coefficient.

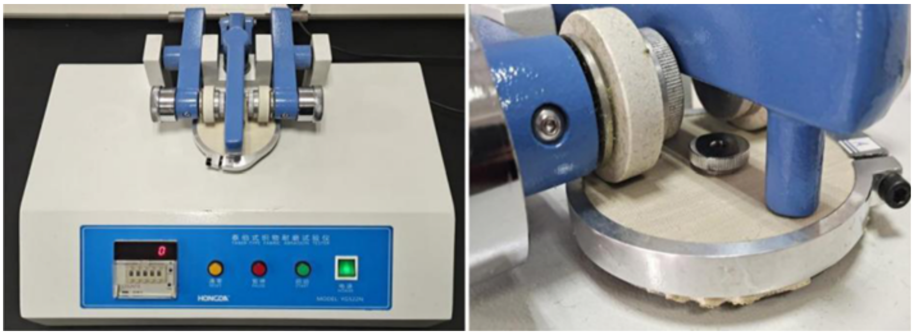

Figure 5. (a) YG522N fabric abrasion tester and (b) the core structure of the device.

Results and Discussion

Friction Properties Coated with PTFE

Figure 6 shows the coefficient of kinetic friction of Kevlar fabric coated with PTFE under different conditions. When spraying PTFE at 100 mm/min, the PTFE coating obtained on the Kevlar fabric is weak in uniformity. As a continuous layer of PTFE lubrication formed on the surface, the uniformity of the coating improved, the coefficient of kinetic friction shows an increasing trend. Compared with the pristine fabric, the coefficient of kinetic friction is reduced by 8.7 % when spraying PTFE twice at 100 mm/min.

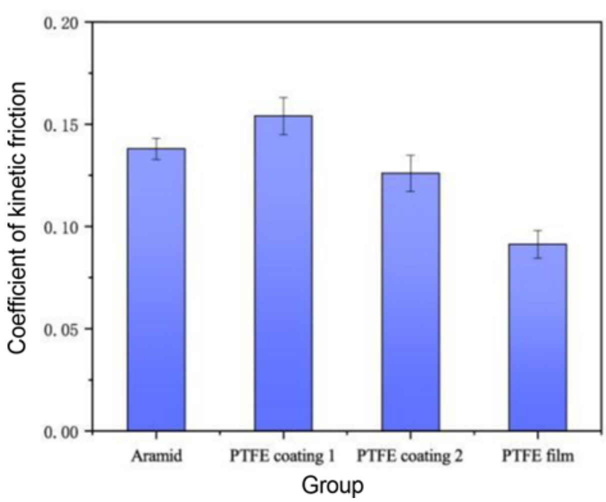

Figure 6. Friction coefficient of fabric coated with PTFE.

Table 2. Performance of fabric with PTFE film

Ambient condition	Coefficient of kinetic friction condition	Maximum peel resistance
Untreated	0.0913	5.4 N
120 ^{o}C, 60 min	0.0893	3.4 N
120 ^{o}C, 90 min	0.0812	3.5 N
-18 ^{o}C, 5 h	0.102	2.8 N

However, the PTFE coating obtained by spraying is easily transferred by friction and the lubricating layer exhibits unfavorable stability. PTFE film pasted on the fabric after spraying PTFE is a viable solution. The stability of PTFE lubricating layer can be improved, the coefficient of kinetic friction reduced by 33.8 %. Table 2 reveals the friction properties of the fabric with PTFE film under high and low temperature conditions. It can be seen that the friction coefficient of the fabric covered with PTFE film decreases under high temperature conditions. With the extension of the treatment time, the coefficient of kinetic friction further decreases. When treated at 120 ^{o}C for 90 min, the coefficient of kinetic friction decreases by 11.1 %. While at -18 ^{o}C for 5 h, the coefficient of kinetic friction increased by 11.7 %. It can be interpreted as the softening or hardening of PTFE film. The appropriate softening of the particles of PTFE coating improve the adhesion of PTFE film to fabric, therefore the smoothness of the surface improved. In contrast, under low temperature conditions for a long time the stiffness and brittleness of PTFE film are increased, the smoothness of the fabric decreases, the coefficient of kinetic friction increases accordingly. Regardless of high or low temperature conditions, the smoothness of the fabric which coated PTFE film is better than that of the pristine Kevlar fabric.

Peel Strength

The Plain Kevlar fabric is of the same warp and weft yarn density, and similar longitude and latitude densities. The shape after peeling is shown in Figure 7. It can be seen from Table 2 that the maximum stripping resistance is 5.4 N, provided by the warp direction of the fabric. During the peeling test, it can be found that the PTFE film is difficult to strip completely and easily break along the weft direction. It is related to the strip of PTFE film, caused by the preparation method of PTFE and due to the stretches twice in the vertical direction. The preparation of commercial PTFE film adopts to the biaxial stretching method. In the first stretching process, the PTFE resin is stretched to form fibers parallel to the stretching direction. After the second stretching, the

PTFE film is formed [21]. Furthermore the latitude and longitude bow wave height has an effect on it. As is shown in Figure 8, the latitude bow wave height is higher than longitude bow wave height, the warp yarns are visible on the outside part, the PTFE film is in close contact with the warp organization point. Along with applying a certain shear force to the PTFE film along the warp direction, the force is continuously and evenly distributed in the warp direction, the PTFE stripped completely. When a certain shear force is applied to the PTFE film along the weft direction, the uneven force distribution lead to the broken of the film. Moreover, as is shown in Table 2, after treated at 120 °C for 60 min, the maximum peel resistance is reduced to 3.5 N. With the extension of treatment time, the maximum stripping resistance is maintained at about 3.5 N. It indicates that although high temperature treatment enhances the adhesion of PTFE film to Kevlar fabric, the maximum peel strength depends on the fracture of PTFE film, and high temperature treatment leads to the weakness of PTFE film, the strength will reduce in a certain extent. And it can be found from Table 2 that the low temperature treatment lead to a significant drop of the maximum peel resistance of the composite material. It is can be interpreted as the PTFE is brittler under the low temperature conditions, the deformation of the PTFE film during peeling is reduced, and fracture occurs earlier.

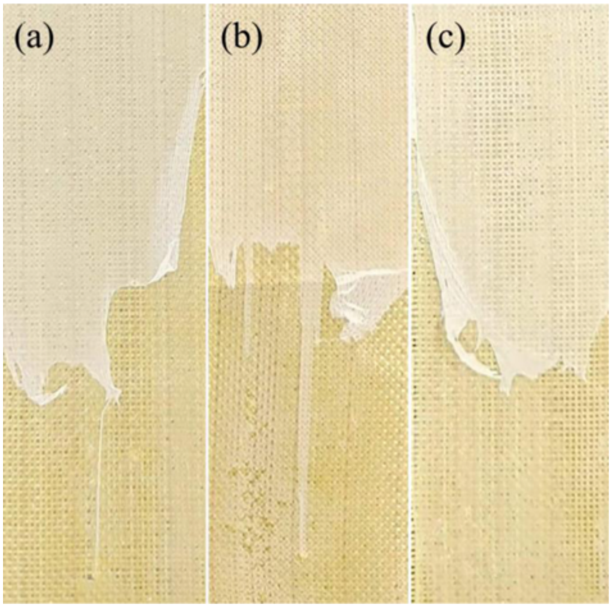

Figure 7. Schematic diagram after peeling; (a) untreated, (b) conditions at low temperature, and (c) conditions at high temperature.

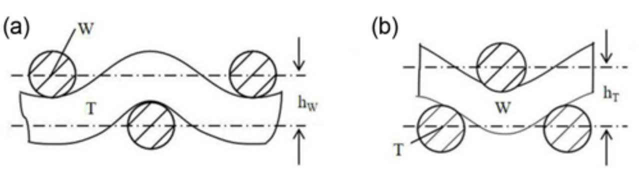

Figure 8. Schematic diagram of bow wave height of yarn in fabric; (a) sectional view along the weft direction and (b) sectional view along the warp direction.

Friction Properties with Hybrid PTFE/Kevlar Fabric

In view of the excellent stability of physical properties of high-performance fibers such as Kevlar and PTFE, the effect of temperature on the friction coefficient of hybrid fabrics is negligible. The coefficient of kinetic friction along warp direction of four different weave structures and blending ratios are shown in the Figure 9. The coefficient of kinetic friction is converted into a decrease as the increase of the blending ratio of PTFE. And it is obviously to seen that when the blending ratio is increased to 33 %, the friction coefficient is significantly reduced. With continuous increased of blending ratio in a certain range, the friction performance is not significantly improved. The effect of weave structure

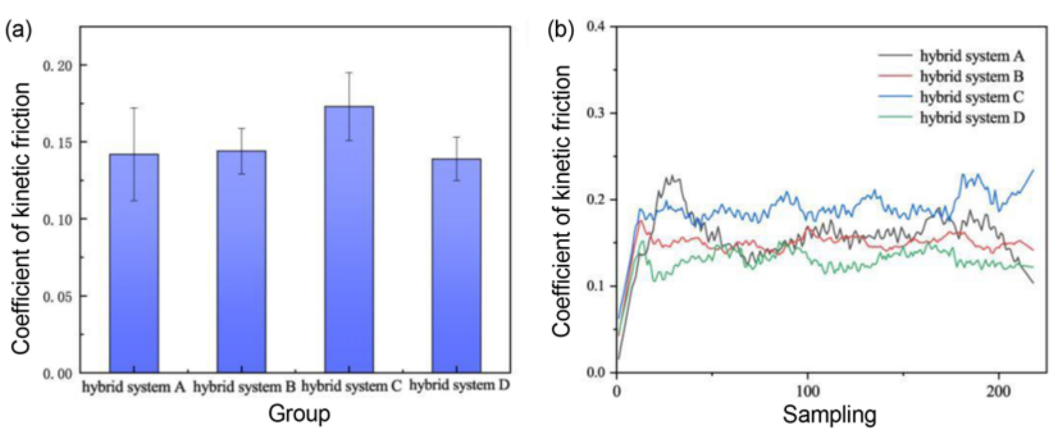

Figure 9. Friction coefficient of hybrid PTFE/Kevlar; (a) average coefficient of kinetic friction and (b) the fluctuation of kinetic friction coefficient.

on friction coefficient depends on the float length of the yarn in the fabric. Appropriately increasing the length of the float line is beneficial to reduce the coefficient of kinetic friction, however, the stability of friction coefficient will be affected. Based on the above factors, twill structure is a workable option. As shown in Figure 9b, the stability of the friction coefficient of the hybrid system B is better than the other three. It indicate that the introduction of a certain amount of PTFE in the weft direction and increases the continuity of PTFE in the warp and weft directions can reduce the

Table 3. Weight wear rate of fabric with PTFE film and hybrid system D

Test group	Weight wear rate (%)
PTFE film/low load	0.325
PTFE film/high load	0.465
Hybrid system D/low load	0.258
Hybrid system D/high load	0.330

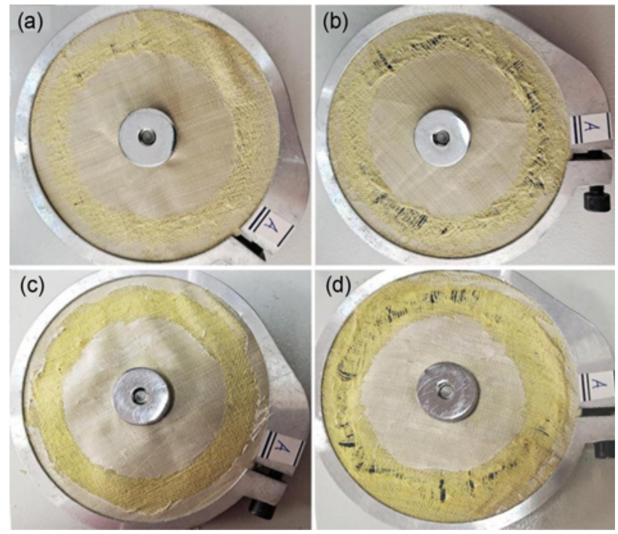

Figure 10. Worn surface appearance. Low load: (a) sliding for 50 r, (b) sliding for 150 r. Heavy load: (c) sliding for 50 r, (d) sliding for 150 r.

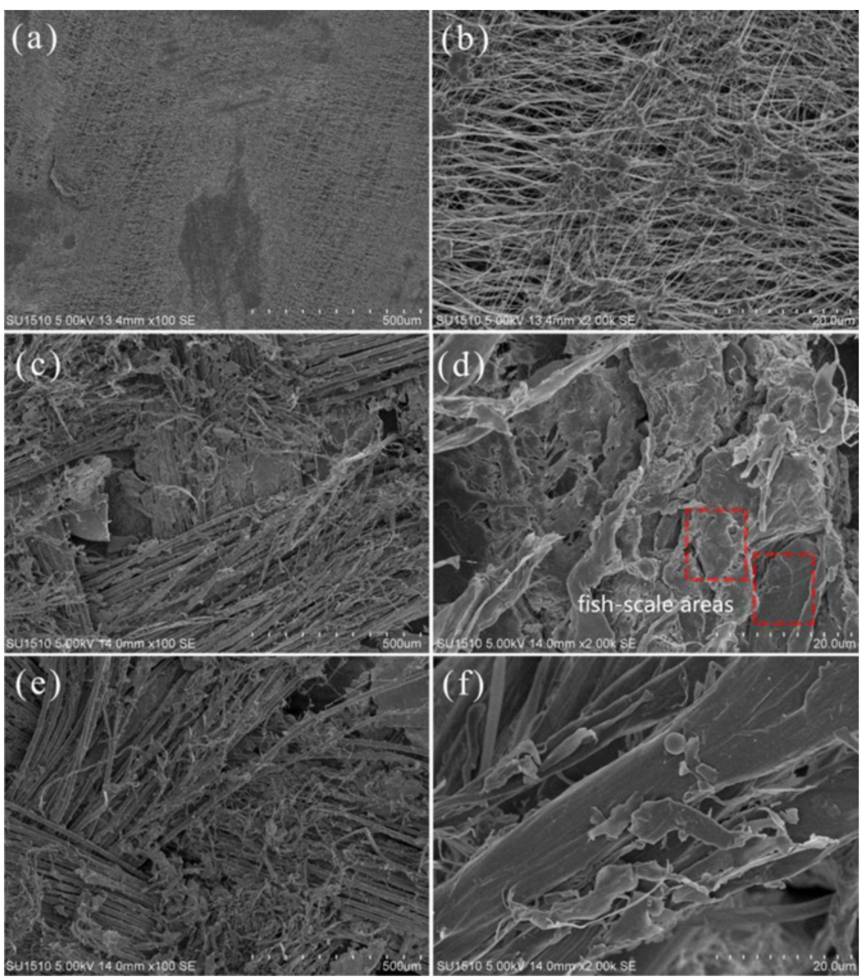

Figure 11. SEM micrographs of worn surfaces of the PTFE film sliding of 2450 Pa; (a) and (b) are the pristine fabric images; (c) and (d) are images of worn surface sliding for 50 r; and (e) and (f) are images sliding for 100 r.

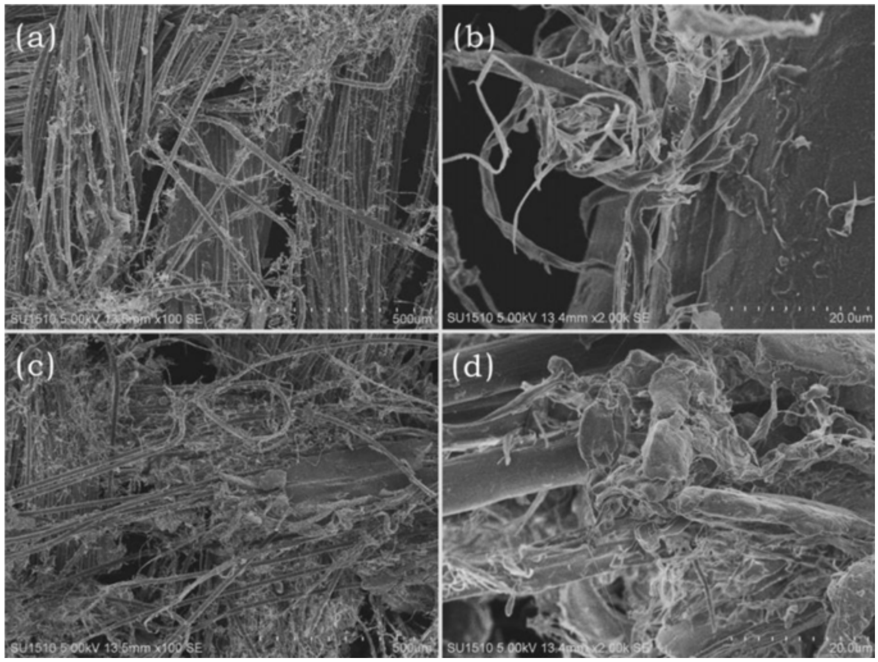

Figure 12. SEM micrograph of worn surfaces of hybrid system D sliding for 150 r; (a) and (b) are sliding at a load of 2450 Pa; (c) and (d) are sliding at a load of 7350 Pa.

deviation of the kinetic friction coefficient.

Wear Performance Test

Wear rates of the fabric with PTFE film and hybrid system D are shown in Table 3. The sliding was performed under dry friction conditions at loads of 2450 Pa and 7350 Pa. Relative to the weight wear rate, blending PTFE in the fabric exhibits outstanding advantages. Compared with the heavy load pressure of mechanical equipment, though the load provided by the fabric abrasion tester is lower, the results are still of reference value.

The worn surface appearances are shown in Figure 10 along with the SEM micrographs depicted in Figure 11 and Figure 12. It is observed from Figure 10b that PTFE nanofibers are deposited on the surface of the fabric. At a load of 2450 Pa, the first stage is that the surface is accompanied by fish-scale areas while there is irregular flaky accumulation as is shown in Figure 10d. The flaky areas form transfer film to reduce friction [22]. The wear mechanism refers to bond damage. With the increase of friction revolutions, the form of the friction and wear can be classified into the second stage. The lubricating layer is severely worn and the fibers are exposed on the surface, the wear mechanism refers to fatigue damage [23]. However, as is shown in Figure 10c, at a load of 7350 Pa, PTFE film is destroyed at an early stage. It suggest that PTFE film is not suitable for lubricating layer under heavy load conditions.

Regarding to the hybrid PTFE/Kevlar fabric, PTFE fibers with poor abrasion resistance are worn out as shown in Figure 12. It can be seen, the worn PTFE is entangled with each other and has a tendency to form flaky lubricating layers. Compared with fabric pasted with PTFE film, the similarity is that the PTFE component forms flaky lubricating layers to protect the Kevlar yarn; the difference is that in the hybrid system, the PTFE component is easy to form a lubrication entangled on the surface of the Kevlar yarn. In the initial stage of friction, the wear mechanism of the hybrid systems is refers to bond damage rather than abrasive damage. The abrasive wear mechanism is that under loading conditions the falling debris would cause further wear damage. The bond damage of the hybrid systems avoided the secondary loss of the fabric from the falling abrasion debris. And the introduction of PTFE provides excellent durability for hybrid system. In summer, regardless of low load or heavy load conditions, the wear mechanism of hybrid systems can be divided into two stages, defined as the bond damage and fatigue damage. As for fabric with PTFE coating, when a high load is applied to it, the PTFE film destroyed at an early stage.

Conclusion

This paper investigated the tribological properties of PTFE coating fabric and hybrid PTFE/Kevlar fabric under dry friction conditions. It shows that the Kevlar fabric with PTFE particles melt-adhered to PTFE film is feasible to reduce the friction coefficient of the fabric by 33.8 %. It can still maintain its low friction coefficient performance under high and low temperature conditions. As the volume blending ratio of PTFE up to 33.3 %, the tribological properties of PTFE/Kevlar hybrid fabric can be significantly improved. Further increase the blending ratio of PTFE, with the decrease of the blending ratio of Kevlar fiber, the strength and wear resistance of the hybrid systems get worse. Besides the wear process can be divided into two stages: bond wear and fatigue wear. In the first stage, PTFE nanofibers or fibers are entangled with each other, forming accumulated flaky lubricating layers during the sliding process. In the second stage, lubricating layers are continuously destroyed, and Kevlar fibers are gradually worn.

Acknowledgment

The authors acknowledge the financial support from the financial support from the National Science Funds of China (11972172, 61902150), the Fundamental Research Funds for the Central Universities (JUSRP22026), and a Project Funded by the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAP).

References

1. Y. Y. Liu, N. Xu, and Y. Wang, *Surf. Coat Technol*., **361**, 196 (2019).
2. F. Guo, Z. Z. Zhang, and W. M. Liu, *Tribol. Int.*, **42**, 243 (2009).
3. H. L. Li, Z. W. Yin, and D. Jiang, *Tribol. Int.*, **80**, 172 (2014).
4. N. Mohan, S. Natarajan, and S. P. Kumaresh Babu, *Mat. Des*., **32**, 1704 (2011).
5. J. Khedkar, I. Negulescu, and E. I. Meletis, *Wear*, **252**, 361 (2002).
6. J. Bijwe, S. Neje, and J. Indumathi, *J. Reinf. Plast. Compos*., **21**, 1221 (2002).
7. S. Beckford and M. Zou, *Appl. Surf. Sci*., **292**, 350 (2014).
8. F. Zheng, Q. H. Wang, and T. M. Wang, *J. Macromol. Sci. Part B-Phys.*, **54**, 927 (2015).
9. Y. J. Shi, X. Feng, and H. Y. Wang, *Wear*, **264**, 934 (2008).
10. Y. X. He, D. Y. Wu, and M. Y. Zhou, *Appl. Surf. Sci*., **506**, 144946 (2020).
11. C. A. Chairman and S. P. K. Babu, *J. Appl. Polym. Sci.*, **130**, 120 (2013).
12. D. P. Gu, Y. L. Yang, and S. W. Chen, *Autex. Res. J.*, **14**, 168 (2014).
13. H. Wang, X. W. Qi, W. L. Zhang, Y. Dong, B. Fan, and Y. Zhang, *Tribol. Int*., **151**, 106507 (2020).
14. H. X. Zhou, Y. S. Sun, and W. S. Wang, *Chin. J. Tribol.*, **36**, 650 (2016).
15. G. N. Ren, Z. Z. Zhang, and X. T. Zhu, *J. Mater. Sci*., **49**, 3716 (2014).
16. W. G. Sawyer, K. D. Freudenberg, and P. Bhimaraj, *Wear,* **254**, 573 (2003).
17. J. J. Qu, Y. H. Zhang, and X. Tian, *Wear*, **322**, 108 (2015).
18. D. P. Gu, C. S. Duan, and B. L. Fan, *Tribol. Int.*, **103**, 423 (2016).
19. M. M. Yang, X. T. Zhu, and G. N. Ren, *Eur. Polym. J.*, **67**, 143 (2015).
20. X. W. Qi, J. Ma, and Z. N. Jia, *Wear*, **318**, 124 (2014).
21. K. Kurumada, T. Kitamura, and N. Fukumoto, *J. Membr. Sci.*, **149**, 51 (1998).
22. Y. X. Wang and F. Y. Yan, *Wear*, **261**, 1359 (2006).
23. D. P. Gu, Y. L. Yang, and X. W. Qi, *Chin. J. Mech. Eng.*, **25**, 1044 (2012).