Influence of Solid Lubricant Reinforcement on Wear Behavior of Kevlar Fabric Composites

Fang Guo,[1,2] Zhao-Zhu Zhang,[1] Wei-min Liu,[1] Feng-hua Su,[1,2] Hui-juan Zhang[1,2]

[1]*State Key Laboratory of Solid Lubrication, Lanzhou Institute of Chemical Physics, Chinese Academy of Sciences, Lanzhou 730000, China*
[2]*Graduate School of Chinese Academy of Science, Beijing 100039, China*

Received 28 May 2007; accepted 4 February 2008
DOI 10.1002/app.28124

ABSTRACT: The friction and wear behavior of Kevlar fabric composites reinforced by PTFE or graphite powders was investigated using a Xuanwu-III friction and wear tester at dry sliding condition, with the unfilled Kevlar fabric composite as a reference. The worn surfaces were analyzed by means of scanning electron microscope, and X-ray photoelectron spectroscopy. It was found that PTFE or graphite as fillers could significantly improve the tribological behavior of the Kevlar fabric composites, and the Kevlar fabric composites filled with 20% PTFE exhibited the best antiwear and antifriction ability among all evaluated cases. The transfer films established with two lubricants in sliding wear of composites against metallic counterparts made contributions to reducing friction coefficient and wear rate of Kevlar fabric composites. In particular, FeF_2 generated in the sliding of Kevlar fabric composites filled with PTFE against counterpart pin improved the bonding strength between the transfer film and counterpart surface, which accounted for the lowest friction coefficient and wear rate of the Kevlar fabric composites filled with PTFE measured in the testing. © 2008 Wiley Periodicals, Inc. J Appl Polym Sci 110: 1771–1777, 2008

Key words: Kevlar fabric composites; solid lubricant; friction and wear; transfer film

INTRODUCTION

Under extreme friction condition conventional polymer composites as bearing liner materials can hardly be effective for antiwear and friction-reduction, for example, under heavy load. The fabric composite composed of fabric, as the matrix, and adhesive resin, as the binder, has been considered as an advanced bearing liner material for tribological application in many high-tech industries such as aero space, aviation, automobile, and so forth owing to it with low density, high strength, high modulus and excellent chemical stability, and antiwear ability.[1,2]

Kevlar fiber, characterized with high tenacity, high modulus and strength, and low electrical conductivity comparing with metallic and carbon fibers, is widely used in aircraft, missile and space applications such as rocket motor casings and nozzles.[3,4] In the case of polymer matrix composites, the friction and wear properties of fiber or fabric reinforced have been systematically discussed in many articles[5–7] in the last few decades. The tribological behavior of fabric composites as bearing liner materials with adhesive resin as binder, however, has not been systemically evaluated,[8,9] especially the solid lubricants reinforced Kevlar fabric composites.

To increase the applicability of Kevlar fabric composites in the bearing industry where the integration and multifunctionalization of bearings made of various composites are of particular interest, it is imperative to seek for effective ways to improve tribological behavior of Kevlar fabric composites. Polymers and coatings filled with solid lubricants have been extensively studied because of the increasing industrial and martial applications.[10–12] However, fabric composites filled with solid lubricants to improve friction and wear behavior have not been systemically studied.[13,14] Some solid lubricants such as PTFE and graphite are widely used to reduce both the friction coefficient and wear rate of some fabric composites or polymeric composites.[15–17]

With this perspective in mind, PTFE powder and graphite powder were selected to reinforce the Kevlar fabric composites in the presence of phenolic adhesive resin. The purpose of this study is to investigate and compare the effects of the two solid lubricants, such as PTFE and graphite, on the improvement of tribological behavior of Kevlar fabric composites and to extend the application of Kevlar fabric/phenolic composites in dry-sliding bearings.

Correspondence to: Z.-Z. Zhang (zzzhang@lzb.ac.cn).
Contract grant sponsor: ''973'' Project of China; contract grant number: 2007 CB607601.

Journal of Applied Polymer Science, Vol. 110, 1771–1777 (2008)

EXPERIMENTAL

Materials

The Kevlar fabrics used in this study were woven from Kevlar fibers that were purchased from Du Pont, USA. The adhesive resin (phenolic resin) was provided by Shanghai Xing-guang Chemical Plant, China. Irradiated PTFE powders (< 20 μm) was provided by Lanzhou irradiation Center of Gansu province, China. Graphite powder (< 38 μm) was provided by Shanghai Colloid Chemical Plant, China.

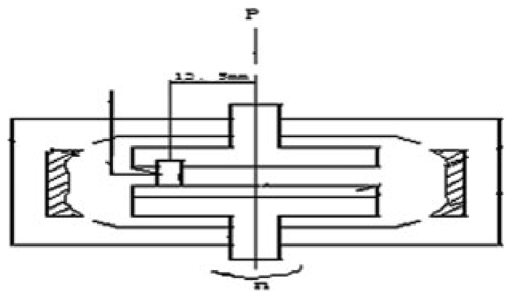
Specimen preparation

The Kevlar fabrics were cleaned using the Soxhlet, continuous extraction in petroleum ether and then in acetone and dried at 80°C for 24 h. The solid lubricants were uniformly mixed with a phenolic resin at proper mass fractions with the assistance of magnetic stirring and ultrasonic stirring. Then the Kevlar fabrics were impregnated in the mixed adhesive containing the solid lubricants and dried. The relative mass fraction of the Kevlar fabrics was about 65% ± 5%. Finally, the impregnated Kevlar fabric composites were affixed on the AISI-1045 steel (surface roughness Ra = 0.45 μm) with the phenolic resin and then cured at 180°C for 2 h under a certain pressure. For comparison, the unfilled Kevlar fabric composite (abridged as KFC) was prepared in the same way. The PTFE, graphite filled and unfilled Kevlar fabric composite specimens were prepared and tested.

Friction and wear test

The friction and wear behavior of Kevlar fabric composites was investigated using a Xuanwu-III pin-on-disk friction and wear tester (Scheme 1). The pin-on-disk tester consisted of loading a stationary pin sliding against a rotating disk that was affixed with the Kevlar fabric/phenolic composites. The pin (AISI-1045 steel) was fixed to the load arm with a chuck. The pin stayed over the disc with two degrees of freedom: a vertical one, which allowed normal load application by direct contact with the disc, and a horizontal one, for friction measurement. The motor had tachogenerator feedback to ensure stable running speeds.

Before the tests, the pin was polished with 350, 700, and 900 grade water-proof abrasive papers to a surface roughness Ra = 0.15 μm, and then cleaned with acetone. The sliding was performed at ambient temperature, with a load between 156.8 and 313.6 N and over a period of 2 h under dry condition. At the end of each test, the wear volume loss (*V*) of the composite was obtained by measuring the depth of the wear scar with a micrometer (±0.001 mm). The wear performance was expressed in terms of wear rate [w, $\mathrm{m}^3 \cdot (\mathrm{N} \cdot \mathrm{m})^{-1}$] as follows: $w = V/p\,L$, where V is the wear volume loss in m^3; P the load in Newton; L the sliding distance in meter.



Scheme 1 Schematic diagram of pin-on-disc friction and wear tester.

The friction coefficient was measured from the frictional torque gained by a load cell sensor, which obtained directly from the computer running the friction-measure software. The contact temperature of the worn surface was monitored by a thermocouple position on the edge of the counterpart pin. The environmental temperature of frictional condition was controlled with the electric furnace and was monitored with a thermocouple in the furnace. Each experiment was carried out three times and the average value was used.

Worn surface analysis

The morphologies of the worn surfaces of the Kevlar fabric composites and counterpart pins were analyzed on a JSM-5600LV scanning electron microscope (SEM). The chemical states of the elements on the counterpart surface sliding against the Kevlar fabric composites filled with 20% PTFE were analyzed on an ESCALAB 210 X-ray photoelectron spectroscopy (XPS).

RESULTS AND DISCUSSION

Tribological properties of Kevlar fabric composites

In Figure 1, the friction coefficient and wear rate of PTFE filled Kevlar fabric composites are plotted versus the PTFE mass content. Results show that with the addition of PTFE, both the friction coefficient and wear rate reduce remarkably. The friction coefficient and wear rate decrease with increasing PTFE mass content up to 20%, and then increase. Therefore, the optimal additive content is 20 wt % according to the friction-reduction and antiwear ability. This content was chosen to investigate the influence of the load, temperature, and sliding speed, respectively.

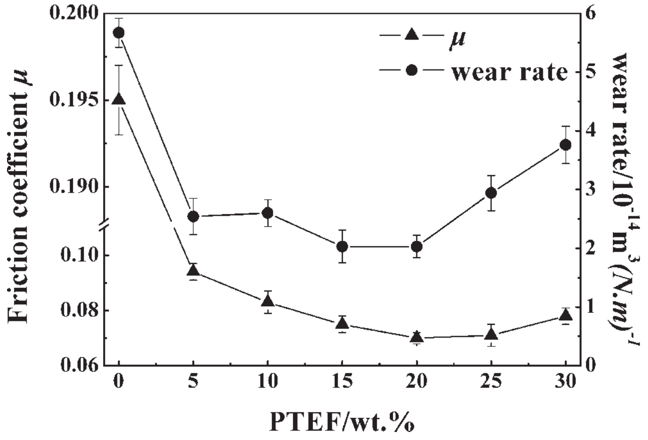


Figure 1 Variations of friction coefficient and wear rate with content of PTFE in Kevlar fabric composites (156.8 N, room temperature, 0.26 m/s).

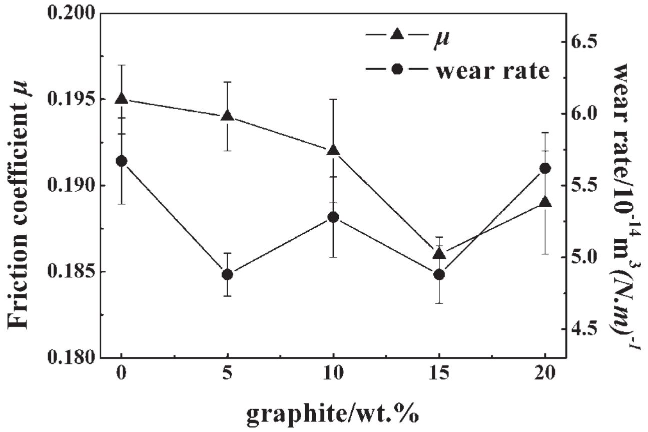


Figure 2 Variations of friction coefficient and wear rate with content of graphite in Kevlar fabric composites (156.8 N, room temperature, 0.26 m/s).

Figure 2 shows the dependence of the friction coefficient and wear rate on the graphite mass content of the graphite filled Kevlar fabric composites under 156.8 N. The effective additive content of graphite is 15 wt %. When the additive content is lower than 15 wt %, the friction coefficient reduces with increasing graphite, whereas the wear rate almost remains the same value. Further addition of graphite increases both the friction coefficient and wear rate, which means excessive fillers tend to conglomerate and lead to the less uniformity of the system and thus reduce the antiwear ability of the composites.

Friction coefficient and wear rate of the unfilled Kevlar fabric composites and that filled with 15% of graphite and 20% of PTFE are plotted in Figure 3 as a function of the load. With the unfilled Kevlar fabric composites, the friction coefficient and wear rate are relatively large, and the friction system is destroyed at a load higher than 219.52 N. The friction coefficient decreases with increasing load up to 188.16 N, and then increases from 188.16 to 219.52 N, which is close to the ultimate load. With the composites filled with 15% of graphite, lower friction coefficient and wear rate are observed. The friction coefficient shows a gradient descent with the increase of the load. A notable decrease in both friction coefficient and wear rate is evident for the Kevlar composites filled with 20% of PTFE under different loads. The results show a monotonic decrease in friction coefficient and monotonic increase in wear rate. For the three different Kevlar fabric composites, all the wear rates show a monotonic increase with increasing load. This is because the friction surface temperature goes up with increasing load, which results in the adhesion of the composites to the counterpart surface and thus decreases the wear resistance.

In Figure 4, the typical variations of the frictional coefficient against the sliding time for these three

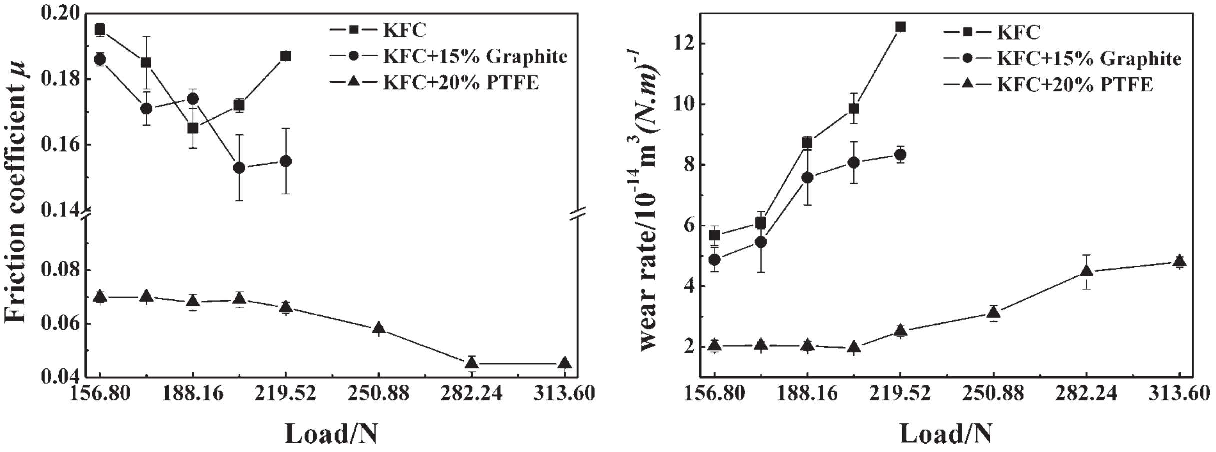


Figure 3 Variation of friction coefficient and wear rate with load for three different Kevlar fabric composites (room temperature, 0.26 m/s).

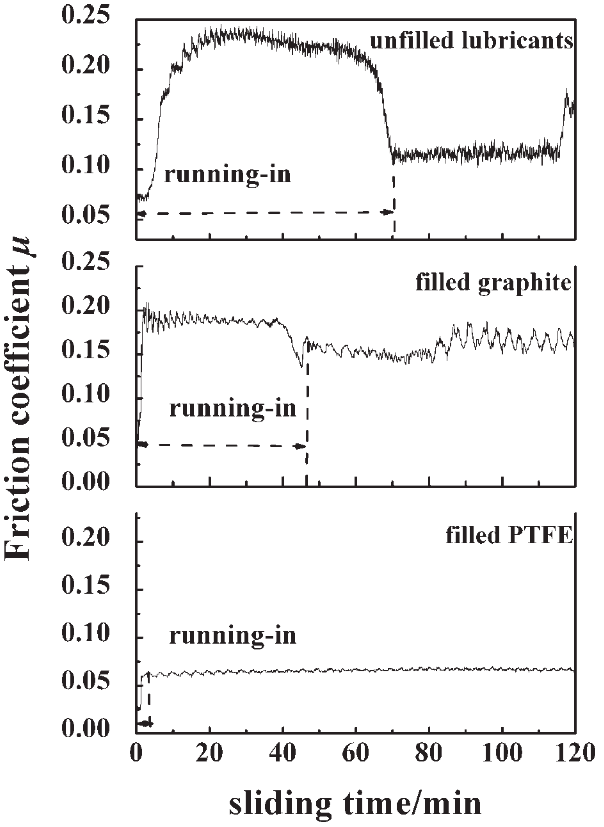


Figure 4 Typical variation of friction coefficient against sliding time of three different Kevlar fabric composites (203.84 N, room temperature, 0.26 m/s).

composites at 203.84 N and 0.26 m/s are shown. Both PTFE and graphite effectively reduce the peak value and duration of the running-in stage, which contributes to the continuous transfer films formed on the counterpart surface and results in a lower friction coefficient. In comparison to the transfer film formed by graphite, the transfer film formed by PTFE has the advantage of the quicker formation of a stable transfer film due to lower binding energy between crystalline slices. So, the composites filled with PTFE achieved the smoothest curve and lowest value of the frictional coefficient.

Since the tribological behavior of the PTFE filled Kevlar fabric composite is better than the graphite filled one, the wear tests under different sliding speeds and temperature conditions are focused on the Kevlar fabric composites filled with PTFE.

The influence of temperature on the friction coefficient and wear rate of the PTFE filled Kevlar fabric composite is depicted in Figure 5. The friction coefficient shows a monotonic decrease from 0.069 to 0.031 with the increase of environmental temperature. Conversely, the wear rate gradually increases with increasing environmental temperature to 180°C and then abruptly increases at the test temperature from 180 to 240°C, denoting severe wear. This is because adhesive resin becomes brittle and loses its ability to bind the Kevlar fabric at a temperature as high as 240°C, which leads to a dramatic decrease in the mechanical strength and wear resistance of the composites.

Variations of the friction coefficient, wear rate, and counterpart temperature of the Kevlar fabric composites filled with 20% PTFE with the sliding speed under a load of 203.84 N are shown in Figure 6. The friction coefficient presents a steady decrease with the sliding speed, which is attributed to surface softening caused by the frictional heating.[18] A decrease in wear rate is evident for the lower sliding speed (0.21 m/s), followed by an increase for tests conducted from 0.26 to 0.37 m/s. A similar variation with sliding speed is found for the counterpart temperature. According to the change of the counterpart temperature, we can understand the variation of the wear rate with the sliding speed. From the above analysis, it can be concluded that the PTFE filled Kevlar fabric composites exhibit better wear resistance at 0.26 m/s speed.

Analysis of worn surface and counterpart surface

Figure 7 shows the XPS of the counterpart surface sliding against the Kevlar fabric composites filled with 20% PTFE. On the XPS of F 1s a peak at 689.2 eV and a peak at 684.9 eV are shown, which are assigned to C-F species and metal fluoride, respectively. In combination with the binding energy of Fe 2p at 711.2 eV, it is inferred that FeF_2 exists on the counterpart surface. Thus, we conclude that FeF_2 generated in the sliding of Kevlar fabric composites filled with PTFE against counterpart pin improves the bonding strength between the transfer film and

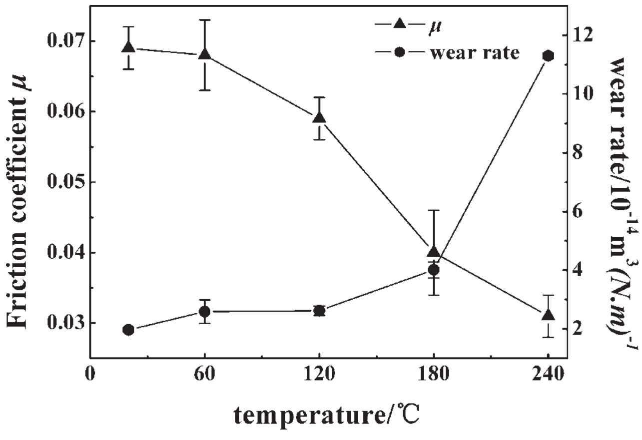


Figure 5 Variations of friction coefficient and wear rate with environment temperature in PTFE filled Kevlar fabric composites (203.84 N, 0.26 m/s).

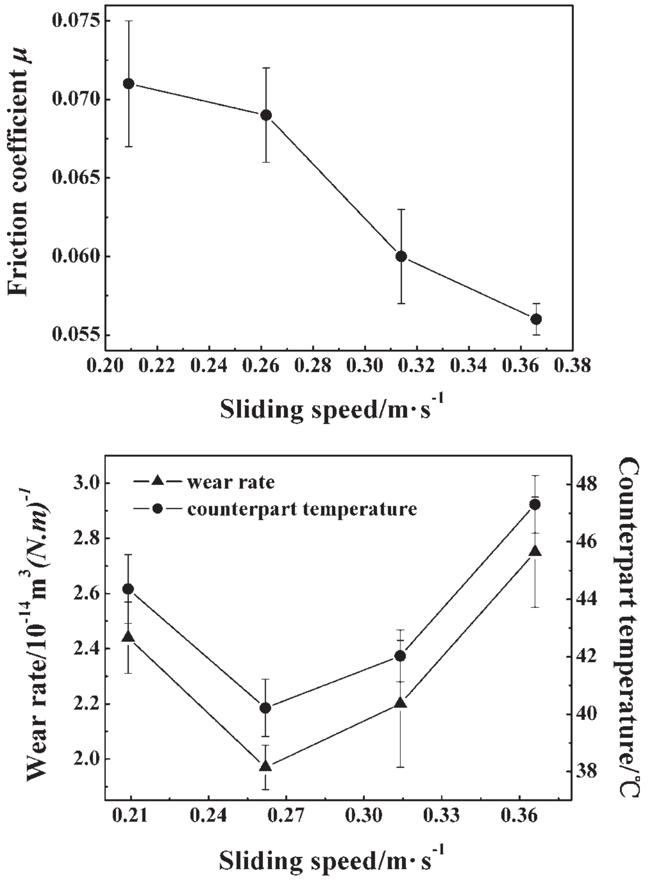


Figure 6 Variations of friction coefficient, wear rate and counterpart temperature with sliding speed in PTFE filled Kevlar fabric composites (203.84 N, room temperature).

counterpart surface, and accounts for the lowest friction coefficient and wear rate of the Kevlar fabric composites filled with PTFE measured in the testing.

Figure 8 shows the micrographs of the counterpart surface of three different composites at 203.84 N and room temperature to illustrate the different antiwear mechanisms of these three composites. It is seen from Figure 8(a) that the transfer film of unfilled Kevlar fabric composites scarcely exists on the counterpart surface, and the counterpart surface appears to be rather rough. This is because the bonding strength between the transfer film and counterpart is very weak and the transfer film is easily scaled off during friction process. So, the protection from the transfer film is nonexistent anymore, which corresponds to the worst antiwear properties of the unfilled Kevlar fabric composites. However, the transfer film of the Kevlar fabric composites filled with PTFE [Fig. 8(b)] appears to be smooth, coherent and with moderate thickness. The continuous transfer film can effectively reduce the ''direct contact'' between the composites and aspirate surface of the metallic counterpart. As a result, the subsurface stresses of the composites can be maintained at lower values and thus lower friction coefficient and wear rate are achieved. Comparatively, the transfer film of the Kevlar fabric composites filled with graphite appears discontinuous and nonuniform [Fig. 8(c)]. Discontinuous black areas can be observed, and this is attributed to the graphite transfer, being related to mechanical embedding. The bonding strength between this transfer film and counterpart is weak, thus the transfer film can not provide efficient lubrication. The various characteristics of the transfer films on the counterpart surfaces also account for the difference in the friction and wear behaviors of three different composites.

Figure 9 shows the SEM morphologies of the worn surfaces of the three Kevlar fabric composites. It is seen that the unfilled Kevlar fabric composites after sliding are characterized by many pulling-out and exposure of Kevlar fibers [Fig. 9(a)], which indicates that the unfilled Kevlar fabric composites undertake a larger contact stress and experience severe peeling off. With the 15% graphite filled one

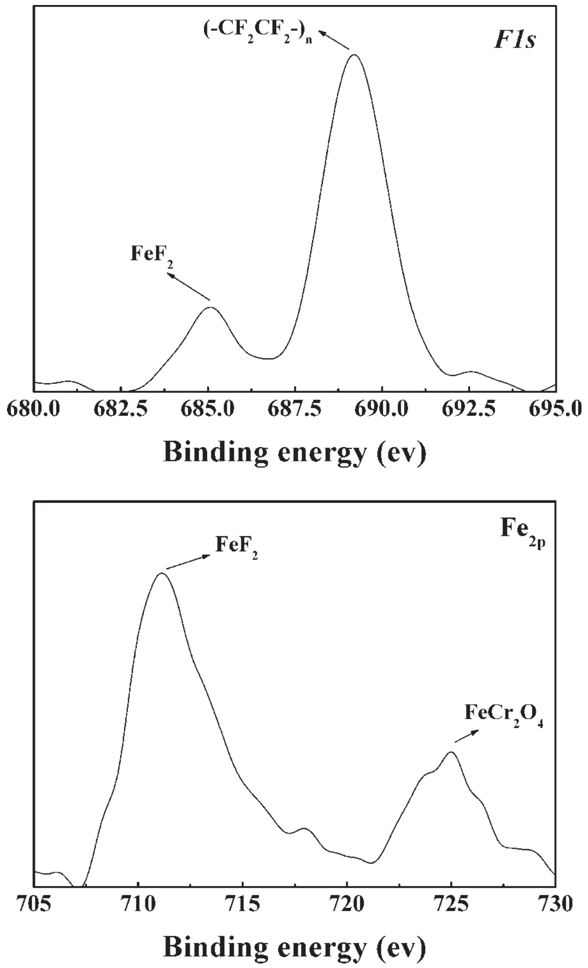


Figure 7 XPS of counterpart surface sliding against 20% PTFE filled Kevlar fabric composites (203.84 N, room temperature, 0.26 m/s, 2 h).

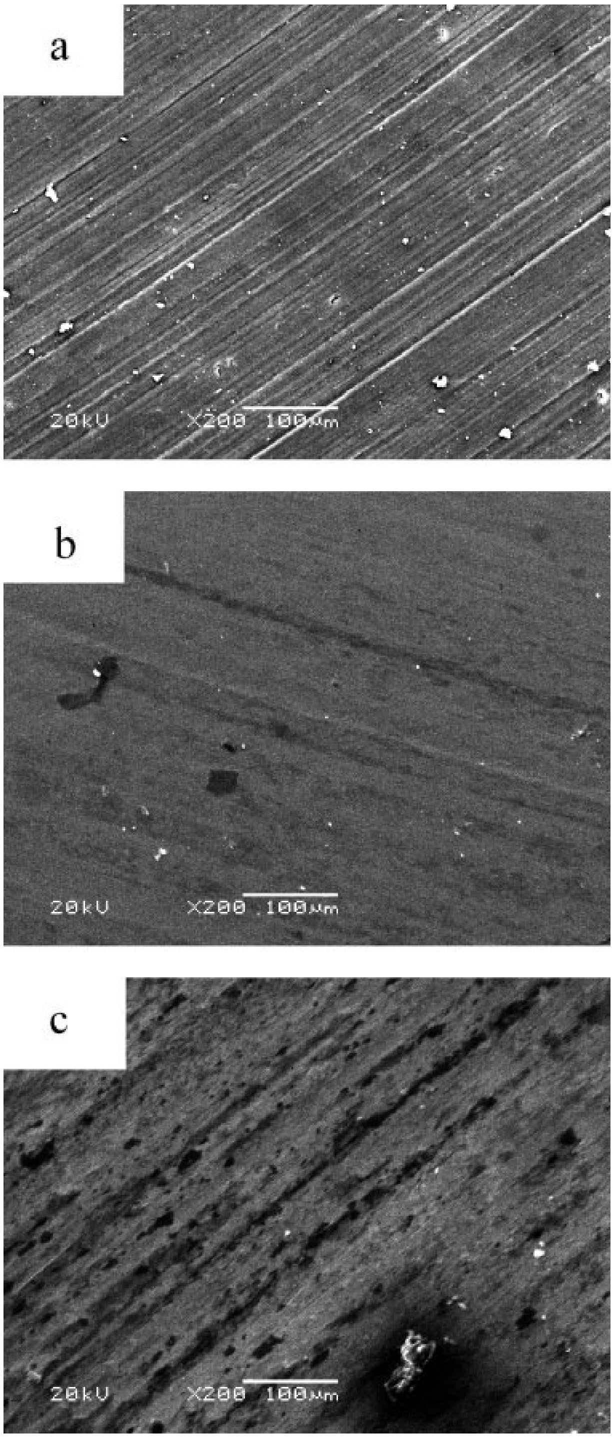


Figure 8 SEM images of counterpart surfaces of (a) unfilled, (b) 20% PTFE filled, and (c) 15% graphite filled Kevlar fabric composites (203.84 N, room temperature, 0.26 m/s, 2 h).

[Fig. 9(b)], there are fewer Kevlar fibers pulled out and cut from the composites in the worn surface. Contrary to the unfilled one, the worn surface of Kevlar fabric composites filled with 20% PTFE at 203.84 N after sliding is relatively smooth and the pulling-out and exposure of the Kevlar fibers are negligible [Fig. 9(c)]. This is in agreement with the highest antiwear and friction-reduction ability of the Kevlar fabric composites filled with PTFE.

To sum up, it is supposed that PTFE fillers react with the metallic counterpart surface during the sliding process to generate FeF_2. This contributes signifi-

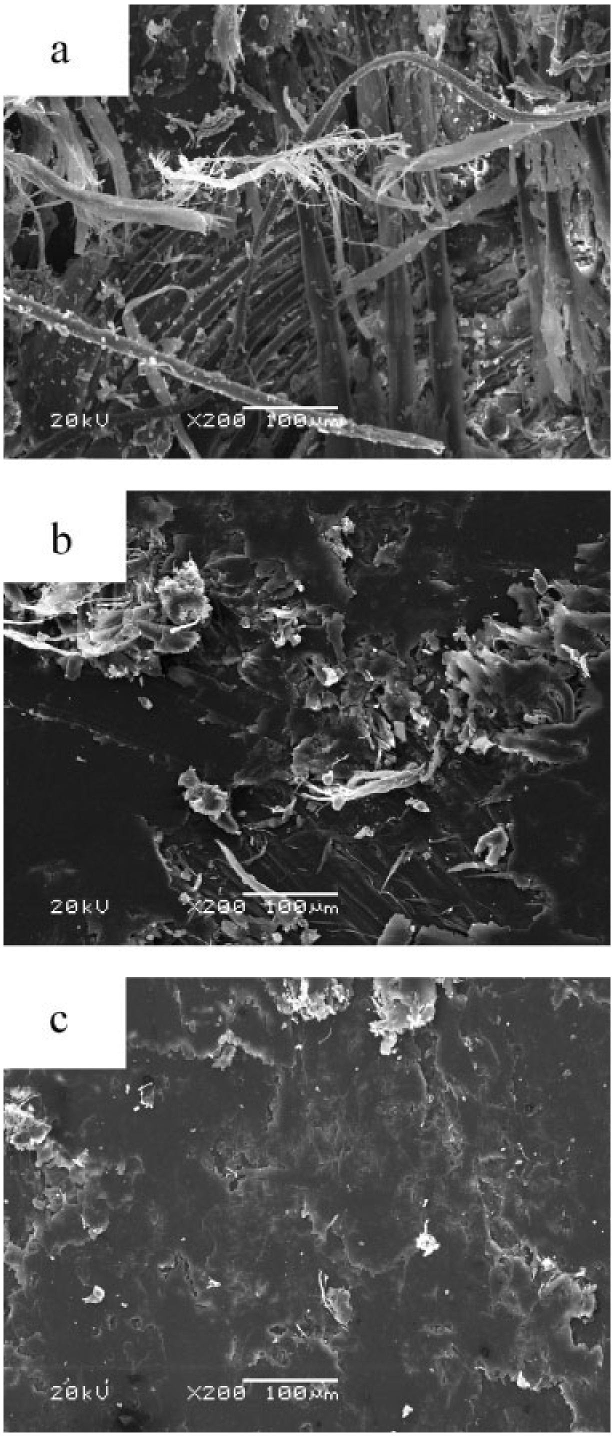


Figure 9 SEM images of worn surfaces of (a) unfilled, (b) 15% graphite filled, and (c) 20% PTFE filled Kevlar fabric composites (203.84 N, room temperature, 0.26 m/s, 2 h).

cantly to the improvement of the friction and wear behavior of the Kevlar fabric composites that measured in the testing.

CONCLUSION

a. Both solid lubricants, PTFE and graphite powders, make positive contributions to the development of the transfer film, thereby reducing the friction coefficient and wear rate of Kevlar fabric composites.
b. FeF_2 generated in the sliding of the Kevlar fabric composites filled with PTFE against counterpart pin improves the bonding strength between the transfer film and counterpart surface, which accounts for the lowest friction coefficient and wear rate of the PTFE filled Kevlar fabric composites measured in the testing.
c. The friction and wear properties of the Kevlar fabric composites filled with PTFE are closely related to the sliding conditions such as load, sliding speed and environmental temperature owing to the variation of friction surface temperatures.

The authors are grateful to Prof. Jiazheng Zhao for his help in SEM analysis.

References

1. Tercan, M.; Asi, O.; Aktas, A. Compos Struct 2007, 78, 392.
2. Lua, J. Compos Appl Sci Manuf 2007, 38, 1019.
3. Yue, C. Y.; Padmanabhan, K. Compos B Eng 1999, 30, 205.
4. Lin, T. K.; Wu, S. J.; Lai, J. G.; Shyu, S. S. Compos Sci Technol 2000, 60, 1873.
5. Oshima, A.; Udagawa, A.; Morita, Y. Radiat Phys Chem 2001, 60, 467.
6. Harsha, A. P.; Tewari, U. S. Polym Test 2002, 21, 697.
7. Cheng, X. H.; Xue, Y. J.; Xie, C. Y. Mater Lett 2003, 57, 2553.
8. Liu, X. J.; Li, T. S.; Yang, S. R. Tribol (China) 1999, 19, 23.
9. Li, T. Q.; Wang, C. Y. Polym Mater Sci Eng 2003, 19, 5.
10. Bijwe, J.; Rajesh, J. J.; Jeyakumar, A. Tribol Int 2000, 33, 697.
11. Song, H. J.; Zhang, Z. Z.; Luo, Z. Z. Surf Coat Technol 2006, 201, 2760.
12. Friedrich, K.; Zhang, Z.; Schlarb, A. K. Compos Sci Technol 2005, 65, 2329.
13. Su, F. H.; Zhang, Z. Z.; Guo, F. Mater Sci Eng A Struct Mater 2006, 424, 333.
14. Su, F. H.; Zhang, Z. Z.; Guo, F. Mater Sci Eng A Struct Mater 2006, 416, 126.
15. Khedkar, J.; Negulescu, I.; Meletis, E. I. Wear 2002, 252, 361.
16. Cenna, A. A.; Dastoor, P.; Beehag, A. J Mater Sci 2001, 36, 891.
17. Bahadur, S. Wear 2000, 245, 92.
18. Zhang, Z. Z.; Liu, W. M.; Xue, Q. J. J Appl Polym Sci 2001, 80, 1891.