Friction and Wear Properties of Solid Lubricants Filled/Carbon Fabric Reinforced Phenolic Composites

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ABSTRACT: The carbon fabric composites (CFC) filled with the particulates of graphite, MoS_2, and PTFE, respectively, were prepared by dip coating and hot press molding technique. The tribological properties of the resulting composites were investigated systematically on a model ring-on-block test rig under dry sliding conditions. Experimental results showed that the addition of graphite and MoS_2 significantly improved the friction and wear behavior, but PTFE as filler was harmful to the improvement of the tribological properties of the CFC. Tribological tests also revealed that the CFC showed better tribological properties under higher load and exhibited worse tribological properties under higher sliding speed. Moreover, it also can be concluded that the transfer film formed on the counterpart surface during the friction process largely accounted for the friction and wear behavior of CFC. J Appl Polym Sci 117: 2480–2485, 2010

Key words: fabric composites; tribological properties; solid lubricants

INTRODUCTION

In recent years, polymer and polymer-matrix composites have been extensively studied because of the increasing industrial and martial applications.[1–6] Fabric composites with fabric as reinforcement, and the polymer matrix as the binder, have been considered as advanced materials for tribological application due to good self-lubricating and anti-wear abilities. Many researches have shown that the fiber surface treatment, solid lubricants, and nanoparticles have great effect on the friction and wear of fabric composites.[7–12] Wang and coworkers[7] found that both coupling agent and HNO_3 oxidation can help in improving the friction and wear behavior of carbon fabric composite, while combined surface treatment is the most effective to decrease the friction coefficient and wear rate of the composite. Su et al.[11] found that the incorporation of nano-$CaCO_3$, nano-SiO_2, and nano-TiO_2 contributed to increase the wear resistance of the carbon fabric composites (CFC). Zhang and coworkers[12] studied the friction and wear properties of Nomex fabric composites using a pin-on-desk wear tester under dry sliding conditions. It was found that PTFE significantly improved the tribological behavior of Nomex fabric composites. While, graphite and MoS_2 were harmful to the improvement of friction and wear behavior. However, conventional solid lubricants filled carbon fabric reinforced polymer composites have not been systematically studied. As is known, the friction and wear performance of fabric reinforced composites is a complex phenomenon. Typical wear mechanisms of fiber reinforced polymer matrix composites are fiber breaking, fiber–matrix debonding, and matrix fracture.[13–18] Apart from the fabric composites composition, sliding conditions can also exert much influence on the tribological behavior.[12,19]

With this perspective in mind, MoS_2, graphite, and PTFE were selected to fill the CFC in the presence of phenolic adhesive resin. The object was to investigate and compare the effect of solid lubricants on the improvement of tribological behavior of the CFC. It is expected that this work will bring a new application of carbon fabric reinforced polymer composites in dry sliding bearings.

EXPERIMENTAL

Materials and specimen preparation

In the present study, the adhesive resin (204 phenolic resin adhesive) was provided by Shanghai Xingguang Chemical Plant of China. Carbon fabric used was supplied from Shanghai Sxcarbon Technology Co. (Shanghai, China). MoS_2 and graphite powder

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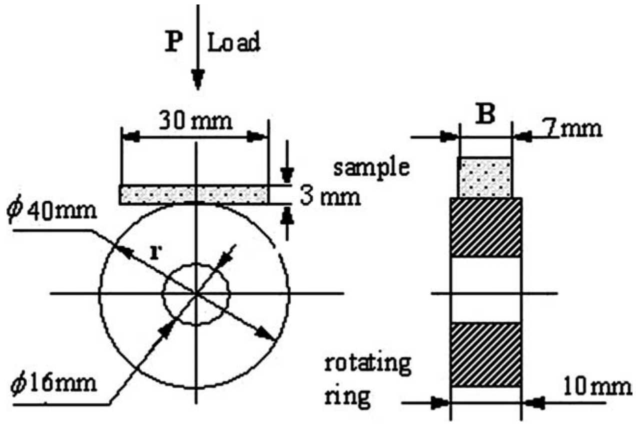

Figure 1 The contact schematic for the friction couple.

(<1.5 μm) were provided by Shanghai Colloid Chemical Plant, China. PTFE powder (<75 μm) was provided by Shandong Huafu Fluoro-Chemical Co. (Jinan, China). The solid lubricants were uniformly mixed with the phenolic resin at proper mass fractions with the assistance of mechanical, stirring. In the present study, a dip coating process was used to prepare the prepregs of the composites. First, the cleaned carbon fabric was dipped into phenolic resin solution containing the solid lubricants and ultrasonically immersed in the solution for 10 min. Then the fabric was put into an oven at 40°C to evaporate the solvent. A series of repeated dipping and coating of the carbon fabric were performed until the mass fraction of carbon fabric was about 60%. The final CFC were fabricated by means of hot press molding technique. The prepregs were compressed and heated to 180°C in the mold with intermittent deflation. The pressure was held at 15 MPa for 240 min to allow full compression sintering. At the end of each run of compression sintering, the resulting specimens were cooled with the stove in air, and then cut into preset sizes for friction and wear tests.

Characterization

The friction and wear tests were conducted on an M-2000 model friction and wear tester. A schematic diagram of the block-on-ring type friction and wear tester used in this study is shown in Figure 1. The specimens for wear tests were machined with a geometry of 30 mm × 3 mm × 7 mm. The stainless GCr15 steel rings with a hardened and smoothly polished surface served as counterparts, the chemical composition of which was given in Table I. Sliding was performed under ambient conditions over a period of 120 min at a sliding velocities of 0.431 m/s and 0.862 m/s, normal load ranging from 200 to 500 N. Before each test, the surfaces of the block specimens and counterpart rings were polished to a roughness (Ra) of about 0.3 μm and cleaned with acetone-dipped cotton. The friction force was measured using a torque shaft equipped with strain gages mounted on a vertical arm that carried the block, which was used to calculate the friction coefficient (μ) by taking into account the normal load applied. The width of the wear tracks was measured with a reading microscope to an accuracy of 0.01 mm. Then the specific wear rate (ω) of the specimen was calculated from eq. (1) as follows.

$$\omega = \frac{B}{L^{*}P}\left[\frac{\pi r}{180}\arcsin\left(\frac{b}{2r}\right) - \frac{b}{2r}\sqrt{r-\frac{b}{2}}\right] \ (\mathrm{mm^3/N\,m}) \tag{1}$$

Where B is the width of the specimen (mm), r is the semi diameter of the stainless steel ring (mm), and b is the width of the wear trace (mm), L is the sliding distance in meter, P is the load in Newton. In this study, three replicated wear results were averaged and taken as the wear results. The morphologies of the worn surfaces of the CF composites and the transfer films formed on the counterpart steel rings were analyzed on a JSM-5600LV scanning electron microscope (SEM). To increase the resolution for the SEM observation, the tested composite specimens were plated with gold coating to render them electrically conductive.

RESULTS AND DISCUSSION

Friction and wear behavior of CF composites

The friction and wear behavior of the CF composites filled with different solid lubricants, sliding against the GCr15 steel ring, is shown in Figures 2–4, respectively. It can be seen that the friction coefficient and wear rate of the unfilled carbon fabric is high. It also can be seen that graphite and MoS_2 with optimal mass content can significantly decrease the friction coefficient and wear rate, however, PTFE as filler is harmful to the friction and wear behavior. In the tested system regarding the friction coefficient and wear rate, the optimal content of graphite and MoS_2 is about 15 wt % and 25 wt %, respectively. With an further increase in the concentration of graphite and MoS_2, the tribological properties deteriorated. Excessive graphite and MoS_2 tend to conglomerate and lead to the less uniformity of the

TABLE I
Chemical Composition of the GCr15 Steel Ring

Chemical composition (wt %)					
C	Mn	Si	P	S	Cr
0.95–1.05	0.25–0.45	0.15–0.35	≤0.025	≤0.025	1.40–1.65

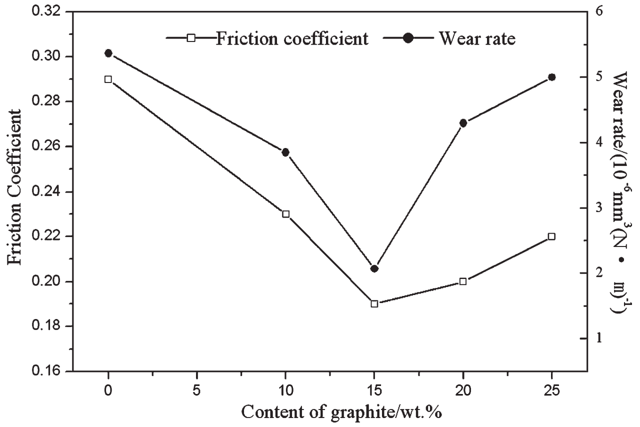

Figure 2 Friction coefficient and wear rate of graphite filled CF composites.

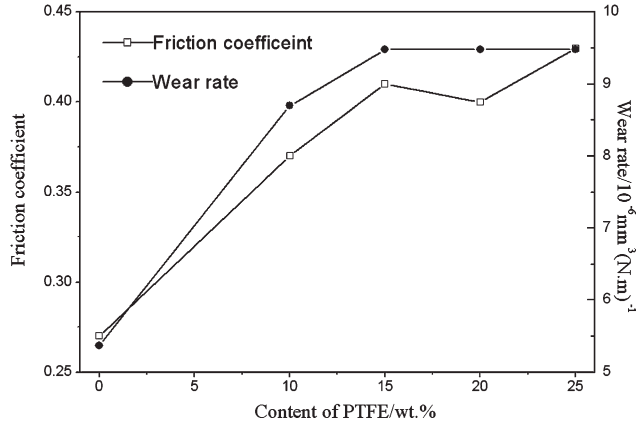

Figure 4 Friction coefficient and wear rate of PTFE filled CF composites.

system, the serious abrasive wear took a dominant place, thus impaired the friction-reduction and anti-wear abilities of the composites. So, the pure and 15% graphite, 25% MoS_2, and 10% PTFE filled CFC were chosen to study the effect of load and sliding speed on the friction and wear behavior of CFC.

Variations of the friction and wear behavior of the CF composites with load are shown in Figures 5 and 6, respectively. It can be seen that both the friction coefficient of the pure and graphite and MoS_2 filled CF composites decrease remarkably with an increase in load. While, the friction coefficient of PTFE filled CF composites exhibit a obvious increase from 200 N to 300 N and decrease with further increasing load. The decrease in the wear rate are observed in the unfilled and graphite and PTFE filled CF composites. The MoS_2 filled CF composites exhibit a minor increased from 200 N to 300 N and then decrease with further increase in load. With an increase in load, some big particle shaped or flaky debris in the wear surface would be crushed or sheared into smaller particles or thinner flakes and acted as lubricants. Moreover, the newly formed debris would come into being a more integrated layer on the worn surface and reduced the cutting action of counterpart to the worn surface, thus, carbon fibers did not break off as easily from the phenolic matrix to form abrasion. Both of them brought about smaller friction coefficient because of decreased degree of two-body abrasive wear. With an increase in load, a relative uniform and coherent transfer film can easily form within a shorter period of time and subsequent sliding occurred between the surface of the CF composites and the transfer film. Consequently, a lower friction coefficient and wear rate is inevitable.

Figure 7 shows the friction and wear behavior of the CF composites under low speed (0.431 m/s) and high speed (0.862 m/s). It is clearly seen that all the CF composites assumed a higher friction coefficient under high sliding speed compared with that under low sliding speed. The wear rate of the unfilled and graphite filled CF composites decreased, while the wear rate of MoS_2 and PTFE filled CF composites increased under high sliding speed. Friction-induced heat surely provokes an increase in the contact temperature owing to the low thermal conductivity of the phenolic matrix. An increase in the sliding speed

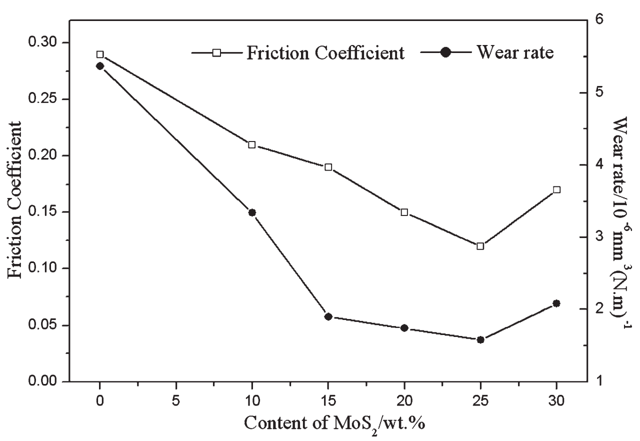

Figure 3 Friction coefficient and wear rate of MoS_2 filled CF composites.

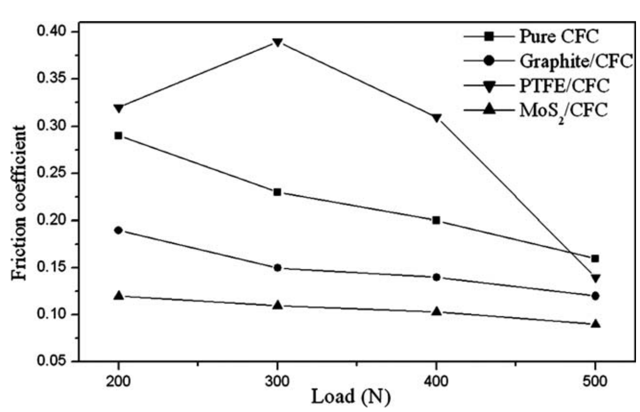

Figure 5 Effect of load on the friction coefficient of CF composites.

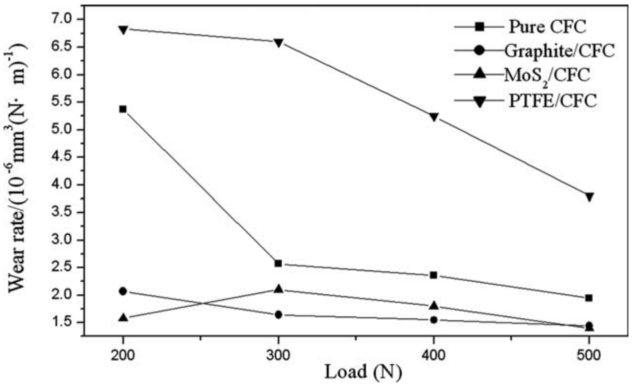

Figure 6 Effect of load on the wear rate of the CF composites.

will result in a higher contact temperature. On one hand, the worn surface enter the transfer period from visoelastic state to viscous state, carbon fibers can easily fell out from the matrix and ruptured without the support and protection of the phenolic matrix. Then the serious abrasive wear took the dominant place, which lead a drastic increase in the friction coefficient. On the other hand, the exposed carbon fibers on the worn surface can inhibit the cutting action of micro-convexity to the matrix of the CF composites. The exposed carbon fibers bore most of the load between the contact surface and reduced the real contact area, The final friction coefficient and wear rate is determined by their competitive effect.

Figure 8 shows the SEM morphologies of the worn surface of the CF composites sliding against GCr15 steel at a sliding speed of 0.431 m/s and 200 N. As is shown in Figure 8(a), some cracks existed on the worn surface of the pure CF composites, and the pulling out and cutting phenomena of carbon fibers are seen, which results in a abrasive

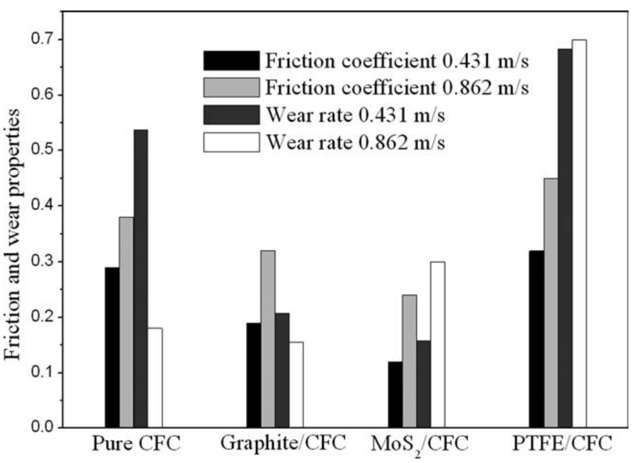

Figure 7 Effects of sliding speed on the friction coefficient and wear rate of the CF composites.

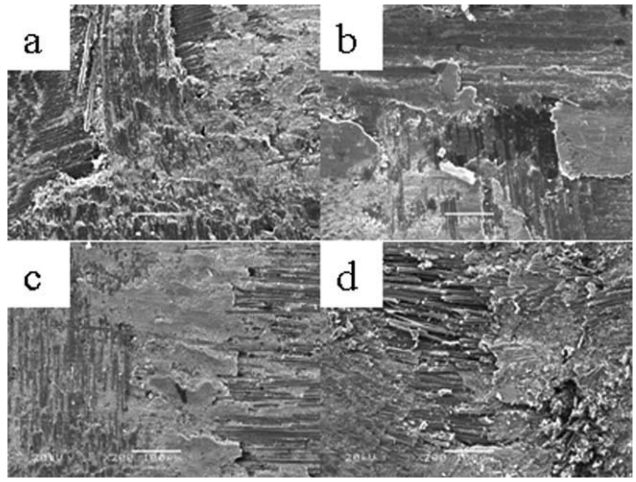

Figure 8 SEM morphologies of the worn surface of the CF composites (200 N, 0.431 m/s). (a) Pure CFC; (b) Gr/CFC; (c) MoS_2/CFC; (d) PTFE/CFC.

wear. Thus, the friction coefficient and wear rate is high. Contrary to the unfilled one, the worn surface of 15% graphite and MoS_2 filled CF composites is very smooth, and the pulling-out and exposure of fiber are invisible [Fig. 8(b,c)]. This indicates that graphite and MoS_2 particles can increase the interfacial bonding between carbon fiber and phenolic

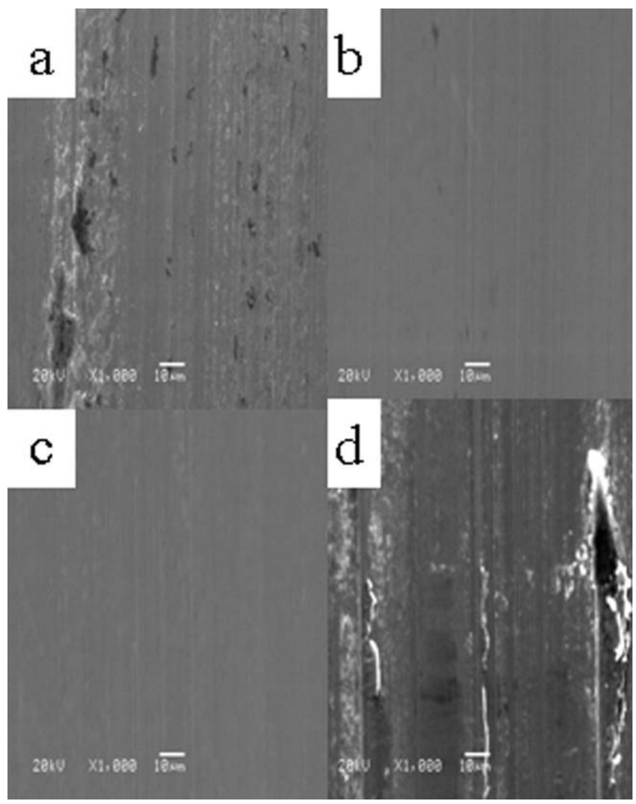

Figure 9 SEM morphologies of the transfer film (200 N, 0.431 m/s). (a) Pure CFC; (b) Gr/CFC; (c) MoS_2/CFC; (d) PTFE/CFC.

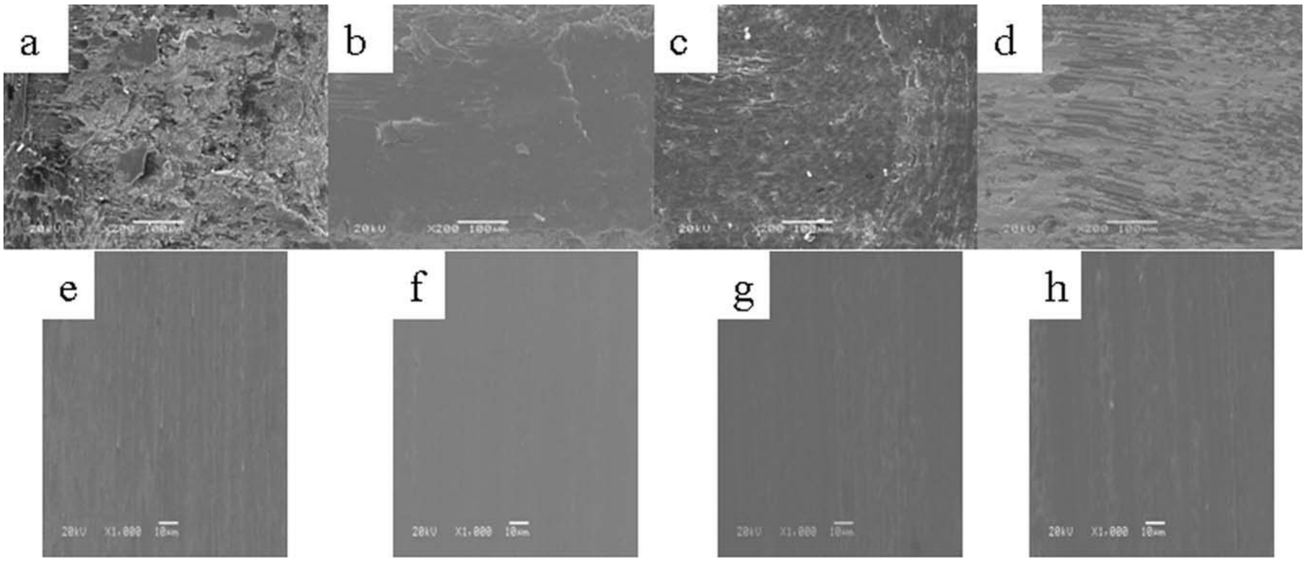

Figure 10 SEM morphologies of worn surface and transfer film of the CF composites at 500 N and 0.431 m/s. (a) Pure CFC; (b) Gr/CFC; (c) MoS_2/CFC; (d) PTFE/CFC; (e) transfer film of (a); (f) transfer film of (b); (g) transfer film of (c); (h) transfer film of (d).

matrix, and hence to improve the tribological properties of the composites. However, the worn surface of 10% PTFE filled CF composites is rough and shows signs of carbon fiber pulling-out [Fig. 8(d)], which correspond to its worst tribological properties.

The SEM morphologies of the transfer film of the CF composites sliding against GCr15 steel at a sliding speed of 0.431 m/s and 200 N are shown in Figure 9. It can be seen that the transfer film of the unfilled CF composites appears to be thick, rough, ununiform [Fig. 9(a)]. Signs of scuffing and lots of wear debris are obviously observed on the counterpart, which correspond to the poor tribological properties. However, the transfer film of 15% graphite and MoS_2 filled CF composites is relatively thin, uniform, and continuous [Fig. 9(b,c)], and the scuffing signs abated, which conformed to the significantly improved tribological behavior. However, The transfer film of 10% PTFE filled CF composites is ununiform and shows obvious signs of scuffing, and lots of wear debris appear on the counterpart [Fig. 9(d)]. This indicated that 10% PTFE filled CF

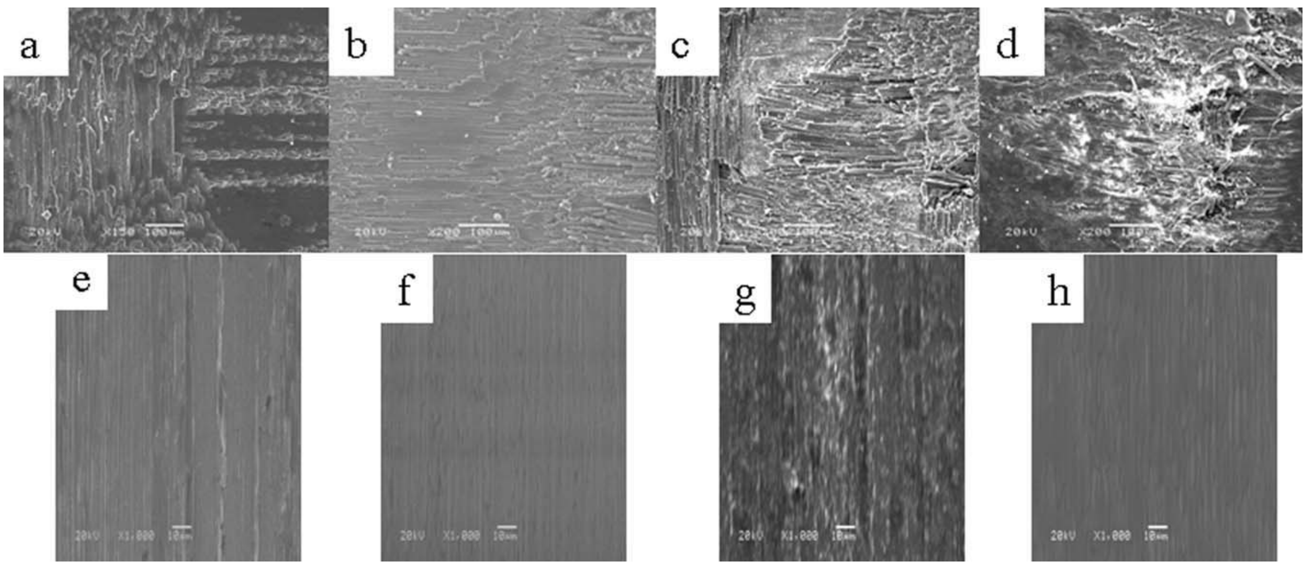

Figure 11 SEM morphologies of worn surface and transfer film of graphite and CNTS filled CF composites at 200 N and 0.862 m/s. (a) Pure CFC; (b) Gr/CFC; (c) MoS_2/CFC; (d) PTFE/CFC; (e) transfer film of (a); (f) transfer film of (b); (g) transfer film of (c); (h) transfer film of (d).

composites experienced severe abrasive wear, which resulted in the worst tribological behavior.

The worn surfaces of the CF composites sliding at 500 N and 0.431 m/s are shown in Figure 10. The pulling-out and of cutting phenomena of carbon fibers abate, moreover, a few wear debris are observed on the worn surface and most wear debris are crushed into the worn surface [Fig. 10(a)]. The transfer film is thick but continuous [Fig. 10(e)]. The worn surfaces of graphite and MoS_2 filled CF composites are smooth and fiber pulling-out phenomena is invisible [Fig. 10(b,c)]. Moreover, there exists a more compacted wear debris layer on the worn surface, thus prevent the polymer composites from the cutting of the counterpart. The transfer film [Fig. 10(f,g)] became thinner, more coherent, and uniform. With the formation of a more uniform and coherent transfer film, subsequent sliding occurred between the surface of the CF composites and the transfer film, a decrease in the friction coefficient and wear rate is inevitable. Under high load, the worn surface of PTFE filled CF composites also becomes smooth, and the fiber are strongly bonded with polymer matrix [Fig. 10(d)]. There is no signs of fiber pulling out and cutting phenomena. The transfer film is thick but continuous and few wear debris are observed on the counterpart [Fig. 10(h)], which confirmed to the improved tribological properties. The worn surfaces and transfer film of the CF composites sliding at 200 N and 0.862 m/s are shown in Figure 11. It can be seen the phenolic matrix of the unfilled and graphite filled CFC experienced molten phenomena and entered the transfer period from visoelastic state to viscous state [Fig. 11(a,b)]. Meanwhile, the worn surfaces became smoother, which were in respondence to their better anti-wear abilities sliding under high sliding speed. On the contrary, the worn surfaces of the CFC filled with MoS_2 and PTFE were rougher [Fig. 11(c,d)]. Carbon fibers can easily fell out from the matrix and ruptured without the support and protection of the phenolic matrix. The transfer film of the pure and graphite and PTFE filled CFC [Fig. 11(e,f, and h)] are rough, thick and ununiform, and shows signs of scuffing phenomen. As for MoS_2 filled carbon fabric composite, there exists many wear debris on the counterpart steel ring, the transfer film [Fig. 11(g)] is also thick, rough, and ununiform. The worse transfer film, sliding under high sliding speed, correspond to their worse tribological behavior compared with that sliding under low sliding speed.

CONCLUSIONS

A systematic investigation on the tribological properties of graphite, MoS_2, and PTFE filled carbon fabric reinforced phenolic composites was carried out in this work. Based on the results in the present study, the following conclusions can be made:

1. An appropriate content of graphite and MoS_2 can improve the tribological properties of CF composites, greatly. However, PTFE as fillers is harmful to the improvement of the tribological properties of CF composites. For best combination of friction coefficient and wear rate, the optimum content of graphite and MoS_2 is about 15 wt % and 25 wt %, respectively.
2. The differences in the friction and wear properties of CF composites are closely related with the sliding conditions such as load and sliding speed. Research results show that the CF composites exhibit better tribological properties under higher load and show worse tribological properties under higher sliding speed.

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