

Tribological behaviors of carbon series additions reinforced CF/PTFE composites at high speed

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ABSTRACT: The tribological, mechanical, and thermal properties of carbon series additions reinforced CF/PTFE composites at high speed were investigated. In this work, carbon fiber (CF) filled polytetrafluoroethylene (PTFE) composites, which have excellent tribological properties under normal sliding speed (1.4 m/s), were filled with some carbon materials [graphene (GE), carbon nanotubes (CNTs) and graphite (Gr)] respectively to investigate the tribological properties of CF/PTFE composites at high sliding speed (2.1 and 2.5 m/s). The results reveal that the carbon series additions can improve the friction and anti-wear performances of CF/PTFE, and GE is the most effective filler. The wear rate of 0.8 wt % GE/CF/PTFE was decreased by 50 – 55%, 55 – 60%, 40 – 45% at 1.4, 2.1, and 2.5 m/s compared with CF/PTFE. SEM study shows GE could be helpful to form smooth and continuous transfer film on the surface of counterparts. Meanwhile, GE can improve its tensile strength and elastic modulus obviously. Thin layer structure of GE could enhance the thermal conductivity, which can be helpful to dissipate heat of CF/PTFE composites wear surface. © 2016 Wiley Periodicals, Inc. *J. Appl. Polym. Sci.* **2016**, *133*, 43236.

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INTRODUCTION

Miniaturization has become the main development direction for the high-tech mechanical equipments. However, the resulting high speed needs higher requirements for the thermal tolerance, friction and anti-wear performances of the dynamic sealing elements.¹ Carbon fiber (CF) filled polytetrafluoroethylene (PTFE) composites are reckoned as a class of advanced materials used in bearing and seal applications under normal sliding speed due to their superior properties, such as excellent wear resistance, high creep resistance and compressive strength.² However, the increasing temperature during wear, especially at high sliding speed, can affect the structures and properties of polymer matrices, due to the nature of their viscoelasticity.³ Under higher speed, the efficiency of carbon fiber reinforcement is not distinct due to the serious softening of PTFE in the CF-free region and non-continuous transfer film.⁴

Carbon series fillers, such as graphite (Gr) and carbon nanotubes (CNTs), were widely used in polymer based composites to improve the tribological properties. Carbon atoms can bind through different covalent bonds to form a large family of car-

bon allotropes with fascinating properties.⁵ Gr has special features of very high thermal and thermo-oxidative stability, specific strength, thermal conductivity, and self-lubricity, and thus can be an ideal choice for tribo-composites.^{6,7} CNTs are mechanically strong and have a high aspect ratio, which are expected to improve the tribological properties of PTFE-based composites significantly.⁸ Recently, the use of graphene (GE) and graphene oxide (GO) has been regarded as the effective fillers to get relatively high thermal conductivity at the low loading, and thus the issues associated with the density and mechanical properties can be minimized.^{9,10}

GE is a two dimensional sheet with nano-meter scale thickness.¹¹ Its features, for instance, good thermal stability,¹² low shear strength,¹³ and high intrinsic strength, make it have the potential to improve wear resistance of polymer composites and minimize the thermal effect generated under higher speed. In addition, its nano-meter scale layer structure makes it easy to enter the contact surface, avoiding the direct contact of these two rough sliding surfaces. Meanwhile, a plenty of sp² hybridized carbons exist on the GE basal plane, which are conducive to the storage and dissipation of frictional heat. Therefore, GE

can improve the tribological properties of the CF/PTFE composites. Recently, GE has been concerned on the atomic-scale and macro-scale friction behaviors by a lot of scientific researchers.^{14,15} There are several main polymer matrix using GE as nanometer packing, including epoxy resin,¹⁶ polyimide (PI),¹⁷ polystyrene (PS),¹⁸ polyurethane (PU),¹⁹ nylon 12,²⁰ high-density polyethylene (HDPE),³ etc. However, to our knowledge, there are few studies about the effect of carbon materials (such as CNTs, GE) on the tribological properties of CF/PTFE composites at high speed.

The purpose of this work is to study the friction and wear properties of the CF/PTFE composites filled with GE, CNTs, and Gr at high sliding speed (1.4, 2.1, and 2.5 m/s). The mechanical and thermal performances of the carbon series additions reinforced CF/PTFE composites were also investigated.

EXPERIMENTAL

Materials

In the experiments, the PTFE powders with average particle size of 25 μm were supplied by DuPont (7A-J, commercial product). The carbon fibers with an average diameter and length of 5–25 μm and 10–300 μm , respectively were from Dalian Branch of carbon fiber Co. GE with an average thickness of 1–5 nm and diameter of 1–10 μm was synthesized by the authors.²¹ High-purity (99.85%) Gr powders (particle size <30 μm) were provided by Sinopharm Chemical Reagent, China. CNTs were commercially available from Baytubes C150P (purity: >97%, outer diameter distribution: 10–40 nm, length distribution: 5–15 μm).

Preparation of CF/PTFE Composites

All the materials were dried at 120 °C for 12 h before use. From our previous work, the 15 wt % CF could reduce the friction coefficient and wear rate of PTFE composites effectively.² So the mass fraction of CF in PTFE blend was fixed at 15 wt %. The preparation process was described as follows: at first, PTFE, 15% CF and carbon series fillers with various mass fractions (Gr: 2, 5, 10, 15 wt %; GE and CNTs: 0.2, 0.5, 0.8, 1.1 wt %, respectively) were prepared. Then the carbon series fillers were mixed with CF and PTFE powders at the selected mass fractions in the ethanol with the assistance of high energy mechanical and ultrasonic stirring, followed by drying, and finally the CF/PTFE composites were molded into the slab specimens by compression molding under 70 MPa for 5 min. After that, the composite blocks were sintered at 380 °C for 4 h, then cooled at a rate of 1 °C/min to room temperature. To do friction and wear tests, the block was cut to a shape that was 26 mm in external diameter, 22 mm in inner diameter and 2.5–3 mm in shoulder height [Figure 1(b)]. For mechanical properties tests, the tensile specimens was cut to a shape that is 115 \pm 1 mm in the initial distance between the clamp, 10.0 \pm 0.2 mm in the width of the narrow section and 4.0 \pm 0.2 mm in the preferred thickness.

Test Details

Wear behavior tests were conducted on an MPX-2000 (ring-on-ring model) friction and wear Testing Machine (Xuan hua Testing Factory, China). The contact schematic diagram of frictional parts is shown in Figure 1. The counterpart material was

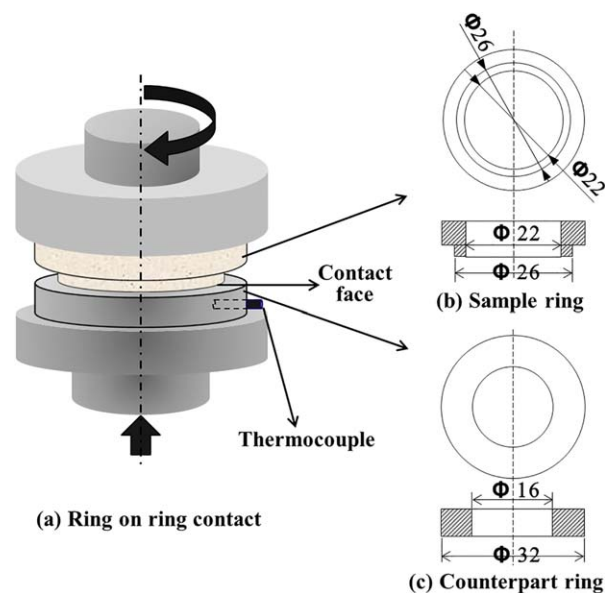


Figure 1. Configuration of the friction pairs: (a) Ring on ring contact, (b) sample ring, (c) counterpart ring. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

AISI1045 Steel. Test was performed under dry friction and ambient conditions (temperature: 25 °C, humidity: 50 \pm 5%) at sliding speed of 1.4, 2.1, or 2.5 m/s and normal load of 200 N. The test duration was 120 min. The friction force was measured with a torque shaft provided with strain gauges, and the coefficient of friction was calculated from the friction force. Before each test, the surfaces of each specimen and counterpart ring (32 mm in external diameter and 16 mm in inner diameter and 8 mm in thickness) were polished with 1200- and 2000-grit abrasive paper to a surface roughness of 0.2–0.4 μm and were cleaned with alcohol. The specific wear rate [W (cm^3/Nm)] was calculated with the following equation:

$$W = \frac{\Delta m}{\rho \cdot N \cdot L} \quad (1)$$

Where Δm is the specimen's mass loss after test (g), ρ is the density of the composite (g/cm^3), N is the normal load (N), and L is the sliding distance (m).²² Three replicate tests were carried out and the average of the three replicates was reported.

Morphologies of raw materials, the fractured surfaces of the CF/PTFE composites, the transfer film and the CF/PTFE composites' worn surfaces after wear tests were observed using scanning electronic microscope (SEM, QUANTA-200).

Tensile tests were carried out on a Universal Tester (CMT-4254, Sans Co., China) at room temperature at a beam rate of 50 mm/min, according to Chinese National Standards GB/T 1040.2-2006. The data reported here is the average value of five tests.

Hardness measurements were carried out on 3 mm thick specimens as according to Chinese National Standard GB/T 2411-2008 on a shore D scale. Indentations were made at several locations for each specimen and the average hardness value was calculated. The indentation load for each measurement was 50 N and hold time was 15 s.

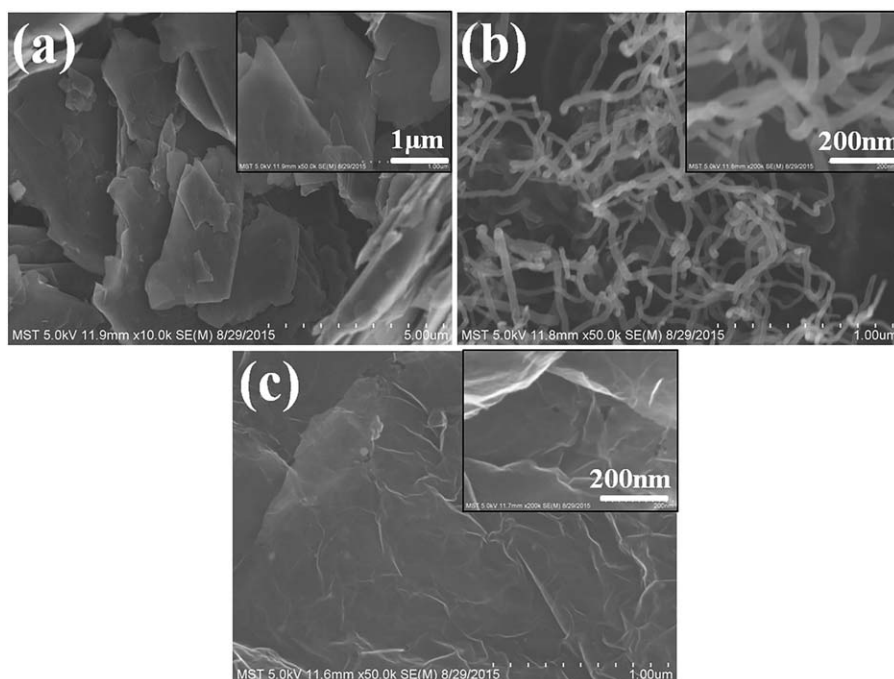


Figure 2. SEM micrographs of Gr, CNTs and GE: (a) Gr; (b) CNTs; (c) GE.

To study the effect of different fillers on thermal stability of CF/PTFE composites, thermogravimetric (TGA) analyses were performed by a NETZSCH TG209F3 analyzer from 35 to 800 °C under air atmosphere at a heating rate of 10 °C/min.

The effects of different filler type on the melting points of CF/PTFE composites were evaluated using a DSC instrument (Diamond, Perkin-Elmer Co.). The weights of all samples were about 18 mg, and these samples were heated to 450 °C at a heating rate of the 10 °C/min under a dry nitrogen flow.

The thermal conductivity of CF/PTFE composites at room temperature was measured by the axial flow method run on the SKW-5 digital display to control temperature measuring chronograph apparatus.

RESULTS AND DISCUSSION

Morphologies of Carbon Series Fillers

Typical SEM images of the Gr, CNTs and GE are shown in Figure 2. The typical morphologies of CNTs and Gr are shown in Figure 2(a,b). Figure 2(c) depicts well-dispersed layered structures of GE with stack wrinkles and folds. This structure has a striking effect on improving the tribological properties.²³

Microstructure of the CF/PTFE Composites

To investigate the dispersion state of carbon series fillers in the CF/PTFE matrix, the fractured surfaces of CF/PTFE composites with various fillers were observed on a scanning electron microscope (SEM) in Figure 3. The fractured surface of GE/CF/PTFE composite presented in Figure 3(b) indicates that the GE exists in the specimen and well disperses in the PTFE matrix. Moreover, according to the investigation of Kandapur *et al.*,²⁴ the graphene can greatly improve the tribological properties due to the reinforcement effect of its high mechanical strength. CF, Gr flakes, and CNTs are clearly noticed from the fracture surface of

the CF/PTFE composite [Figure 3(c,d)]. In addition, high resolution SEM image [inset in Figure 3(d)] also shows CNTs well disperse at the interface layer and contact with PTFE closely. Moreover, CNTs are also embedded with polymer matrix in both the composites well. A large number of reacting points existed on the CNTs large specific surfaces could favor better bonding effect.²⁵ At last, the adhesion of PTFE to the carbon fibers could improve dramatically, and thus can enhance fiber/matrix interfacial strength.²⁶

Tribological Properties of CF/PTFE Composites

Effect of Filler Type and Content on the Friction and Wear Properties of CF/PTFE Composites. To determine the optimized mass fractions of GE, CNTs and Gr, the effects of GE, CNTs, and Gr' contents on the tribological properties of CF/PTFE composites were investigated systematically (Figure 4).

Figure 4 compares the effect of filler type and content on the friction and wear of the CF/PTFE composites at 2.1 m/s and 200 N under dry sliding conditions. The friction coefficients of GE/CF/PTFE decrease with increasing the content of GE from the Figure 4(a). While the friction coefficients of CNTs/CF/PTFE increase as the CNTs contents increase. From the Figure 4(a,b), it can be seen that the trend of the friction coefficient is the same as that of the counterpart surface temperature. As we know, the temperature variation of the counterpart surface is influenced by friction-induced heat. The sliding of individual GE planes within few-layered GE platelets might further enhance the lubrication effect and reduce friction coefficient.²⁴ In addition, the increase of friction coefficient of CNTs/CF/PTFE may result from the agglomeration of CNTs in composite matrix with the high CNTs content.²⁷ For Gr/CF/PTFE, as the Gr content increases, the friction coefficient and counterpart

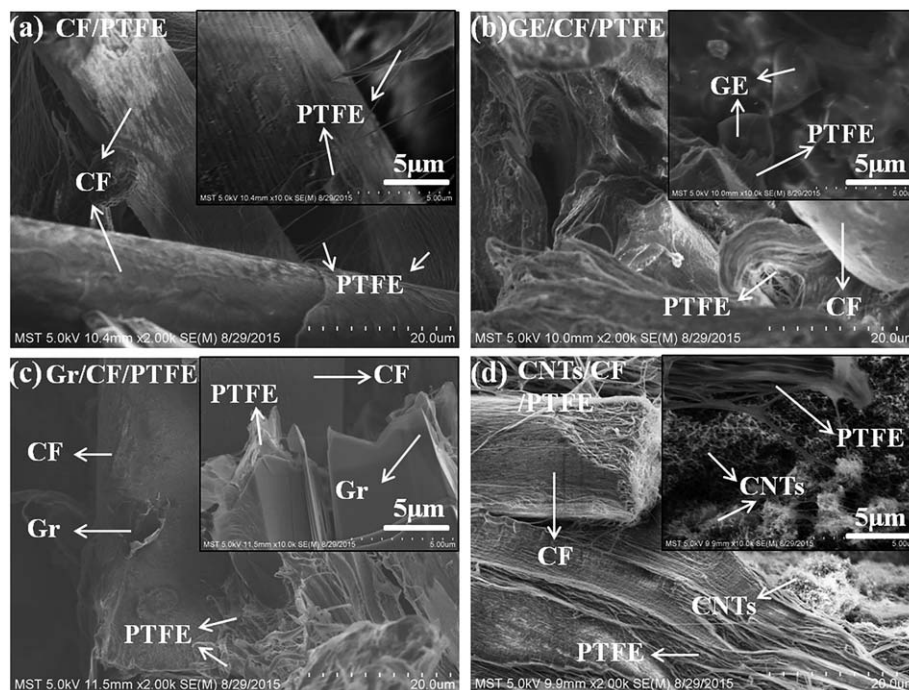


Figure 3. SEM images of the CF/PTFE composites' fracture surface (a) CF/PTFE, (b) GE/CF/PTFE, (c) Gr/CF/PTFE, (d) CNTs/CF/PTFE.

surface temperature increased at first, then decrease and finally increase from the Figure 4(a,b).

Figure 4(c) shows the wear rates of CF/PTFE composites filled with different loadings of GE, CNTs and Gr under 2.1 m/s, 200 N. It is obvious that the anti-wear properties of GE/CF/PTFE and CNTs/CF/PTFE are much better than that of Gr/CF/PTFE. During the sliding process, nanoscale carbonous materials embed into the friction surface, which decrease the shear force and improve the load capacity, and make the transfer film strengthened and recoverable.²⁸ Hence, it may reduce the probability of the fatigue and abrasive wear of composite materials during the friction process, and improve the anti-wear properties. However, the agglomeration of nanoscale carbonous materials will occur at the high loading, which will form a weak performance zone and decrease the mechanical properties. The strengthening and toughening effects of nanoscale carbonous materials decrease, the wear mechanisms of the composites may change. Finally, the CF/PTFE composites filled with 0.8 wt % GE, 0.5 wt % CNTs, and 2 wt % Gr have the best tribological properties.

Effect of Speed on the Friction and Wear Properties of CF/PTFE Composites. Figure 5(a,b) shows the friction coefficient and counterpart surface temperature of CF/PTFE composites filled with different carbonous particles under various speeds. From the Figure 5(a), it can be seen that the friction coefficient of CF/PTFE composites decreases with increasing the sliding speed. Generally, higher sliding speed is beneficial for formation of transfer film between the sliding surfaces, which can help reduce the friction coefficient.^{29,30} Moreover, it is shown that the friction coefficient of GE/CF/PTFE composites is lowest among CF/PTFE composites under the different speeds. It may be attributed to the ultrathin thickness of GE and the homogeneous dispersion in the PTFE, allowing a flexible mobilization on the contact surface and a continuous lubrication for the PTFE matrix.³¹ In addition, for CF/PTFE and GE/CF/PTFE composites, the counterpart surface temperatures decrease by 5% and 3% respectively, when the sliding speed changes from 2.1 to 2.5 m/s [Figure 5(b)]. The transfer film could form more easily on the frictional surfaces with increasing the sliding speed, which will lead to the decrease of surface temperature at

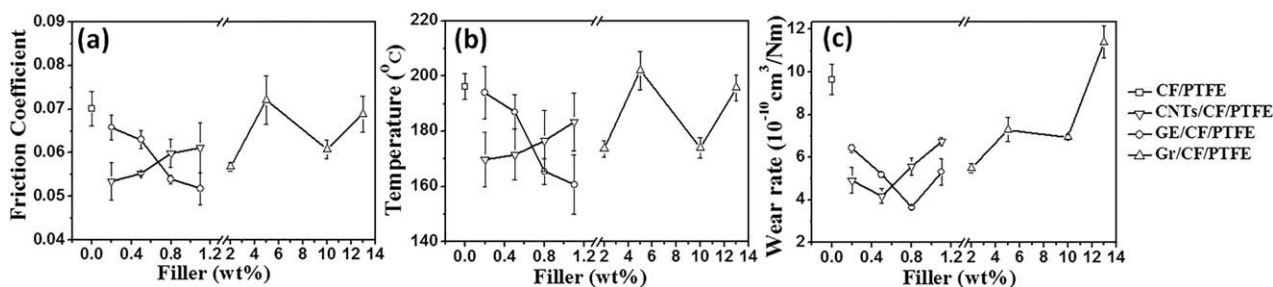


Figure 4. The effect of filler type and content on the friction and wear of the CF/PTFE composites (200 N, 2.1 m/s): (a) friction coefficient; (b) counterpart surface temperature; (c) wear rate.

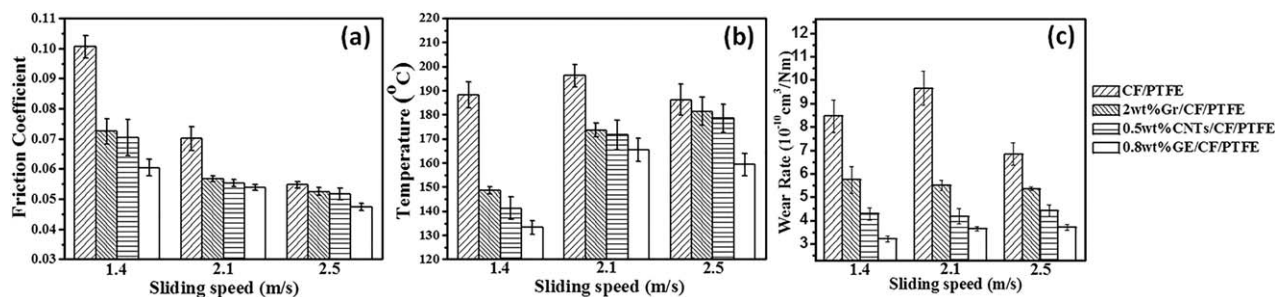


Figure 5. The effect of speed and filler type on the friction and wear of the CF/PTFE composites (200 N, 1.4, 2.1, 2.5 m/s): (a) friction coefficient; (b) counterpart surface temperature; (c) wear rate.

the rubbing surfaces. The sliding of individual GE planes within few-layered GE platelets might further enhance the lubrication effect and reduce friction surface temperature.²⁴ However, for the Gr/CF/PTFE and CNTs/CF/PTFE composites, when sliding speed changes from 2.1 to 2.5 m/s, the counterpart surface temperature of the Gr/CF/PTFE and CNTs/CF/PTFE composites increases. It may be due to more friction heat generated and accumulated on the sliding surface, which will damage the formation of transfer film.

Figure 5(c) shows the wear rates of CF/PTFE composites filled with CNTs, GE and Gr at different sliding speeds. It can be concluded that Gr, CNTs, and GE significantly reduce the wear rate under different speeds. From the independent effect of these three fillers on the friction and wear properties of CF/PTFE composites, GE is most effective, then is CNTs, and Gr is the least. The wear rate of 0.8 wt % GE/CF/PTFE is about decrease by 50%, 55%, 45% under 1.4, 2.1, 2.5 m/s compare with CF/PTFE. It may be due to high aspect ratio of GE and well-dispersed GE in PTFE, which provide a large surface area available for interaction between the polymer molecules and GE, and facilitate good load transfer for the GE network. In addition, with increasing the sliding speed, the wear rates of the Gr/CF/PTFE, CNTs/CF/PTFE, and GE/CF/PTFE composites increase. This result may be attributed to the increasing interface temperature caused by higher sliding speed.³² Due to the viscoelastic nature of polymer matrices, the internal structure and overall performance of a polymer was highly susceptible to temperature. The temperature rise during a high speed wear process can lead to break and reform the secondary bonds in the polymer matrix, and decrease wear property of the composites.³² However, for CF/PTFE composites, the wear rate decreases by 29%, when the sliding speed is changed from 2.1 to 2.5 m/s. It may be caused by the enhanced worn surfaces temperature and micro-melting under the higher sliding speed, which will be helpful to form a low shear force transfer films on the metal counterpart ring and protect the composites from direct contacting with the steel.

SEM and the Wear Mechanism Studies. To find further information regarding the effect of different speed on the friction and wear properties of CF/PTFE composites, the worn surfaces and transfer films of CF/PTFE composites filled with GE, CNTs and Gr are studied by SEM, as shown in Figures 6 and 7.

At the relatively low sliding speed (1.4 m/s), the worn surfaces of the CNTs/CF/PTFE and Gr/CF/PTFE composites show obvious tearing damage [Figure 6(c,d)]. Some broken, pulled-out CF and leaving several pores are observed on the worn surface. In addition, severe wear tracks and surface damages are seen on the counterpart surface in Figure 7(c,d). The detached CF and several wear debris are visible on the worn surface of CF/PTFE and GE/CF/PTFE composites [Figure 6(a,b)], and the transfer films also are discontinuous and nonuniform [Figure 7(a,b)].

When the relatively high sliding speed (2.1 or 2.5 m/s), the worn surfaces of CF/PTFE composite are characterized by some broken wear debris and few fiber pulling-out [Figure 6(e,i)] and the transfer films are rough, nonuniform [Figure 7(e,i)], which correspond to its poor tribological properties. The worn surfaces of CNTs/CF/PTFE composite have also some slight broken and wear debris [Figure 6(g,k)] and the transfer films show signs of scuffing [Figure 7(g,k)]. Compared with other CF/PTFE composites, the worn surface of Gr/CF/PTFE composite are characterized by large scale serious plastic deformation, tearing, and peeling [Figure 6(h,l)]. Meanwhile, the corresponding transfer films are discontinuous and nonuniform in Figure 7(h,l), which may be responsible for the highest friction coefficient of Gr/CF/PTFE. However, the worn surfaces of GE/CF/PTFE composite [Figure 6(f,j)] are smooth and the transfer films are continuous and uniform [Figure 7(f,j)], which could lead to the lowest wear rate of GE/CF/PTFE composite. Besides, many embedded carbon fibers are distributed and protruded on the worn surface of GE/CF/PTFE composite, which can effectively bear major normal and tangential stresses on the contact surface. Moreover, the continuous and uniform transfer films of GE/CF/PTFE composites result in better tribological properties at higher sliding speed.³³ Hence, the addition of GE into CF/PTFE composites makes the sliding surface suffer less plowing damage during the sliding process. GE and CF worked synergistically to reinforce PTFE composite and ameliorate the interfacial combination of PTFE matrix, which explain why the GE/CF/PTFE composite has excellent tribological properties under higher sliding speed. GE with high toughness and intensity could prevent the crystalline band of PTFE in GE/PTFE blend from being drawn out during the friction process, and CF with high strength and modulus as well as good wear resistance could help to increase the speed-carrying capacity of PTFE matrix.³⁴

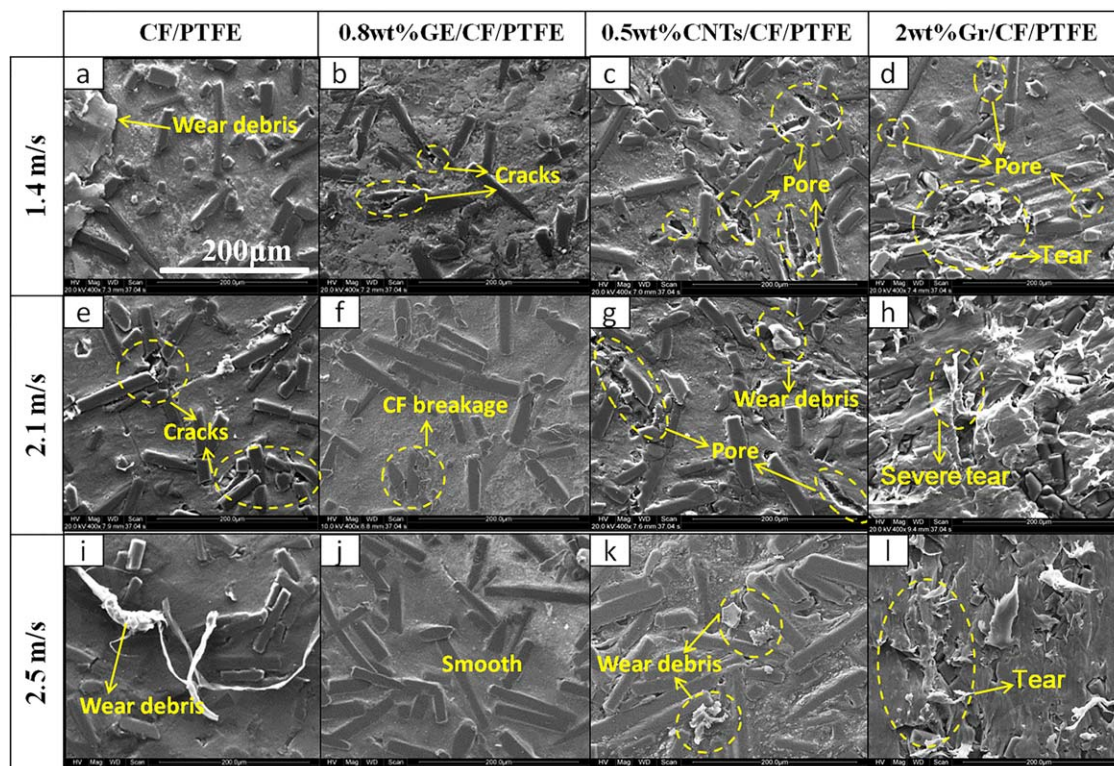


Figure 6. SEM morphologies of the worn surface under different sliding speed, 200 N: CF/PTFE under 1.4 m/s (a), 2.1 m/s (e), 2.5 m/s (i); 0.8 wt % GE/CF/PTFE under 1.4 m/s (b), 2.1 m/s (f), 2.5 m/s (j); 0.5 wt % CNTs/CF/PTFE under 1.4 m/s (c), 2.1 m/s (g), 2.5 m/s (k); 2 wt % Gr/CF/PTFE under 1.4 m/s (d), 2.1 m/s (h), 2.5 m/s (l) (400 \times). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

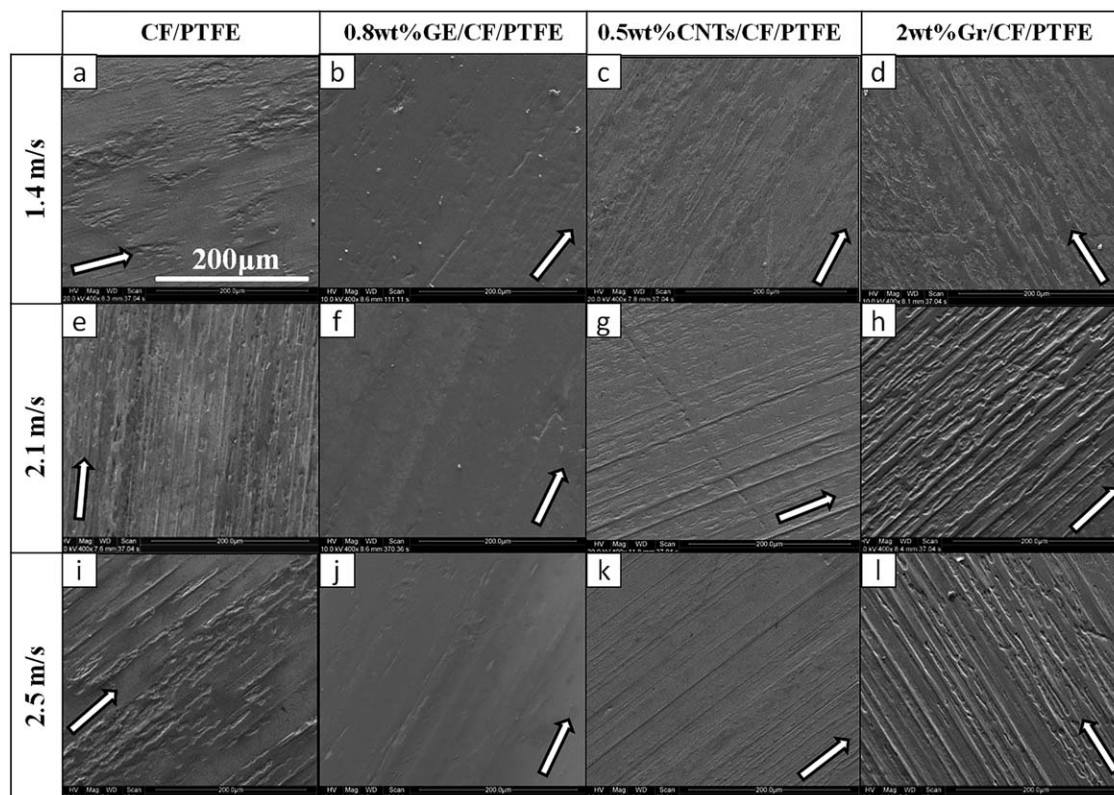


Figure 7. SEM morphology of the counterpart surface under different sliding speed, 200 N: CF/PTFE under 1.4 m/s (a), 2.1 m/s (e), 2.5 m/s (i); 0.8 wt % GE/CF/PTFE under 1.4 m/s (b), 2.1 m/s (f), 2.5 m/s (j); 0.5 wt % CNTs/CF/PTFE under 1.4 m/s (c), 2.1 m/s (g), 2.5 m/s (k); 2 wt % Gr/CF/PTFE under 1.4 m/s (d), 2.1 m/s (h), 2.5 m/s (l); Arrows indicate sliding direction (400 \times).

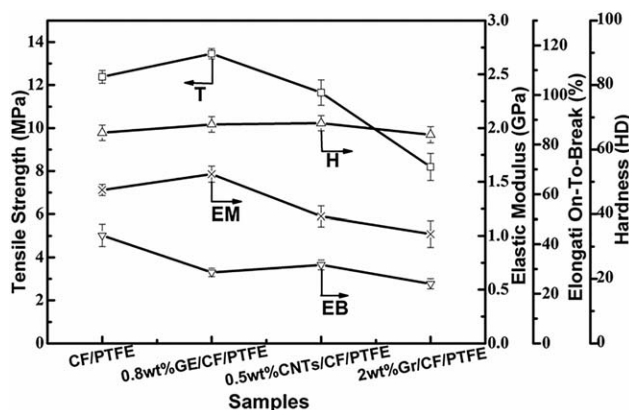


Figure 8. Tensile properties and hardness of CF/PTFE composites contain different carbonous fillers.

Mechanical Properties of CF/PTFE Composites

The filler types may have a great influence on the mechanical properties of the composites. The tensile properties and hardness of CF/PTFE composites with different carbonous fillers are shown in Figure 8. Among all the CF/PTFE composites, the tensile properties of 0.8 wt % GE/CF/PTFE are best. The tensile strength and elastic modulus of the 0.8 wt % GE/CF/PTFE are improved by 13% and 8% compared with the CF/PTFE composites. For filler reinforced composites, the more excellent mechanical performances could also have the better anti-wear properties. Liu *et al.*³⁵ found that the composite with the higher tensile strength and hardness exhibits the lower friction coefficient and wear rate. The investigation of Liu *et al.* together with our results proofed the fact that the mechanical property and tribological property of composites are closely related to each other. It can be seen from the Figure 8 that the elongation at break of the GE composites is about lower than the CF/PTFE composites. The decreased ductility may be caused by stress concentration in the vicinity of the filler. This typically occurs when tough fillers are merged into a brittle matrix.^{36–38} In addition, agglomeration of GE can lead to defects in the matrix that can act as seed points for crack initiation and premature fracture.³⁸ Besides, from the hardness study, it can be found that all the CF/PTFE composites have similar hardness despite of the filler types.

Table I. Data of Thermal Analysis of the Different CF/PTFE Composites

Samples	CF/PTFE	0.8 wt % GE/CF/PTFE	0.5 wt % CNTs/CF/PTFE	2 wt % Gr/CF/PTFE
W_{T180} (%) ^a	99.41	99.42	99.16	99.03
W_{T200} (%) ^b	99.38	99.27	98.99	98.86

^a Weight loss at 180 °C.

^b Weight loss at 200 °C.

Thermal Properties of CF/PTFE Composites

The heat generated by friction during the sliding is potential threat to the polymer. The contact temperature will increase at the high PV value, especially at high sliding velocity, which will affect the structures and properties of polymer matrices severely. Therefore, to meet the demand for good wear performance stability and long service life, polymer composites with high thermal stability is necessary.

Currently, the highest temperature limit of oil-free lubricated piston rings of PTFE composites is 180–200 °C under different pressure conditions. Because of softening and unacceptable oxidation, PTFE composites could not be used for the sliding condition at temperatures higher than about 220 °C.^{39–41} According to the above factors, the 180 °C and 200 °C weight loss are chosen to evaluate the thermal properties of the CF/PTFE composites. Figure 9(a) shows the TGA curves of all the CF/PTFE composites. The 180 °C weight loss (W_{T180}) and the 200 °C weight loss (W_{T200}) are listed in Table I. It is found that the 0.8 wt % GE/CF/PTFE composites show the lowest weight loss compared with other composites at the 180 °C. Because GE layers prevent small molecules moving into the PTFE during the period of thermal decomposition, when the movement of main molecular chain has been hampered, PTFE molecular chain needs more fracture energy in the heating process.⁴² Therefore, the thermal stability of 0.8 wt % GE/CF/PTFE composites is slightly improved. However, the addition of carbon fillers actually deteriorates the thermal stability of the original composite, although the impact is very small. Figure 9(b) shows the DSC curves of the CF/PTFE composites measured for the first heating cycle up to 450 °C. For CF/PTFE composites filled

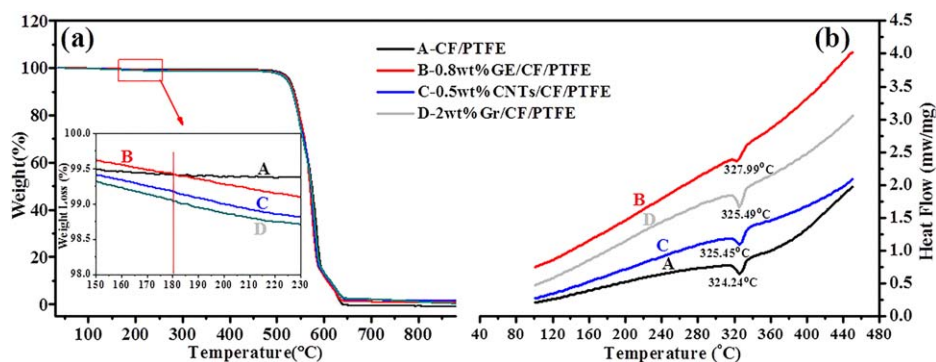


Figure 9. The TGA (a) and DSC (b) curves of CF/PTFE composites and CF/PTFE composites containing different filler. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

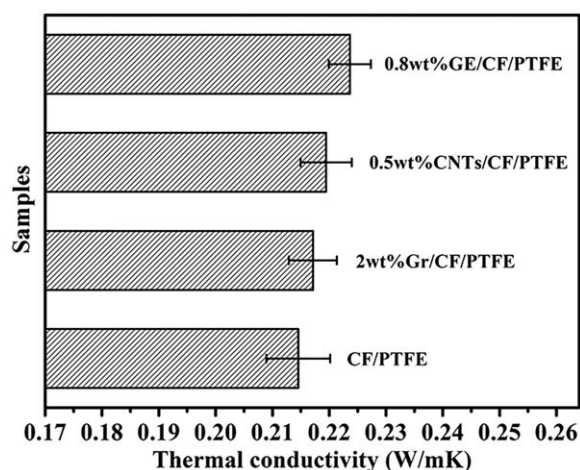


Figure 10. Thermal conductivity of CF/PTFE composites filled with different fillers at 180 °C.

with different fillers, the melting points T_m are 324.24 °C (CF/PTFE composites), 325.45 °C (CNTs), 325.49 °C (Gr), and 327.99 °C (GE), respectively.⁴³ Thus, the introduction of the graphene material into the polymer increases the CF/PTFE composites melting temperature by almost 3 °C. However, it is hard to see obvious changes in T_m in the CF/PTFE composites, which indicate that the carbon series fillers couldn't lower the melting point of CF/PTFE composites.

Figure 10 shows the effect of filler types on thermal conductivity of CF/PTFE composites at 180 °C. It can be observed that the thermal conductivity is improved owing to the addition of different fillers, and the thermal conductivity of 0.8 wt % GE/CF/PTFE composites is highest. This result indicates that the 0.8 wt % GE/CF/PTFE composite is more prone to transfer and dissipate friction heat. This could be attributed to the two-dimensional GE framework of high thermal conductivity in the CF/PTFE composites. However, the increase in thermal conductivity of the composites is far lower than expected when considering the ultra-high in-plane thermal conductivity of GE.⁴⁴

CONCLUSIONS

CF/PTFE composites were filled with GE, CNTs, and Gr respectively to improve their tribological properties at higher sliding speed (2.1 and 2.5 m/s). The mechanical properties, hardness, thermal stability, and thermal conductivity of the CF/PTFE composites were also investigated. The conclusions can be drawn as follows:

1. Gr, CNTs, and GE could improve the wear resistance of CF/PTFE composites by different loadings (2.1 m/s, 200 N). Besides, among all the CF/PTFE composites, the tribological properties with 0.8 wt % GE, 0.5 wt % CNTs, and 2 wt % Gr are best.
2. GE/CF/PTFE composites has superior friction and anti-wear performances than CNTs/CF/PTFE and Gr/CF/PTFE. The wear rate of CF/PTFE composites could be decreased by 55 – 60%, 40 – 45% with addition of 0.8 wt % GE at higher speed (2.1 and 2.5 m/s), respectively.

3. SEM study shows GE can be helpful to form smooth and continuous transfer film on the counterpart surfaces, which lead to the lowest wear rate of GE/CF/PTFE composite. Moreover, the SEM images of the composites' fracture surface indicate that GE sheets could be well dispersed in PTFE matrix.
4. The carbon series fillers have little influence on the composites' thermal stability and hardness. However, GE can improve its tensile strength and elastic modulus. Thin layer structure of GE could enhance the thermal conductivity, which can be helpful to dissipate heat of CF/PTFE composites wear surface. This work may open up opportunities to produce high performance GE/polymer nano-composites for the high speed industrial application.

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