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Research on Tribological Behavior of PEEK and Glass Fiber Reinforced PEEK Composite

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Abstract

The tribological behaviors of pure polyetheretherketone (PEEK) and PEEK composites reinforced by 30wt% short glass fibers (GF) were comparatively evaluated on a ball-on-disc configuration at room temperature. The effects of applied load and sliding time on the friction coefficient and wear loss of the GF/PEEK were examined. The mechanical property, morphology and thermal performance of the composite were studied. The results indicated that the friction coefficient and wear loss of the composite increased gradually and tended to be a stable state as the increase of applied load and sliding time. The GF/PEEK has an excellent wear resistance, compared with PEEK. The SEM and EDS indicated that the short glass-fibers were extruded from the composite rather than pulverized into the composite. Compared with that of pure PEEK, the thermal decomposition temperature of GF/PEEK composite had an increase of 75℃. The tensile strength and flexural strength of the composite were increased by 64% and 66%, respectively.

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Keywords: Polyetheretherketone; Short glass fiber; Friction; Wear

1 Introduction

The applications of polymers which are replacing traditional materials are increasing， polymers such as polyetheretherketone (PEEK) and polytetrafluoroethylene (PTFE) are important engineering materials in recent years. PEEK is a popular matrix material for high performance composites due to its high mechanical strength and elastic modules, high melting temperature, chemical inertness, high toughness, easy processing and wear resistance.

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PEEK has also many applications in engineering and medicine because of its high strength and high melting point relative to other polymers, as well as its resistance to chemical and biological action[1,2].

Vast number of investigations related to the tribological behavior of PEEK and its composite has been reported that the PEEK reinforced with some fibers has a beneficial effect on its strength and tribological properties[3, 4].The addition of short fibers that enhance the thermal conductivity are often of great advantage, especially if effects of temperature enhancement in the contact area are to be avoided in order to prevent an increase in the specific wear rate. Since glass fibers have low strength, high flexural modulus and low expansion rate, they are the most common fiber reinforcements of thermoplastics to reduce the expansion rate and increase the flexure of PEEK[5, 6].

M. Sumer and H. Unal have studied the tribological performance of pure PEEK and 30wt% fiber glass reinforced PEEK under dry sliding and water lubricated conditions. The results showed that the friction coefficient and specific wear rates for pure PEEK and GF/PEEK slightly increased with the increase in applied loads. The influence of glass fiber on the friction coefficient and wear loss of the GF/PEEK composite is more pronounced under dry condition[7]. Bijwe and Nidhi have investigated the mechanism of adhesive wear of PEEK reinforced with GF, carbon fibers(CF) and solid lubrificants (PTFE and graphite). According to these authors, the inclusion of 30 wt% carbon fibers benefited the strength properties but not the tribological performance. On the contrary, the solid lubrificants influenced the friction and wear performance of PEEK composites[8]. Hanchi and Eiss have studied the friction and wear of PEEK-CF30(wt%) at elevated temperatures. The reinforcement with carbon fibers increased the mechanical resistance with the temperature increasing. As temperature increased from below to above the glass transition temperature (Tg) of the polymer matrix, the friction and wear performance of the composite slightly decreased [9]. X.X. Chu and Z.X. Wu have investigated the mechanical and thermal expansion properties of glass fibers reinforced PEEK composites at cryogenic temperatures .It was found that a dependence of mechanical properties of glass fibers reinforced PEEK composites on temperature and the thermal expansion coefficient of PEEK matrix was nearly a constant in this temperature region, and it can be significantly decreased by adding glass fibers[10].

In this work, the tribological behavior and the mechanical properties of pure PEEK and PEEK containing 30 wt% short-cutting glass fibers were studied at room temperature. SEM and EDS are used to study the strengthening and toughening mechanisms of GF/PEEK after testing, thermal decomposition of pure and GF/PEEK were also investigated by thermogravimetric analysis.

2 Experimental

2.1 Materials

The pure PEEK and 30wt% short-cutting glass fibers reinforced PEEK composites (GF/PEEK) were supplied by Sino®-rich as injection molded 80×80mm^2 plaques with thickness of 2mm. Test samples of dimensions approximately 20×15×2 mm^3 were cut by a diamond cutter.

2.2 Mechanical Testing

Tensile and flexural test were performed according to the national standards as GB/T 1447-2005 and GB/T 1449-2005 respectively, using JIN DAO AG-1 testing machine at room temperature. The tensile modulus and flexural modulus, tensile strength and flexural strength of the materials were measured at room temperature. Five specimens were tested for each composition to improve the reproducibility. The cross-head speeds are 10 mm/min and 5 mm/min for tensile and flexural testing. The geometries and dimensions of the specimens for the experiments are shown in Fig. 1.

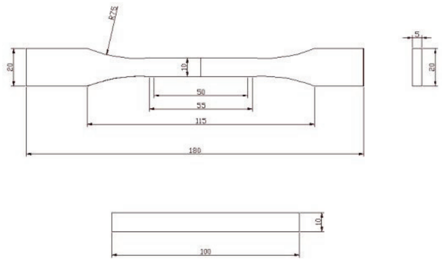

Fig.1.The geometries and dimensions of the specimens for (a) tensile and (b) flexural. Friction and wear tests

Fig. 2(a) shows the ball-on-disc wear test apparatus that was designed and used to study the tribological properties of PEEK composites. During testing, the polymeric samples were supported by a steel support(Fig. 2b). The methodology consist of a stainless steel table which is mounted on a turntable, a variable speed motor which provides the reciprocating motion to the turntable, and the steel ball which is mounted on the spring suspension is pressed against sample with the desirable load which is controlled by the press sensor. Before each test, the polymeric samples and the steel ball were cleaned with acetone. All the tests were performed under dry conditions. The parameters used are shown in Table 1. The friction coefficient was obtained directly through the computer. The wear loss was calculated from the mass difference before and after the tribo-testing by a precision analytical balance. Each test was repeated three times. The close results were considered and their average values were presented.

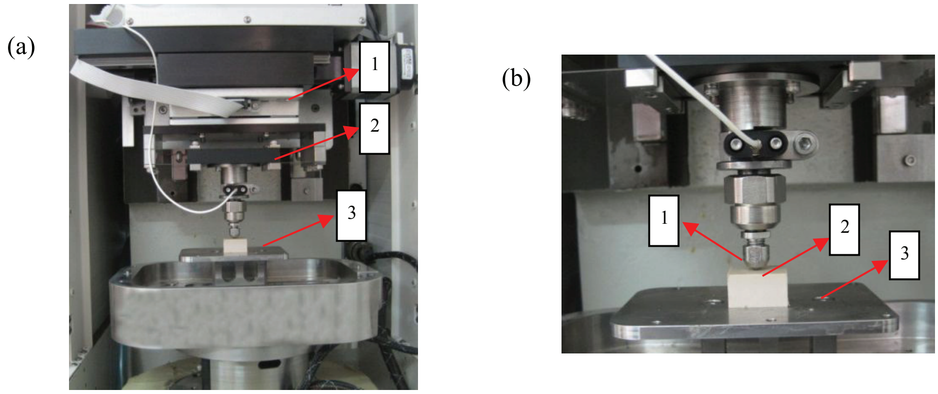

Fig. 2.(a) Experimental set up: ball-on-disc CETR tribo-tester. 1: force sensor; 2: spring suspension; 3: ball-on-disc (b)1:ball;2:sample of polymeric material;3 stainless steel disc.

2.3 Surface morphology characterization

The surface morphologies of pure PEEK and GF/PEEK composites were observed by a Nova NanoSEM 450/650 scanning electron microscope(SEM). Before SEM examination, the fracture surfaces were cleaned with alcohol. A sputtering device from Balzers SCD 050 sputter coater was used to make a conductive coating on the sample surface. An accelerating voltage of 15 kV was used for the investigation. The surface composition of the worn surfaces was determined using EDX which was coupled with SEM.

2.4Thermogravimetric analysis

Thermal decomposition was investigated by thermogravimetric analysis (TGA) in an inert atmosphere using a Mettler Toledo TGA/SDTA 851. Measurements were performed on samples of 10 mg under a nitrogen atmosphere with a heating rate of 10℃/min and flow rate of 50 mL/min.

Table 1 Materials and test conditions

Materials	Parameter				
	Loading stress/N	Time/min	Rate of recurrence/ Hz	Test temperature/℃	Humidity/%
Pure PEEK	100	30	2	18	56
	200	120			
	300	30			
	400	30			
GF/PEEK composites	100	30			
	200	120			
	300	30			
	400	30			

3 Results and Discussion

3.1Mechanical Properties

Table 2 presents the mechanical properties of pure PEEK and GF/PEEK. The tensile strength and tensile modulus values of GF/PEEK were increased by 64% and 75%, respectively. The flexural strength and flexural modules of GF/PEEK were increased by 66% and 140% compared with pure PEEK. It is clear that the reinforcing material of glass fiber strongly affected the mechanical properties of PEEK.

Table 2 The mechanical properties of pure PEEK and GF/PEEK

Sample	Pure PEEK	GF/PEEK
Tensile strength (MPa)	90.3	148.2
Tensile modulus (GPa)	2.8	4.9
Flexural strength (MPa)	139.1	230.7
Flexural modulus (GPa)	3.7	8.9

3.2 Wear loss and friction coefficient

Fig. 3 presents the variation of friction coefficient for pure PEEK and GF/PEEK with the sliding time under the applied load of 200 N. An increase in the friction coefficient is observed with the increase in sliding time. Initially, a sharp increase of friction coefficients indicating the initial running-in period was observed. Then the friction coefficient tended to be stable. The friction coefficient of GF/PEEK was higher than that of pure PEEK throughout the whole test.

Fig.4(a) shows the variation of friction coefficient for pure PEEK and GF/PEEK with the change of applied load. The friction coefficient of PEEK increased steadily with the increase of applied load. The friction coefficient increased by about 60% when the load changed from 200 N to 300 N. The friction coefficient of GF/PEEK decreased initially and then slightly increased with the applied load. It is well known that PEEK polymer is a visco-elastic material, so the variation of friction coefficient with the load follows the equation $\mu=K N^{(n-1)}$, where μ is the friction coefficient, N is the applied load, K is a constant and n is also a constant with values between 2/3 and 1[11]. According to this equation, the friction coefficient decreases with the load increasing. However, when the load increases to the critical load of the pure PEEK, the friction and wear will increase sharply. This behavior is because that the friction heat raised the temperature of friction surfaces, which leads to relaxation of polymer molecule chains.

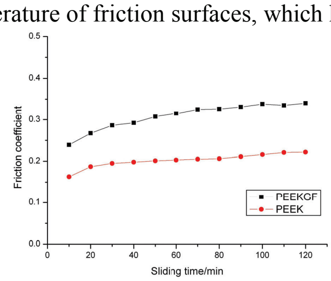

Fig.3. Variation of the friction coefficient for the PEEK and GF/PEEK, applied load=200 N

Fig. 4(b) shows wear losses of PEEK and GF/PEEK under different applied load. A linear increase of the weight loss is observed as the increasing of the applied load. The increase for the PEEK is more noticeable than that for GF/PEEK, indicating GF/PEEK has greater wear resistance than PEEK.

(a) (b)

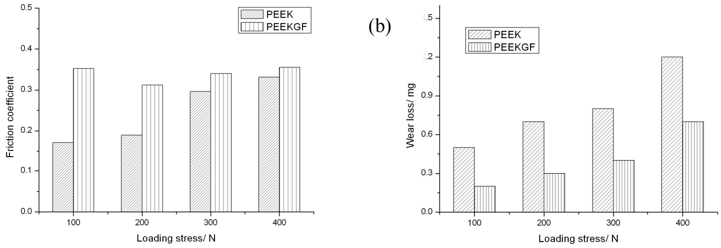

Fig.4. The variation of friction coefficient and wear loss with applied load of pure PEEK and GF/PEEK, sliding time=30min.

3.3 Worn surface analysis

The worn surfaces were observed by scanning electron microscopy(SEM), to identify the wear mechanisms. Fig.5 shows the worn surface morphologies of PEEK. It can be seen from the Fig.5(a) that the wear debris of PEEK adhered to the matrix of polymer. The formation and adhesion of the wear debris are typical features of the wear process of PEEK[12]. Fig.5(b) shows a higher magnifying view(5000×).It can be observed that the PEEK wrapped into together. This is explained as under grinding time longer generates heat at the polymer and steel counterface contact area, the PEEK polymer surface is softening and as a result of increasing in friction coefficient and wear loss.

(a) (b)

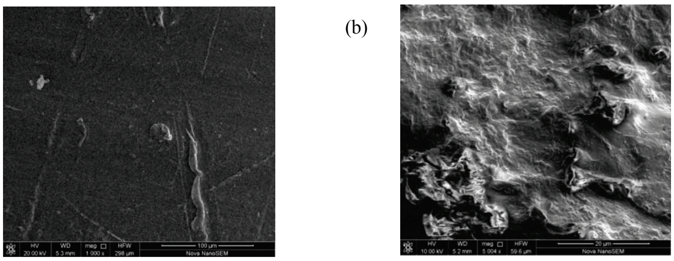

Fig.5 SEM pictures of pure PEEK under the applied load of 200N and sliding time of 30min

Figs. 6 show the worn morphologies of GF/PEEK composites. The glass fibers were dispersed disorderly in the matrix. Short pull-out lengths of the fibers were the evidence of strong fiber/matrix interfacial bond. Fig. 6(b) illustrates the worn surface of the GF/PEEK where the material removal of the matrix is interrupted by the fibers, causing the accumulation of wear debris around the glass fiber (indicated by arrow) [13].

(a) (b)

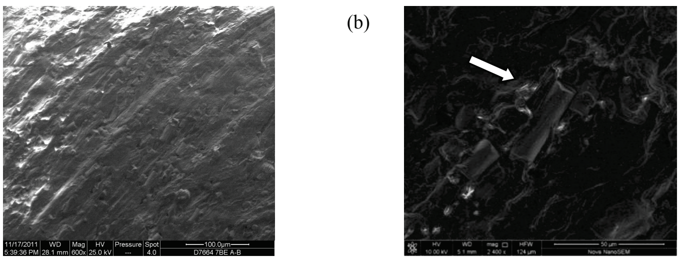

Fig.6 SEM pictures of GF/PEEK under 200N applied load and sliding time of 30min

Fig. 7(a) illustrates the low magnification worn surface of the GF/PEEK under the applied load of 400N and the sliding time of 120min. An obvious boundary was produced between the worn area and the unworn area (indicated by the red line). The worn area was very rough which may be due to the compatibility between PEEK and short glass fibers, or caused by the molding process. A smoother surface is observed in the worn area compared with the unworn area. Fig. 7(b) is medium magnification SEM of the boundary between the worn area and unworn area. Part of the matrix material was squeezed out of the surface due to the compressive load and no glass fibers included (similar to the process which was observed under single point scratch studies with the same material[14]) covered the unworn areas, providing temporarily an additional protection of the underlying fiber ends, it was associated with a high degree of fiber/matrix debonding. The microanalysis for X-ray(EDS) showed that the short glass was extruded from the composites by the applied load rather than pulverized into the composite. The EDS of worn and unworn area are given in Fig. 7(c) and 7(d). The debris that covered the unworn area only contained carbon and oxygen element(Spectrum 1). The short glass fibers contained silicon, calcium and aluminum element(Spectrum 2). Fig. 7(e) shows a higher magnifying view (5000×), the remained glass fibers well embedded in the polymer matrix and the matrix material around the fibers was disrupted. The short glass fibers significantly improved the triblogical and mechanical properties of GF/PEEK composites.

3.4 Thermogravimetric Analysis

In general, introduction of the filler increases the thermal stability owing to high temperature degradation as

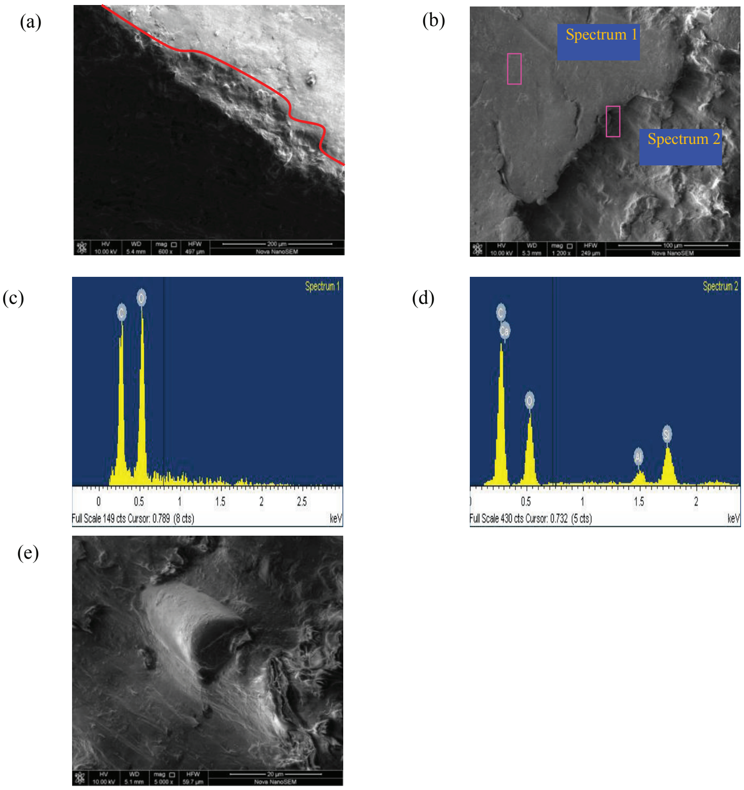

Fig. 7 Surface damage mechanisms of a short glass fiber reinforced PEEK at 200N applied load. a low magnification of wear, b medium magnification, c the EDS of spectrum1, d the EDS of spectrum2, e higher magnification(5000×).

compared with the polymer matrix. Fig 8 shows the typical TG weight loss curves for the pure PEEK and GF/PEEK. The incorporation of short glass fiber into the PEEK polymer matrix increases thermal stability. It is evident that the weight loss temperature of GF reinforced composites is about 75℃ higher than that of pure PEEK. The GF/PEEK composite exhibits higher thermal stability over the entire temperature range, compared with the pure PEEK.

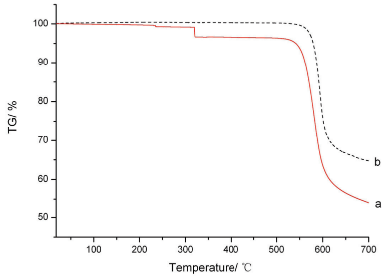

Fig 8 the typical TG weight loss curves for the pure PEEK and GF/PEEK

4 Conclusion

The mechanical properties, tribological behavior and thermal properties of pure PEEK and 30wt% short glass fibers reinforced PEEK prepared have been studied in this paper, considering the used methodology:

(1) The tensile strength, tensile modulus, flexural strength and flexural modulus of GF/PEEK were higher than those of pure PEEK, the incorporation of short glass fibers into PEEK polymer matrix obviously improved the mechanical performance.

(2) For all the tested materials, the friction coefficient and wear loss increased with the increase of the sliding time and the applied load. The GF/PEEK presented better wear resistance than PEEK.

(3) The bond between short glass fiber and the PEEK was strong fiber/matrix interfacial bond. The short glass fibers were extruded from the composite rather than pulverized into the composite.

(4) The weight loss temperatures of GF reinforced composites were about 75℃ higher than that of pure PEEK, the incorporation of short glass fiber into the PEEK polymer matrix increased the thermal stability.

Acknowledgements

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References

[1] Parina Patel, T. Richard Hull, Richard E. Lyon, et al. Investigation of the thermal decomposition and flammability of PEEK and its carbon and glass-fiber composites[J]. Polymer Degradation and Stability, 2011(96):12-22.

[2] G.Y. Xie, G.X. Sui, R. Yang. Effects of potassium titanate whiskers and carbon fibers on the wear behavior of polyetheretherketone composite under water lubricated condition[J]. Composites Science and Technology, 2011

(71):828-835.
[3] Avci A, Arikan H, Akdemir A. Fracture behavior of glass fiber reinforced polymer composite[J]. Cem Concr Res, 2004(34):429-34.
[4] T.C.Ovaert, H.S.Cheng. Counterface topographical effects on the wear of polyetheretherketone and a polyetheretherketone-carbon fiber composite[J]. Wear, 1991(150):150-157.
[5] Shang LG. Characterisation of interphase nanoscale property variations in glass fibre reinforced polypropylene and epoxy resin composites[J]. Composites Part A 2002, 33(4):559-76.
[6] Z.P.Lu, K.Friedrich. On sliding friction and wear of PEEK and its composites[J]. Wear, 1995:624-631.
[7] M.Sumer, H.Unal, A.Mimaroglu. Evaluation of tribological behavior of PEEK and glass fibre reinforced PEEK composite under dry sliding and wear lubricated conditions[J]. Wear, 2008(265):1061-1065.
[8] J. Bijwe, Nidhi. Potential of fibres and solid lubricants to enhance the triboutility of PEEK in adverse operating conditions[J]. Industrial Lubrication Tribology, 2007 (4) :156-165.
[9] J. Hanchi, N.S. Eiss Jr. Dry sliding friction and wear of short carbonfiber-reinforced polyetheretherketone (PEEK) at elevated temperatures[J]. Wear, 1997 (203-204): 380-386.
[10] X.X. Chu, Z.X. Wu, R.J. Huang, et al. Mechanical and thermal expansion properties of glass fibers reinforced PEEK composites at cryogenic temperatures[J]. Cryogenics, 2010(50):84-88.
[11] H.Uetz, J.Wiedemeyer. Trbologie der Polymere, Carh hanser Verlag, Munchen Vienna, 1985.
[12] H.Voss, K.Friedrich. On the wear behavior of short-fiber-reinforced PEEK composites. [J].wear, 1987,116:1-18.
[13] J.Paulo Davim, Rosaria Cardoso. Effect of the reinforcement(carbon or glass fibers) on friction and wear behavior of the PEEK against steel surface at long dry sliding [J].wear,2009,266:795-799.
[14] Friedrich, K., Goda, T., Varadi, K., Wetzel, B.: FE-Simulation of the fiber/matrix debonding in polymer composites produced by a sliding indentor, Part 1: Normally oriented fibers[J]. J. Compos. Mater. 2004,38, 1583-1606.