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The lubricity and reinforcement of carbon fibers in polyimide at high temperatures

Fengxia Dong [a,b], Guoliang Hou [a], Fengxiang Cao [a,b], Fengyuan Yan [a,*], Liang Liu [a,b], Jianzhang Wang [a]

[a] State Key Laboratory of Solid Lubrication, Lanzhou Institute of Chemical Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China

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ABSTRACT

The friction and wear behaviors of neat PI and carbon fibers reinforced polyimide (CF/PI) composites were investigated at various temperatures. The results showed that the introduction of carbon fibers could greatly improve the wear resistance in the whole temperature range, while the friction coefficients strongly depended on sliding temperatures. The lubricity of carbon fibers was only found occurring at high temperatures of 180–260 °C, which can be attributed to the graphitization of carbon fibers that promotes the generation of friction and transfer films with excellent lubricity on the worn surfaces. This study is expected to provide guidance for the application of carbon fibers both as lubricating and reinforcing additives in polymer matrix sliding at high temperatures.

1. Introduction

As compared to metallic and ceramic materials, the favorable use of polymer materials in dry sliding is indicated by their excellent performances, including self-lubricating and anti-wear abilities, low density, high strength and wide performance tailorability [1–5]. However, due to the low thermal stability and loss of mechanical properties at high temperatures, many technical polymers, such as polyethylene terephthalate (PET), polyamides (PA) and polyethylene (PE) cannot be widely used under extreme sliding conditions [6,7]. As one of the most common engineering materials with both linear or cyclic imides group and aromatic groups, thermoplastic polyimide (TPI), possessing excellent mechanical, chemical properties and thermal stability, has received a great deal of attention as a potential candidate for use in tribological systems under harsh conditions, such as high temperatures, high normal loads, and/or high sliding velocities [8–11]. For all that, there are also some problems that usually encountered in TPI applications: (I) the friction coefficient (μ) is relatively high, and (II) the wear rate (Ws) is also high because of the brittleness, making TPI is not suitable to be used as self-lubricating materials directly, especially at high temperatures. In order to improve the mechanical and tribological characteristics, polyimide-based composites have been developed in recent years by adding some appropriate additives, such as solid lubricants, nanoparticles or fibers into polyimide matrix.

Carbon fibers (CFs), combining high specific strength and modulus, damping capacity, excellent thermal stability and conductivity, and potentially lubricating ability, has been widely used as reinforcements and/or lubrications in tribological applications of polymer composites [12–15]. Generally, they can improve the wear resistance of composites because of the increase of loading capability, while it is unclear under what conditions CFs can induce low friction coefficient [16–18]. According to Wang and Zhang, the incorporation of carbon fibers can significantly improve the friction-reducing and anti-wear abilities of polyimide under dry sliding conditions [19], while Li and Cheng found the incorporation of carbon fibers into polyimide can generally reduce the wear rate of composites, but may either increase or reduce the friction coefficient with different carbon fibers contents [20]. Unfortunately, these researches mainly focus on the friction and wear behaviors of CF/PI composites at room temperature, which still cannot satisfy the requirements for their use at high temperatures. Until now, only several researches have been conducted to investigate the influence of sliding temperature on the tribological properties of CF/PI composites [10,21]. Apparently, there still is large room to systematically investigate and fully understand the wear behavior, combined with the wear mechanism of CF/PI composites sliding at high temperatures, especially the lubrication mechanism of CFs.

Bearing those perspectives in mind, in this research polyimide composites reinforced with carbon fibers were fabricated by hot press molding technique and the friction and wear behaviors of neat PI and CF/PI composites were investigated sliding against steel ball at various

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[*] Corresponding author.
E-mail address: fyyan@licp.cas.cn (F. Yan).

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temperatures. In addition, the mechanisms of high improvements in friction-reducing and anti-wear abilities at high temperatures were deeply discussed in relation to their mechanical properties, worn-surface features and formation of friction and transfer films. The present research, hopefully, is to provide references for application of CF/PI composites as self-lubricating materials at high temperatures, as well as the application of CFs as lubricating additives in polymer composites at high temperatures.

2. Experimental

2.1. Materials and specimens

Thermoplastic polyimide powder (YS-20) with an average particle size of 30 μm and a density of 1.38 g/cm^3 was purchased from Shanghai Synthetic Resin Institute, (China). PAN-based carbon fibers with length of 28–56 μm and diameter of 7 μm and a density of 1.77 g/cm^3 were provided by Nanjing Fiber-glass Research and Design Institute (China).

The samples of neat PI and CF/PI composites with a fixed volume content of carbon fibers of 10% were fabricated by means of mechanical mixing followed by hot pressing technique. Specifically, the neat PI powder was mixed with carbon fibers by simply mixing at room temperature, then the neat PI powder or mixed powders were filled into a mold, compressed and heated up to 375 °C and held at 30 MPa for 60 min to allow full compression and sintering. After cooled in the stove in air and released from the mold, target specimens with different dimensions were obtained.

2.2. Test apparatus and experimental procedures

Friction and wear tests were carried out in a ball-on-disk contact configuration with a high temperature friction and wear testing machine (CSEM-THT07-135). A contact schematic diagram of the frictional couple is shown in Fig. 1. The polymer samples (*Ra* is about 0.03 μm) were used as the lower specimens, and commercially available GCr15 (AISI 52100) steel balls with a diameter of 3 mm (hardness is about 9 GPa, *Ra* is about 0.02 μm) were used as the upper specimens. The sliding was performed with a sliding speed of 0.3 m/s (rotational speed: 573 r/min), load of 5 N, and duration of 30 min. Prior to each test, the stainless steel balls were ultrasonically cleaned with acetone for 30 min to remove the oil thoroughly on the surfaces. The friction coefficient curves were recorded automatically with a computer connected to the friction and wear tester. The wear volume loss was measured with a NanoMap three dimensional (3D) contact surface mapping profile. The specific wear rate (mm^3/Nm) was calculated as below:

$$K = \frac{V}{F \cdot S}$$

where V is the wear volume loss (mm^3), F is the normal load (N), and S is the total sliding distance (m). Tests were carried out in ambient air with relative humidity of 10 ± 2%. Three repeated friction and wear tests were carried out for each specimen and the average of the three repeated test values was reported in this paper.

2.3. Characterization

Thermal gravimetric analysis (TGA) was performed under N$_2$ atmosphere with a NETZSCH STA449C thermal analyzer from 30 to 900 °C with a heating rate of 10 °C/min. Dynamic mechanical analysis (DMA) was carried out in nitrogen on a NETZSCH DMA-242C analyzer. The specimens were rectangular bars (60 mm × 10 mm × 4 mm) and performed under a three-point bending mode from 30 to 350 °C at a heating rate of 3 °C /min and a frequency of 1 Hz.

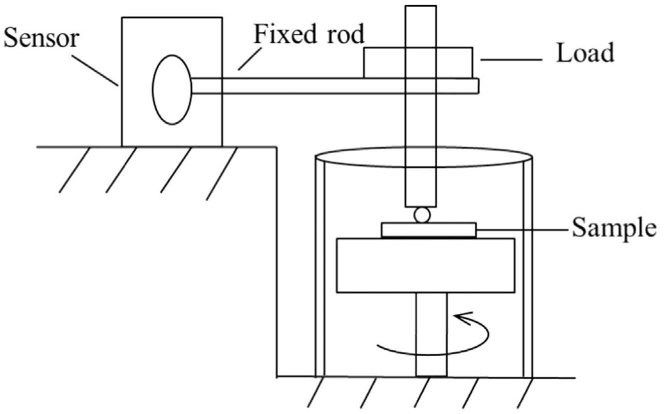

Fig. 1. Contact schematic diagram for unidirectional rotational sliding friction.

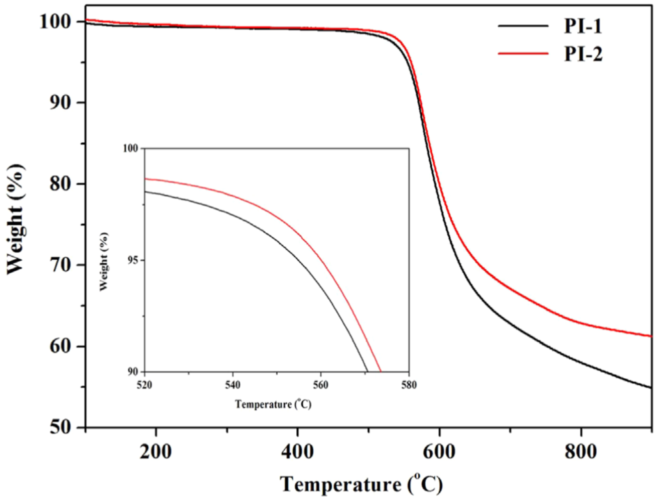

Fig. 2. TGA thermograms of neat PI (PI-1) and CF/PI (PI-2) composites.

Table 1
Data on TGA and flexural strength of neat PI (PI-1) and CF/PI (PI-2) composites.

Material	TGA				Flexural strength (MPa)
	T_d[a] (°C)	T_5[b] (°C)	T_{10}[c] (°C)	R_w[d] (%)	
PI-1	545	555	570	55	142 ± 3
PI-2	550	560	573	62	171 ± 2

[a] T_d: the onset decomposition temperature.
[b] T_5: the temperature at 5 wt% of weight loss.
[c] T_{10}: the temperature at 10 wt% of weight loss.
[d] R_w: residual weight retention at 900 °C.

The flexural strength of samples was determined using a DY35 universal testing machine with a span of 64 mm and crosshead speed of 2 mm/min. The specimens were 80 mm × 10 mm × 4 mm and the test surface was 80 mm × 10 mm. The specific flexural strength (σ_f) of specimens was calculated as below:

$$\sigma_f = \frac{3FL}{2bh^2}$$

Where F is the maximum load (N), L is the span length (mm), b is the width of the specimen (mm), and h is the thickness of the specimen (mm). At least three measurements were conducted for each sample in the bending test.

The worn surfaces of PI and CF/PI composites were examined using a JEM-5600LV (JEOL, Japan) scanning electron microscope