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# Effects of nanoscale expanded graphite on the wear and frictional behaviors of polyimide-based composites

Zhining Jia [a,b,*], Caizhe Hao [a], Yanhong Yan [b,**], Yulin Yang [b]

[a] Chengde Petroleum College, Chengde 067000, PR China
[b] College of Mechanical Engineering and National College of Defense Technology, Yanshan University, Qinhuangdao 066004, PR China

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ABSTRACT

The effects of adding nanoscale lamellar-structure expanded graphite (nano-EG) on the friction and wear properties of hot-molded polyimide (PI)-based composites were investigated. Friction and wear tests were carried out using a Type 1045 steel ring rotating against a composite disk. The coefficients of friction, wear rate, worn surface morphology were investigated. Experimental results indicated that the tribological properties of PI/nano-EG composites highly depend on the content of nano-EG under dry sliding conditions. Compared with that of PI, wear resistance of PI/nano-EG composites was increased by a factor of 200. Best tribological properties occurred when the nano-EG content is 15 wt%. The transfer film generated on the mating surface of the self-lubricating PI/nano-EG composite is smooth and continuous, which is likely to be responsible for its low wear rate. Such composites can offer considerable potential for engineering applications such as bearings and slideways where they can reduce both the friction coefficient and the wear rate.



## 1. Introduction

Due to properties such as high specific strength, good thermal stability and corrosion resistance, polymeric materials have been used in a range of industrial applications [1–3]. Polyimide (PI) is a leading engineering polymer because of its outstanding combination of performance and ease of synthesis [4–6]. In some cases, it has replaced traditional steels, which is of great significance in view of the decreasing availability of steels [7]. However, the ability of PI to be used as a bearing material is limited by its relatively high wear rate and coefficient of friction compared with other polymers [8–10]. Therefore, in order to improve the tribological properties of PI, researchers have used a variety of ways, including the preparation of PI-based composites.

Introducing various fibers or particles into polyimide matrix has been verified to be an effective way to improve the tribological properties of PI. Using polymer blending process also can achieve the target. On account of good lubrication of PTFE, the transfer film (hybrid PI and PTFE) formed on counterface has a low coefficient of friction and high wear resistance, and the polymer alloy of PI/PTFE composite shows improved tribological properties compared with pure PI and pure PTFE, respectively [11,12]. Some fibers such as carbon fiber, glass fiber, carbon nanotube, usually are incorporated into polymers. Because of tangle and carrying load of fibers, the mechanical properties of polymer-based composite filled with fibers are improved. Meanwhile, even when fibers break, they can still maintain good carrying capacity, which results in high wear resistance of polymer/fiber composites [13–15].

Almost all types of nanoparticles can be used as reinforcement phase for polymer-based composites, such as $Al_2O_3$, $ZrO_2$, $TiO_2$ and Cu [16–19]. The rigid nanoparticles incorporated into polymer matrixes can act as support loads, also can form micro-bearings on counterface, which leads to a low coefficient of friction. Moreover, the self-lubricating transfer film generated on counterface separates polymer-based composites from couple pairs, which is beneficial to reduce the wear of composites [20,21]. But not all nanoparticles will lead to high tribological properties for polymer-based composites. Some nanoparticles added into polymer matrix, to a certain extent, also deteriorate tribological properties of polymer-based composites [22,23]. However, the addition of some nanoscale solid self-lubricating materials for improving the tribological properties of polymer composites is indeed very significant, which is mainly due to the self-lubricating properties of added materials [24,25].

In previous studies, expanded graphite with nanoscale lamellar structure (nano-EG) was prepared. For its self-lubricating properties, tribological properties of PTFE/nano-EG composite were studied [26]. The research results showed that the addition of nano-EG significantly improved the wear resistance of PTFE composites.

* Corresponding author at: Chengde Petroleum College, Chengde 067000, PR China. Tel.: +86 15831439791.
** Corresponding author. Tel.: +86 13933625810.
E-mail addresses: ysujia@163.com (Z. Jia), yhyan@ysu.edu.cn (Y. Yan).

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In order to expand its application, this paper aims to investigate the impact of nano-EG content on the tribological properties of PI-based composites. One of our purposes is to seek a PI-based composite with better self-lubricating properties and high wear resistance, which could be used in rolling or sliding bearings.

## 2. Material preparations

### 2.1. Preparation of nano-EG by microwave radiation

Firstly, worm-like expanded graphite (EG), which is of interest for a number of applications [27–29], was prepared by using technology of microwave radiation [30]. Because of the conductivity of the commercial expandable graphite, the sharp heat effect of eddy current in expandable graphite under microwave caused quick expansion between layers of graphite, and then the EG was fabricated. Compared with Ref. [27,31], the opening diameter of EG was bigger than that acquired by chemical intercalating method, besides being more easy to operate and more efficient. Secondly, the EG was dipped into alcohol solvent and further broken into small pieces under ultrasonic cavitation and mechanical agitation for some time. Thirdly, alcohol solvent was evaporated and the expanded graphite with nanometer lamellar structure (nano-EG) was acquired. Fig.1 is the preparing procedure of nano-EG by microwave radiation method. Fig. 2a indicates the field emission scanning electron microscope (FESEM: HITACHI S-4800, made in Japan) images of nano-EG. Fig. 2b is a partially enlarged morphology of graphite sheet in Fig. 2a. From the figure, it can be seen that the average lamellar thickness of nano-EG is about 25 nm.

### 2.2. Preparation of PI/nano-EG composite

The PI and nano-EG were acquired in powder form. The PI powder has a particle size of approximately 300 mesh number (GCPI®PI, supplied by Changzhou Guangcheng new plastics Co. Ltd., China). After pre-mixing a certain mass fraction of nano-EG and polyimide, we put the powders mixture into a dedicated high-speed mixer and blended for 5–10 min. The aim of the process is to make the mixed powders disperse uniformly. Then, the compound was diverted into a mold cavity and heated to 340 °C at 10 MPa, and maintained for 1 h to ensure enough compression sintering. In the process of preparation of PI/nano-EG composite, vacuum force technology was used to ensure the specimens to be compacted. Appling the hot compression technology, the corresponding sample was cooled to 200 °C inside the furnace and continuously cooled in air. Finally, the sintered sample was machined into final specimens which were 45 mm in diameter and 3–5 mm in thickness, and ready for friction and wear test.

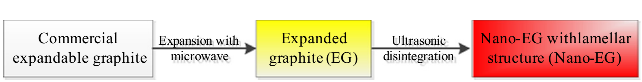


**Fig. 1.** Preparing procedure of nano-EG by microwave radiation and ultrasonic cavitation.

## 3. Tribological tests

Friction and wear tests of PI/nano-EG composites sliding against steel were evaluated on a ring-on-disk friction and wear tester (model MMU-5G, Jinan SiDa Instruments Co., Ltd., China). Fig. 3a shows the schematic experimental device of the friction and wear pair. The upper specimen is AISI-1045 steel (HRC: 23–26; $R_a$=0.1–0.2) and its average rotational diameters were 23 mm. The lower specimen is PI/nano-EG composite. To exclude frictional heat occurring in contact process and also commodious to enhance contact pressure, the equally spaced grooves on upper specimen were machined, as shown in Fig. 3b [32].

For the tribological tests, the ring specimen was rotating and the disk specimen (PI/nano-EG) composite was in stationary. All tests were done at a liner sliding velocity of 0.48 m/s, applied load of 200 N, continued sliding time of 90 min. In addition, in order to guarantee the data reliability, the ambient temperature was kept at (25 ± 5) °C and the relative humidity of (55 ± 5)%. The wear resistance of PI/nano-EG composites was determined by the following equation:

$$W = \frac{\Delta V}{FL}\left[\mathrm{mm}^3(\mathrm{N\cdot m})^{-1}\right] \tag{1}$$

where $W$ is specific wear rate of PI/nano-EG composite, $F$ is applied load, N, and $L$ is sliding distance, m, $\Delta V$ is volume loss, $mm^3$, which was characterized by the relationship:

$$\Delta V = \pi\left(R^2 - r^2\right)(\Delta h) \tag{2}$$

where $R$ and $r$ is the outer and inner radius of the ring specimen, respectively, mm, and $\Delta h$ is wear depth, mm. To avoid discrete experimental data, each test was repeated three times, and then took the average as the final result.

## 4. Results and discussion

### 4.1. Frictional coefficient and wear rate

Fig. 4 represents the coefficient of friction and wear rate for all the tested PI/nano-EG composites sliding against ring specimens. With the different content of nano-EG, the coefficient of friction of PI/nano-EG composites varies widely. When nano-EG content is zero (i.e. pure PI), the coefficient of friction is 0.354. Even a small amount of nano-EG being added into PI, the coefficient of friction of PI-based composites is greatly improved. For the PI/nano-EG

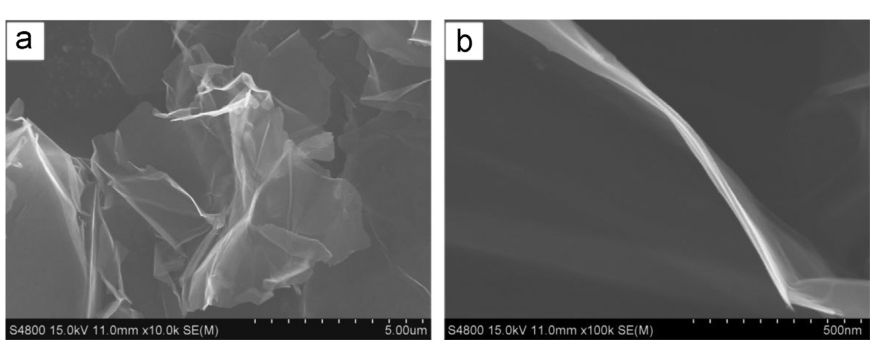


**Fig. 2.** SEM/FESEM micrograph of worm-like expanded graphite and nano-EG.