Tribology International 103 (2016) 208–217

Contents lists available at ScienceDirect

Tribology International

journal homepage: www.elsevier.com/locate/triboint

Tribological investigations of glass fiber reinforced epoxy composites under oil lubrication conditions

Fuyan Zhao [a], Guitao Li [a], Werner Österle [b], Ines Häusler [b], Ga Zhang [a,*], Tingmei Wang [a], Qihua Wang [a,*]

[a] State Key Laboratory of Solid Lubrication, Lanzhou Institute of Chemical Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[b] Federal Institute for Materials Research and Testing (BAM), 12205 Berlin, Germany

ARTICLE INFO

Article history:
Received 11 April 2016
Received in revised form
7 June 2016
Accepted 3 July 2016
Available online 4 July 2016

Keywords:
Reinforced epoxy composites
Short glass fiber
Oil lubrication
Tribofilm

ABSTRACT

The tribological performance of short glass fibers (SGF), solid lubricants and silica nanoparticles filled epoxy (EP) composites was investigated under oil lubrication conditions. It is demonstrated that the addition of SGF greatly reduces the friction and wear of EP. However, further addition of solid lubricants and silica nanoparticles does not change obviously the friction and wear. It is identified that the high tribological performance of SGF reinforced EP is related to the high load carrying capacity and abrasion resistance of SGF. The nanostructure of the tribofilm was comprehensively characterized. It is deemed that the tribofilm plays an important role in the tribological performance by avoiding the direct rubbing of the sliding pairs exposed to boundary and mixed lubrication conditions.

1. Introduction

With the development of modern industries, the operating environments of mechanical motion components under lubrication conditions get harsher owing to the frequent start-stop, speed variation and high load [1,2] etc. In order to ensure the reliability of the motion system under this situation, one way to solve this problem is improving the properties of lubricating medium [3,4], and another solution is developing high performance nonmetal-metal friction pairs to replace the traditional metal-metal ones. During the past several decades, the tribological properties and mechanisms of polymer-based composites, especially fiber reinforced polymer composites, have been studied by many researchers [5–8]. In recent years, it was revealed that the addition of sub-micron and nano inorganic particles, e.g. TiO_2, ZnS, SiO_2 etc., further enhances the tribological performance of fiber reinforced polymer composites. In fact, due to the self-lubricating properties, polymer composites have been widely used in mechanical parts for replacing metal materials subjected to the dry friction conditions [9,10].

However, so far, the lack of knowledge about tribological mechanisms of polymer-based composites under lubrication conditions becomes the bottleneck problem of designing special friction pairs of engineering applications, such as mechanical motion equipment and automotive filed. Therefore, some studies have been carried out to investigate the tribological performances of polymer composites under oil lubrication conditions. Xue et al. [11] compared the influence of different kinds of fibers and whisker on the tribological properties of PTFE composites under oil lubricated conditions, and found that fibers promoted the formation of tribofilm onto the counterpart. The effect of surface treatment of fibers on tribological properties of polymer composites under oil-lubricated condition was investigated in [12–14], the authors revealed that the interfacial adhesion between the fibers and polymer matrix played an important role on the tribological properties of polymer composites. Our previous study indicated that in the case of PEEK-based materials slid under mixed and boundary lubrication, the formation of a tribofilm on the counterface was important for the tribological behavior of the frictional system [1].

High performance epoxy (EP) composites have been widely studied, but up to now, majority of the investigations confined their research to dry sliding conditions [15–20], very few results on the tribological characteristics of EP-based composites under oil lubrication have been reported [21,22]. Therefore, it is essential to study the friction and wear behaviors of EP composites under oil lubrication conditions. Carbon fibers and glass fibers are most widely used reinforcing fillers for polymer matrix. It is generally recognized that under dry sliding conditions carbon fibers enhance more tribological performance of polymer matrix than SGF [10]. [23] reported that carbon particles mixed with other wear

* Corresponding authors.
E-mail addresses: gzhang@licp.cas.cn (G. Zhang), wangqh@licp.cas.cn (Q. Wang).

http://dx.doi.org/10.1016/j.triboint.2016.07.002
0301-679X/

products are transferred to the counterface and thereby improve the tribological performance under dry sliding conditions. With respect to SGF, it can scratch the metallic counterface due to its high hardness [24]. Therefore, in practical applications of dry sliding, when SGF is used as reinforcing fillers in polymer-based self-lubrication composites, the addition of solid lubricants, e.g. graphite, PTFE, MoS_2, is usually necessary [25]. The solid lubricants lead to the formation of a lubricating transfer film which protects the metallic counterface from being scratched by the SGF. However, solid understanding on the tribological behaviors of SGF reinforced polymer composites under oil lubrication conditions is still lacking.

Our previous study has reported the tribological properties of short carbon fibers (SCF) reinforced EP composites under water [24] and oil lubrication conditions. It was revealed that SCF improves significantly the wear resistance of EP. The enhanced wear resistance is ascribed to the higher abrasion resistance of the reinforcing fibers and the formation of a tribofilm on the counterface. However, the addition of SCF into EP matrix does not obviously reduce the friction coefficient of EP in boundary and mixed lubrication regimes [21,26]. Thus, it will be of practical interest to develop EP composites exhibiting simultaneously a low friction and a high wear resistance under oil lubrication conditions.

In this study the tribological behaviors of short glass fibers (SGF) reinforced EP composites were investigated under oil lubrication conditions. The influence of SGF content, additional fillers (SiO_2 nanoparticles, graphite and PTFE) on tribological behaviors of EP was studied using a block-on-ring apparatus. The worn surfaces of selected composites and transfer films formed on the counterpart ring were investigated by optical microscope, scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDX), X-ray photoelectron spectroscopy (XPS), focused ion beam technique (FIB) and transmission electron microscopy (TEM). The corresponding lubrication and wear mechanisms were analyzed based on the characterization of the worn surfaces of composites and counterpart.

2. Materials and methods

2.1. Material preparation

EP composites were prepared using a bisphenol-A epoxy resin (DER331, Dow), hardened by a cycloaliphatic amine curing agent (HY 2954, Huntsman). The diameters of SGF (E-glass, FG400/060, STW) are in the range of 9–14 μm and the average length is 230 μm. Graphite flakes (RGC39TS, Superior graphite) and polytetrafluoroethylene particles (PTFE, TF 9207, Dyneon) were used as additional fillers with an average size of 8.9 μm and 4 μm, respectively. SiO_2 nanoparticles were supplied as a silica masterbatch (Nanopox F400, Evonik) in EP colloidal. The mean diameter of the SiO_2 nanoparticles is 20 nm.

Three series of composites were investigated: pure EP, EP filled with SGF and EP filled with combined fillers. The compositions of EP composites are listed in Table 1. The EP composites were prepared by mixing the silica masterbatch with required amount of EP resin using a vacuum dissolver (Dispermat, VMA-Getzmann, Germany). SGF, graphite flakes and PTFE particles were mixed in sequence with the resin and dispersed in the vacuum dissolver. Afterwards, the compounds were blended with the curing agent by stirring in the dissolver under vacuum. Finally, the mixture was poured into aluminum molds, and kept at the gel temperature 70 °C for 8 h, followed by the final curing temperature at 120 °C for 8 h. The detailed procedures for preparing the composites can be found in a previous work [21].

Table 1
Compositions of epoxy composites (vol%).

Sample abbreviation	Matrix	SGF	Graphite	Nano-SiO_2	PTFE
EP	100	0	0	0	0
5SGF	95	5	0	0	0
10SGF	90	10	0	0	0
15SGF	85	15	0	0	0
SGF/Si	87	10	0	3	0
SGF/G	82	10	8	0	0
SGF/G/PTFE	80	10	5	0	5
SGF/G/PTFE/Si	81	10	3	3	3

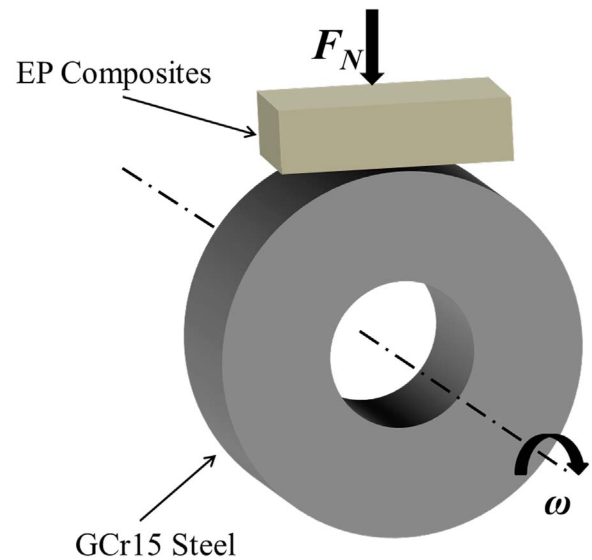

Fig. 1. Schematic illustration of block-on-ring contact configuration.

2.2. Tribology tests

Tribological tests were performed using block-on-ring (BOR) apparatus (MM-P2, Jinan Shidai Shijin, China). Schematic diagram of the BOR contact configuration are shown in Fig. 1. The polymer samples investigated had a dimension of $30 \times 7 \times 7$ mm^3. The counterpart was a GCr15 (C 0.95–1.05 wt%, Mn 0.25–0.45, Si 0.15–0.35, P ≤ 0.025, S ≤ 0.025, Cr 1.40–1.65) steel ring with a diameter of 40 mm and a roughness, R_a of 0.1–0.2 μm which was polished by W20 SiC metallographic abrasive papers. The surface of the counterpart was covered during the entire sliding test by lubricant (PAO4, provided by China National Petroleum Corporation) which was dropped by gravity continuously onto the wear track through an elastomer tube. The testing conditions were as follows: the normal load was 200 N, the sliding speed was 0.44 m/s. Each test lasted 6 h.

After each test, excess oil was gently removed from the surfaces of the composite sample and counterpart with tissue paper. And then the sample and counterpart were cleaned in petroleum ether bath by ultrasonic for one minute in order to remove the residual oil. The friction coefficient was recorded online using a force transducer. The wear scar width of the block was measured using a digital-reading optical microscope over 6 random regions along the length of the wear scar. The specific wear rate of the specimen was calculated and averaged by the Eq. (1).

$$W_s = \frac{l}{L \cdot N}\left[r^2 \cdot \text{arc}\ \sin\left(\frac{W}{2r}\right) - \frac{W}{4}\sqrt{4r^2 - W^2} \right] \quad (1)$$

In Eq. (1), where W_s represents the specific wear rate (mm^3/Nm), r is the radius of the counterpart ring (mm), l and W are the width