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Tribological behavior of PEEK-based materials under mixed and boundary lubrication conditions

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ABSTRACT

In modern industries, more and more mechanical components are exposed to mixed and even boundary lubrication conditions, inducing fast wear and even scuffing of the motion systems. In order to enhance the lifetime and reliability of the motion systems, replacing metal–metal friction pairs by metal–polymer ones can be one of the most effective approaches. The present work focuses on tribological behavior of pure polyetheretherketone (PEEK) and a formulated PEEK composite lubricated with diesel and engine oil. It was demonstrated that in mixed and boundary lubrication regimes the structure of PEEK materials affect significantly the tribological performance. Formation of a tribofilm on the surface of metallic counterbody plays an important role on the tribological behavior of the PEEK-based materials.

1. Introduction

Numerous mechanical components in modern industries often run under mixed and even boundary lubrication conditions, owing to extremely high loading conditions, frequent start–stop etc. There are several characteristics that identify boundary lubrication regime, i.e. the hydrodynamic lifting effect is negligible and therefore majority of the load is carried by direct asperity contacts [1]. With respect to mixed lubrication regime, both hydrodynamic lubrication and asperity contact carry appreciable load. The tribological properties of materials in mixed and boundary lubrication regimes govern the lifetime and reliability of numerous motion components. In order to reduce friction and wear of metallic components subjected to mixed and boundary lubrication contacts, it is essential to prevent direct rubbing of the metallic parts by forming high-performance tribofilms, i.e. the transfer of solid lubricants and boundary layer [2]. The boundary layer generated as a result of tribo-chemical reactions usually carries load, reduces friction and wear of rubbing surfaces. It is believed that the formation of a high-performance tribofilm is of great importance for reducing friction and wear of metal–metal contacts [3–6].

However, the boundary lubricity is directly affected by various factors (such as loading parameters, interface temperature, lubricant type and additives, friction induced heat, humidity etc.), which may complicate the formation of tribofilms and make boundary lubrication problematic. Once the lubrication of tribofilm fails, friction and wear would drastically increase due to direct rubbing of metal–metal. Thus, high temperature develops as a consequence on the friction interface, and thereby scuffing problems can occur [7]. Thus, high friction, wear and even catastrophic system failures probably take place in this poorly understood lubrication regime. In order to achieve the maximum service life, the highest reliability and the minimum energy consummation, it is essential to understand the friction and wear behavior of materials subjected to boundary and mixed lubrication conditions. This is true especially when poor-lubricity lubricant is utilized or in case oil starvation happens.

In view of the aforementioned challenges related to boundary and mixed lubrication regimes, many efforts have been dedicated to the development of anti-wear materials. Owing to their self-lubricating capability, polymer materials attract extensive interests from both academia and industry. Samad et al. [8] reported that a carbon nanotubes (CNT) reinforced ultra-high-molecular-weight polyethylene (UHMWPE) nanocomposite coating on an Al substrate reduced the wear of Al mating material effectively when the system is lubricated with base oil. Shiao et al. [9] reported that a low friction coefficient (0.02) of polyoxymethylene (POM) materials could be achieved by "properly" combining the polarities of the fillers in the POM matrix and the lubrication medium. However, it seems that the contribution of hydrodynamic effect was not considered in the work. Our recent work [10] demonstrated that epoxy (EP) composites reinforced with fibers exhibited a high wear resistance when subjected to boundary lubrication with diesel. It was evidenced that the formation of a high-performance tribofilm on the steel counterface was important for reducing the friction and wear of the EP composites [10].

Poly-ether-ether-ketone (PEEK) is a temperature-resistant thermoplastic exhibiting high mechanical properties, an inherently high

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chemical stability and very low moisture and liquid adsorption rates. In addition, the high thermal–mechanical properties of PEEK enable applications under elevated temperatures up to 250 °C. Large-scale compounding and manufacturing of PEEK composites filled with multifunctional fillers can be carried out based on conventional melt processing techniques like extrusion, injection molding etc. The broad processing window allows wide applications of PEEK materials. That is why PEEK is regarded as one of the most ideal matrix polymers for formulating high-performance tribo-composites for applications under severe conditions. Up to now, numerous works have been dedicated to the tribological behaviors of PEEK and its composites under dry sliding conditions [11–16]. Yamamoto et al. [17,18] carried out interesting research on the tribological properties of PEEK under water lubrication conditions. Nevertheless, the tribological behavior of PEEK materials under fuel and engine oil lubrication conditions was rarely reported. In particular, a solid understanding of their tribological mechanisms under mixed and boundary lubrication regimes is still lacking. In order to fill the distinct gap between important application potentials and the lack of material formulation theory, it is of great importance to reveal the tribological mechanisms of PEEK materials under boundary and mixed lubrication conditions.

In the present work, the friction and wear properties of pure PEEK and a formulated PEEK composite, subjected to diesel and engine oil mediums and slid against a steel counterbody, were investigated. When exposed to diesel lubrication, the effects of several parameters, i.e. diesel quantity, loading pressure and sliding velocity, were studied. The tribological mechanisms were investigated by analyzing both the worn surfaces of polymer samples and the tribofilms formed on the counterface. Stribeck curves of the PEEK materials when exposed to engine oil lubrication were derived, with stepwise decreasing sliding speeds. Furthermore, the tribological properties of PEEK materials lubricated with engine oil were compared to that of a low alloy steel. It was also objective of this work to study the feasibility of replacing steel–steel friction pairs exposed to mixed and boundary lubrication contacts by using a polymer–steel pair.

2. Experimental

2.1. Material preparation

In order to study the effect of formulations of PEEK materials, pure PEEK and a PEEK composite filled with multiple fillers were investigated in the present work. Pure PEEK was supplied by Victrex (UK) in forms of granulates (product grade: 450G). Dumbbell-shaped sample plates of pure PEEK were manufactured by using injection molding technique (Arburg, Germany) (melt PEEK at 380 °C and inject it into a mold). The PEEK composite, which was optimized in a previous work [19] under dry sliding conditions, was filled with multiple fillers, i.e. short carbon fibers, solid lubricants and ceramic particles. The PEEK composite was compounded via a twin-screw extruder and finally injection molded into plates with a dimension of $80 \times 80 \times 4\ \mathrm{mm}^3$. The PEEK composite is thereafter referenced as PEEK-Com in the paper. The E-modules of the PEEK and PEEK-Com are 3.6 and 13.0 GPa, and their tensile strengths are 97.2 and 150.1 MPa, respectively. It was demonstrated that under dry sliding conditions the PEEK composite shows much lower friction coefficient and wear rate than pure PEEK [19].

2.2. Tribology tests

Ultra-low sulfur diesel and engine oil were utilized as lubricants, respectively. It is generally agreed that ultra-low sulfur diesel shows bad lubricity owing to its low physisorption capability onto metal surface. Boundary lubrication with ultra-low sulfur diesel is therefore sometimes problematic. The diesel used in this work had a dynamic viscosity of 1.6×10^{-3} Pa·s at 40 °C. The engine oil used in this work was a blend of highly refined mineral oil, polyolefin and additives and it had a dynamic viscosity of 28.0×10^{-3} Pa·s at 40 °C.

The tribological properties of PEEK and PEEK-Com with diesel lubrication were studied with Block-On-Ring (BOR) tests using a four-lever testing system. Fig. 1a shows the BOR test rig and Fig. 1b gives a closer view of the sliding pairs of BOR test. The load was applied by dead weight from the lever as indicated by an arrow in Fig. 1a and the friction force was measured by a load cell instrumented onto the test rig (cf. Fig. 1a). The rotation direction of the counterbody ring is indicated in Fig. 1b. More details with respect to the testing methodology and a schematic illustration of the test principle were given in our previous publication [10]. The counterpart was a 100Cr6 steel ring with a 60 mm diameter and a mean roughness R_a of 0.2–0.3 μm. The polymer specimens had a dimension of $4 \times 4 \times 12\ \mathrm{mm}^3$ (contact surface: $4 \times 4\ \mathrm{mm}^2$). Before friction tests the specimens were "pre-worn" with grinding papers (firstly P600 and then P1200) to an arc outline matching the counterpart configuration. The initial mean roughness R_a of the PEEK specimens was averagely 0.45 μm. Each test lasted 20 h, allowing the system to reach a steady friction and wear process. After each test, both the polymer pin and counterbody ring were changed.

In order to simulate the working condition of a certain diesel-lubricated component in a fuel pump, the bulk temperature of the counterbody was kept constant at 70 °C by combining heating via an infrared heater and cooling via enhanced air convection. During friction tests, diesel was added onto the wear track of the steel ring by using an injection pump, which enabled a continuous diesel flow. In order to understand the tribological behavior when diesel starvation takes place and severe solid–solid contact situation occurs, effects of diesel flow rate varying from 2 to 50 μL/h were investigated and the contact pressure was fixed at 5 MPa. The studied sliding speeds varied from 0.3 to 1.8 m/s. Elasto-hydrodynamic (EHD) modeling revealed that under the conditions studied, the hydrodynamic pressure of diesel film was negligible and therefore the system lied in boundary friction regime [20]. This is true, especially when a plane-parallel gap of the contact is formed after the running-in period. The specimen's mass loss Δm was calculated by measuring its weights before and after the test. The specific wear rate was calculated using following equation:

$$w_s = \frac{\Delta m}{\rho F L}\ (\mathrm{mm}^3/\mathrm{Nm}),$$

where ρ is the density of the specimen, F is the normal load applied. L is the total sliding distance.

The tribology properties of the PEEK materials when exposed to engine oil lubrication were assessed with Plate-On-Ring (POR) tests using the same four-lever testing system. The POR contact configuration is schematically illustrated in Fig. 1c. The sliding counterbody was a 100Cr6 ring with a diameter of 25 mm and R_a of 0.2–0.3 μm. The polymer specimens had a dimension of $50 \times 10 \times 4\ \mathrm{mm}^3$ (thickness). The contact pairs were fully immersed in an oil bath, as shown in Fig. 1d. Oil temperature was maintained constant at 45 °C by using an oil circulating system. A constant load of 200 N was applied on the polymer plate. According to Hertzian contact theory, the mean contact pressures in case of pure PEEK and PEEK-Com were 0.03 and 0.05 GPa, respectively. Note that the variety of pressure level in different applications with oil-lubrication is very large. The testing condition in this work was chosen according to a certain application of thrust bearings under oil lubrication. In order to study the influence of hydrodynamic effect on the friction behavior of PEEK materials, the sliding velocity was stepwise decreased from 1.8 to 0.03 m/s in one continuous test, without changing polymer sample and counterbody. The friction coefficient was measured online using a force transducer and the wear volume of the materials was measured after friction tests using a white light profilometer (FRT, Germany). The Stribeck