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High load capacity with ionic liquid-lubricated tribological system

Jian Wu [a], Jiahua Zhu [b], Liwen Mu [c], Yijun Shi [d], Yihui Dong [a], Xin Feng [a,*], Xiaohua Lu [a]

[a] State Key Laboratory of Materials-oriented Chemical Engineering, Nanjing Tech University, Nanjing 210009, PR China
[b] Department of Chemical and Biomolecular Engineering, The University of Akron, Akron, OH 44325, USA
[c] School of Materials Engineering, Nanjing Institute of Technology, Nanjing 211167, PR China
[d] Division of Machine Elements, Luleå University of Technology, 97187 Luleå, Sweden

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ABSTRACT

Engineering polymers with high glass transition temperature have been widely used in dynamic friction systems by oil or solid lubrication. However, in high-load systems, oil lubrication is less efficient due to the viscosity decrease at higher temperatures induced by friction heat. [Bmim][PF_6] ionic liquid was used and compared with traditional L-HM46 oil and solid PTFE. Taking advantage of high [Bmim][PF_6] viscosity, strong steel-[Bmim][PF_6] but poor PEEK-[Bmim][PF_6] interaction, the [Bmim][PF_6] lubricated PEEK/steel slide falls in hydrodynamic lubrication and elastohydrodynamic lubrication region under 150–1500 N. While the oil and PTFE both failed to lubricate under 800 N.

1. Introduction

Engineering polymers with high glass transition temperature are widely used as self-lubricating materials sliding against metals in dynamic friction systems, mainly because the soft polymer chain can form transfer films on the metal surface, giving lower friction coefficient and wear than other materials [1]. However, the major limitation by using engineering polymers in dynamic friction system is their intrinsic higher friction coefficient compared with oil lubricated contacts and the relatively poor thermal conductivity, both will lead to fast accumulation of friction heat especially under high load and velocity [2,3]. Without cooling, the temperature rise at the contact surface is proportionally related to the friction coefficient, sliding velocity and applied load [4]. Friction heat generates at the contact interface and dissipates to the bulk body via heat diffusion. Once the surface temperature reaches the glass transition temperature (mostly also the maximum working temperature), polymer chain softening will occur and eventually lead to fatigue [5]. To reduce the friction and wear of the polymers, two major approaches are widely used: (1) incorporate solid lubricants in polymer matrix and (2) introduce liquid lubricants between friction parts. Solid lubricants, such as polytetrafluoroethylene (PTFE), graphite and MoS_2, are often used as a blended component in polymer composites to serve as internal lubricants [6–8]. During friction, solid lubricants facilitate the formation of a third-body transfer film and thus decrease the friction and wear [9]. Solid lubrication does not require external lubricants, which provides great convenience to implement in existing systems and is more economic. The other advantage of solid lubrication is the wide window of operational temperature [10]. However, there are two primary disadvantages with solid lubrication, e.g. relatively high friction coefficient and low strength/toughness of polymer/solid lubricant composites [2,11,12]. On the occasion of high load and velocity, external liquid lubricants such as mineral oils and greases are mostly used. These liquid lubricants tend to adhere to the sliding interfaces by physical or chemical interaction and form a low friction liquid film. The liquid film prevents direct solid/solid contacts, reduces friction coefficient and dissipates friction heat more efficiently [13]. Generally, a strong solid–liquid interaction and continuous liquid film formation are required to reduce friction and wear [14]. However, it brings more challenge when the friction occurs in extremely high load without cooling system due to the low thermal-stability and decreased viscosity of conventional lubricating oil in association with large amount of friction heat.

Ionic liquids (ILs) with fluoroanions and imidazole rings have been demonstrated effective lubricants in various contacts especially for metallic surfaces [15–17]. Recently, an increasing attention has been paid to design task-oriented novel ILs [18–21]. The negligible volatility, high load-carrying capacity and superior thermal stability properties make ILs ideal candidates as liquid lubricants for friction under severe conditions like high vacuum, high load, high temperature, etc. However, unlike metallic surfaces, engineering polymers themselves are usually chemically inert, ILs can hardly adsorb onto them. Will ILs therefore be effective in friction and wear reduction for PEEK/steel contacts under high loads?

* Corresponding author. Tel./fax: +86 25 83588063.
E-mail address: xfeng@njtech.edu.cn (X. Feng).

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Poly(ether-etherketone) (PEEK) is one kind of high performance engineering polymer, which has promising applications in tribological systems such as bearings, gears, thrust washers and seals for automobiles [9,22,23]. To the best of our knowledge, nevertheless PEEK can stand high load and temperature, there are no reported successful examples to apply PEEK composites in high-load conditions without cooling system [11,24]. Also, very rare work has been done to apply ILs as lubricant for engineering polymer/metal contact systems. In this work, we used a commercial ionic liquid [Bmim][PF_6]: 1-butyl-3-methylimidazolium hexafluorophosphate as external lubricant for PEEK sliding against steel under loads till 1500 N without cooling system, the linear velocity is 0.7 m/s. The antifriction and antiwear performance of [Bmim][PF_6] were studied and compared with traditional external lubricating oil: L-HM46 antiwear hydraulic oil, as well as internal solid lubricant PTFE. After friction and wear tests, surface morphologies of both polymer and metal were studied by SEM-EDX and AFM. For the two external lubricants, viscosity influence during sliding was analyzed, and it was further used to investigate the lubrication regime in Stribeck curve.

2. Experimental

2.1. Materials preparation

PEEK powder in 10 μm size was purchased from ICI Company (Victrix 450P, commercial product; UK). PTFE powder in 25 μm size was supplied by DuPont (7A J, commercial product; USA). L-HM46 (SINOPEC, China) [28] and [Bmim][PF_6] (99%; Linzhou Keneng Materials Technology Co., Ltd., China) were used as received. The main properties which affect the lubricating properties are listed in Table 1. The chemical structures of PEEK, the main components of L-HM46 base oil (neutral mineral oil, mainly hydrocarbons) and the main functional additives of L-HM46: zinc dialyldithiophosphate (ZDDP) and [Bmim][PF_6] are shown in Fig. 1 [26,29]. The counterpart steel is AISI304 austenitic stainless steel (nominal chemical compositions: 18.51 wt% Cr, 9.42 wt% Ni, 2.12 wt% Mn, 0.07 wt% C and balance Fe), which exhibits excellent anticorrosion performance in ILs based on imidazolium derivatives with different substituents and anions [30]. The counterpart has an external diameter of 32 mm, an inner diameter of 16 mm, and a thickness of 2 mm (Fig. 2c). The oil cup is also made of AISI304 austenitic stainless steel with an inner diameter of 55 mm and a wall thickness of 2.5 mm.

2.2. Preparation of PEEK composites

PEEK and PTFE powders were dried at 120 °C for 12 h before use. Then, PTFE and PEEK were blended to produce a well-mixed powder with 16 vol% PTFE [31]. Both pure PEEK and PTFE/PEEK samples were processed by high-temperature compression molding at 355 ± 5 °C and 10 MPa for 90 min. After that, the specimens were cut into a shape with an external diameter of 26 mm, an inner diameter of 22 mm, and a shoulder height of 2.5 ± 0.2 mm (Fig. 2b). The specimens and counterparts were polished with P400, P800 and P1200 grinding paper in sequence for smooth surface and uniform contact with a roughness value of 40 ± 5 nm R_a, and then subjected to ultrasonic cleaning in ethanol for 5 min. After it, the specimens were dried in oven at 105 °C for 10 h to remove the ethanol and water.

Table 1
The main properties of L-HM46 and [Bmim][PF_6].

External lubricants	L-HM46	[Bmim][PF_6]
Main components	Neutral mineral oil	[Bmim][PF_6]
Main multifunctional additive	ZDDP (Zn ≤ 0.12 wt%)	/
Kinetic viscosity at 40 °C (mm^2/S)	45.9	89.1 [25]
Viscosity index	97	172 [26]
Surface tension at 40 °C (mN/m)	43.4–48.8	31.85 [27]
Density at 20 °C (kg/m^3)	872.8	1370.0

2.3. Wettability of liquid lubricants

A SL2008 automatic contact angle detector was used to calculate the wettability of L-HM46 and [Bmim][PF_6] on the specimens' surfaces before friction.

2.4. Friction and wear test

The friction tests were performed on three different systems as summarized in Table 2, and the schematic diagrams of solid lubrication and liquid lubrication are shown as Fig. 2d. The testing configuration is schematically illustrated in Fig. 2a with ring shaped specimen rotating on a stainless steel disc on MPX-2000 friction and wear tester (Xuanhua Testing Factory, China). For friction test with external liquid lubricants, the liquid was added before the specimens were brought into contact, and the liquid level was kept at ~2 mm above the counterpart surface. Tests were performed at ambient conditions (temperature 25 ± 5 °C, relative humidity 50 ± 5%) without temperature control. The normal loads applied on the specimen ranged from 150 to 1500 N, and a linear velocity of 0.7 m/s was applied. The corresponding *PV* values (pressure times velocity) were 0.7–7 MPa m/s. The test duration was fixed at one hour.

The values of the friction coefficient for each test were calculated by averaging the steady-state friction coefficients. The contact surface temperature was measured with a thermocouple in the counterpart, which was 0.2 mm underneath the direct contact surface (Fig. 2a). For PTFE/PEEK, wear rate is directly measured from the specimen weight loss after friction test. With liquid lubrication, specimens were subjected to ultrasonic cleaning in ethanol for 5 min to remove the lubricant, and then the specimens were dried in oven at 105 °C for 10 h so that the weight loss could be determined. The specific wear rate, W (cm^3/N m), was calculated by using the equation: $W = \Delta m/(\rho \times N \times L)$, where Δm is the specimen's mass loss after test (g), ρ is the density of the specimen (g/cm^3), N is the normal load (N), and L is the total

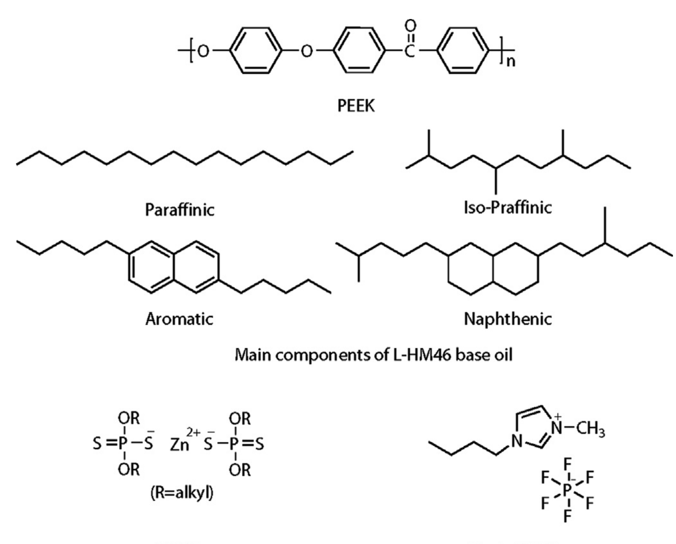

Fig. 1. Chemical structures of PEEK, main components of L-HM46 base oil, ZDDP and [Bmim][PF_6].