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Investigation of porous polyimide lubricant retainers to improve the performance of rolling bearings under conditions of starved lubrication

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ABSTRACT

The current work examines the lubricant retaining effect of porous polyimide (PI) on the performance of rolling bearings under starved lubrication conditions. PI with four different porosities were prepared by cold pressing and sintering processes. The oil-containing and oil-supply properties as well as frictional properties were investigated. Then, PI was used as the retainer for a commercial thrust ball bearing with a race diameter of 18.7 mm. Room temperature tests of retainer performance were conducted with an axial load of 500 N under starved lubrication, in which only residual oil on and in the retainer could work for lubrication. Experimental results show that oil-containing porous PI can easily release oil mainly by thermal expansion rather than centrifugation. Lubrication failure happened quickly with a compact retainer at starved lubrication whereas the bearings with oil-containing porous retainers operated smoothly for 12 h at 800 rpm and 5 h at 1200 rpm. Friction reduction and cooling effects are even more obvious with increased porosity.

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1. Introduction

Lubrication is employed to completely or partially separate the friction surfaces by selectively introducing an interfacial medium (lubricant) that minimizes the friction and wear [1]. However, under some special circumstances, transmission elements like bearings may enter starved lubrication or dry running state, which will lead to lubrication failure [2,3] and damage the bearing retainer easily due to the increased friction and temperature [4–6]. It is necessary and essential to improve the oil-off survivability of bearings in systems such as the helicopter transmission system, which is vulnerable to starved lubrication [7].

Usually, the tribological performance under starved lubrication can be improved by enhancing the mechanical properties of the materials of the friction pair at high temperatures [8], by enhancing the wear resistance of the frictional surfaces [9], and by improving the oil-storage structures in the transmission system [10]. Surface texturing has also been proven useful to improve the anti-seizure ability [11,12] and prolong the life of starved lubrication by obstructing the thermal migration of lubricant [13,14].

Porous polymer is a kind of non-metal material with through and reticular porous structure. They can compensate for situations of starved lubrication in bearings using their ability to self-lubricate [15,16]. The porous structure of such polymers can absorb and store liquid lubricant when it is available, but when needed, release the stored oil to the friction surface continuously and stably [17].

Polyimide (PI) is the kind of polymer materials containing imide ring in the backbone. It has not only good mechanical properties, irradiation resistance, wear resistance and self-lubrication ability, but also excellent heat resistance to thermal oxidation. Therefore, it has received extensive attentions in the field of aerospace, aviation, etc. [18,19].

The material preparation processes of the porous PI have been studied [20,21] and its tribological properties were discussed by many researchers. Tsutomu et al. [22] prepared porous PI films by thermal treatment of poly (urethane-imide) films and found that it had a high glass transition temperature above 400 °C and the tensile strength reached 113 MPa. Samyn et al. [23] investigated the friction and wear behavior of thermoplastic PIs reinforced with short carbon fibers and filled with solid internal lubricant (polytetrafluoroethylene, PTFE). They found that PTFE additives can effectively reduce the coefficients of friction due to their lamellar structure with parallel planes of low shear resistance. Marchetti et al. [24] carried out experimental observation and measurement sintered porous materials (polyimide, stainless steel) and found that centrifugation, creeping by roughness and thermal effects had great impact on supplying a liquid film with lubricant initially contained in porous structure.

However, few publications have reported oil-containing and oil-supply properties of porous PI. Even less was reported on the porous PI with different porosities, which is a key index of porous

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materials that decides the lubrication performance of porous materials. Besides, there is little knowledge about the difference of friction properties between oil-containing and non-oil-containing PI with different porosities. Particularly, limited information is available on the lubrication performance of oil-containing porous PI retainer on the ball bearings, which is essential to guide the applications of porous PI in such systems.

In the current work, the oil-containing and oil-supply properties of porous PI with different porosities were studied as well as their effects on friction and wear. In order to investigate the dry-running performance of rolling bearings, both compact and porous PI samples were prepared and tested in the form of retainers of thrust ball bearings.

2. Experimental section

2.1. Sample preparation

In the current work, PI particles, Ratem®YS20 with glass transition temperature of 266 °C, were purchased from Shanghai Research Institute of Synthetic Resins, and sieved through screen of 200 mesh. Porous PI samples were prepared by cold pressing and sintering process. Table 1 shows the preparation conditions of four porous PIs with different porosities. After the powder compaction and sintering at a certain temperature, the surface of the polymer particles melted and bonded together, formed micro pores. Finally, hot pressing was applied right after the sintering to adjust the density of porous materials.

The porosity of porous material is defined as the ratio of the pore volume over the total volume of the sample, calculated by:

$$\theta = \left(1 - \frac{M}{V\rho_s}\right) \times 100\%, \tag{1}$$

where M is the weight of the sample, V is the volume of the sample and ρ_s is the density of the condensed PI. According to the measurement, the average porosity of the four samples were 0% (compact), 12.6%, 23.6%, and 33.5%, respectively.

The PI samples with different porosities were cut by knife to study the internal structure. As shown in Fig. 1, the difference between compact and porous sample are distinct. The compact PI sample has almost no pore (see Fig. 1(a)) whereas the porous PI samples (see Fig. 1(b, c, d)) have pores that potentially connect to each other. These connected pores can effectively ensure the storage and flow of the lubricant. With the increase of porosity, the pore density increases and distributes more uniformly.

2.2. Oil-supply test

Commercial CD grade diesel engine oil CD15W-40, with a kinematic viscosity of 110.6 mm^2/s at 40 °C and 15.02 mm^2/s at 100 °C, was used as the lubricant in the current work. Polished PI samples with the same volume were firstly immersed in the lubricant for 12 h in a vacuum degassing chamber. The lubricant on the surface was wiped off to get the oil-containing samples. The weight of the samples was recorded before and after immersion.

The oil-containing property of the porous PIs are shown in Table 2. The oil content ratio is defined as the ratio of the volume of the contained oil over the volume of the sample. The result for each sample was the average of three independent tests under the same experimental conditions. For the sample with 12.6% porosity, the oil content was found to be 6%, indicating that only 47% of the pores were occupied by the lubricant. However, when the porosities were 23.6% and 33.5%, the oil content ratios rose to 20.7% and 29.5%, respectively, showing that as high as 87% and 88% of the pores were filled with lubricant. Clearly, not all pores can store lubricant because the oil can only enter the sample through interconnected pores. With the increase of porosity, the permeability and connectivity of the internal pores becomes better, therefore enhances the oil-containing property.

Table 1
Preparation conditions of porous PI samples.

Porosity	Cold pressing pressure (MPa)	Sintering temp (°C)	Sintering time (h)	Hot pressing pressure (MPa)
0%	15	350	1	15
12.6%	15	350	1	3
23.6%	60	350	2	–
33.5%	15	350	1	–

In the course of bearing operation, the supply of lubricant from the oil-containing retainer could be mainly influenced by centrifugation and the thermal effects. Hence, the oil supply ability was evaluated by centrifugation test and heating test, respectively.

In centrifugation tests, the sample with diameter of 30 mm and thickness of 3.2 mm was fixed on a high speed rotation machine. It was found that the samples had good oil retention and almost no oil was spilled at the rotational speed up to 3000 rpm. Hence, the thermal effects was focused instead.

The oil-containing sample was placed on a heating table, whose temperature was increased from 22 °C (room temperature) to 80 °C. A digital video was employed to record the oil spilling process. Fig. 2 shows the oil-spilling process of the oil-containing sample with a porosity of 33.5%. It was found that the oil-containing porous sample is sensitive to temperature increase. There were almost no oil on the surface at room temperature as shown in Fig. 2(a). As soon as the heating process started, the internal lubricating oil in the sample began to spill out due to the thermal expansion. When the temperature was increased to 80 °C, the sample surface was covered with a layer of lubricant film as shown in Fig. 2(b). Interestingly, when the heater was turned off and the sample cooled down, the spilled oil was sucked back into the sample as shown in Fig. 2(c). This is likely due to the contraction of the lubricant inside the sample and capillary effect of pore structure.

During the quantitative evaluating experiments, the spilled oil on the surface was wiped off by cotton cloth continuously during the heating process until there was no longer oil spilled. By weighing the sample before and after heating, the quantity of the spilled oil from the sample can be determined. As shown in Table 2. The measured oil supply content approximately quadrupled when the sample porosity increased from 12.6% to 23.6%. Also, a relatively small increase was observed when the porosity increased from 23.6% to 33.5%. Apparently, with low porosity, the performance of oil spilling performance was poor, the higher the porosity is, the better the oil-supply performance is.

The typical thermal expansion coefficients of the lubricant and the solid PI material are $\alpha_{oil} \approx 8 \times 10^{-3}$ °C^{-1} and $\alpha_s \approx 4.2 \times 10^{-5}$ °C^{-1} [24], respectively, indicating that the thermal expansion of the PI material is only approximately 0.5% of that of the lubricant at same elevated temperature. Hence, it is believed that the observed oil spilling is mainly due to the expansion of the lubricant rather than that of the porous structure. The oil supply by thermal expansion can also be evaluated theoretically. The influential parameters are:

α_{oil} thermal expansion coefficients of lubricant,
T_0, T room and elevated temperature, respectively,
$\rho_{oil,T}$ density of lubricant at elevated temperature T, $\rho_{oil,T} = 0.8365$ g cm^{-3},

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