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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.

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},

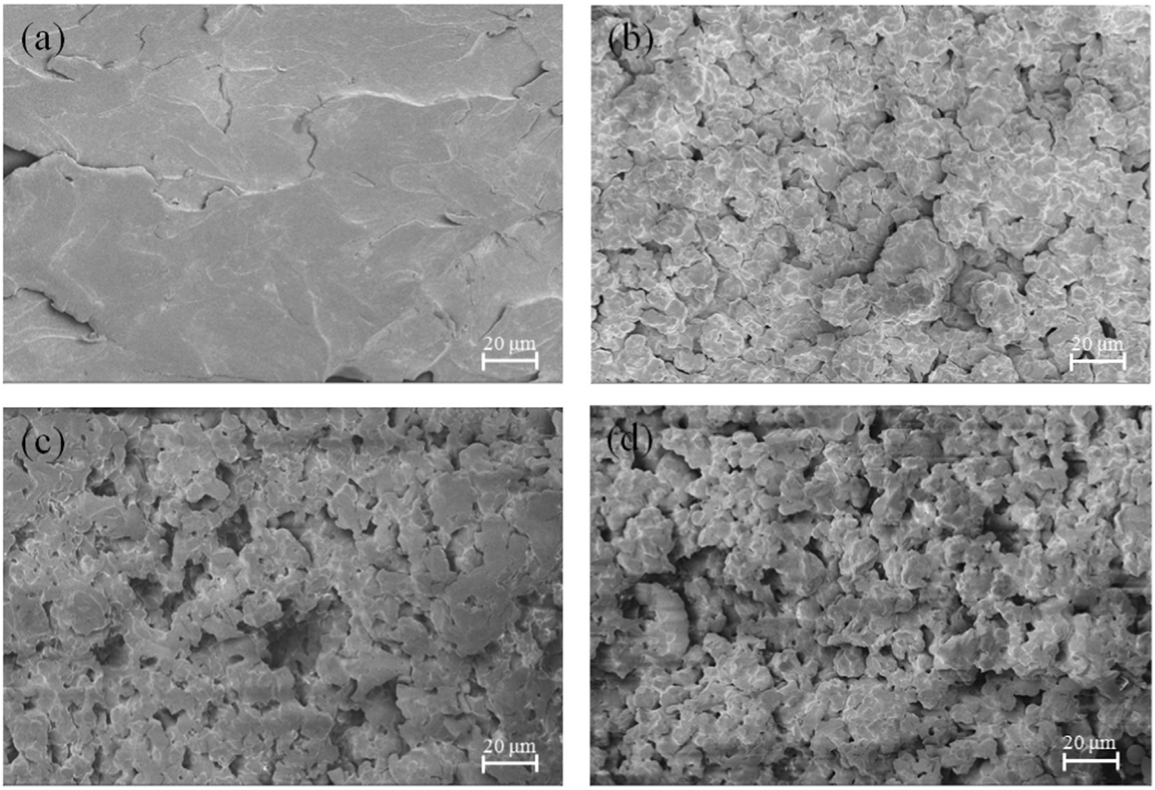

Fig. 1. SEM images of internal structure of PI samples with different porosities. (a) 0%; (b) 12.6%; (c) 23.6%; (d) 33.5%.

Table 2
Oil-containing and oil-supply properties of the porous PI samples.

Porosity	Oil content ratio	Oil supply content (g)	
		exp	*theory*
12.6%	6.0%	0.046	0.052
23.6%	20.7%	0.178	0.181
33.5%	29.5%	0.201	0.257

ϕ the oil content of oil-containing samples,
V the volume of samples at room temperature, $V \approx 2.248$ cm^3.
The weight of the spilled lubricant m can be calculated by:

$$m = \rho_{oil}, T{\cdot}\phi{\cdot}V{\cdot}\alpha_{oil}(T - T_0). \tag{2}$$

Table 2 shows the amount of oil theoretically spilled during the experiments. It can be seen that the theoretically calculated values are a little larger but very close to the experimental values. This confirms that the thermal effects play the dominant role in the oil supply process.

It must be noted that not all stored oil (around 35–55%) could be spilled out under the thermal effects. It is known that the Laplace pressure in opened pores tend to resist oil spilling. The Laplace pressure can be estimated by [24]:

$$P = \frac{2\gamma_{LV}}{R_{pore}}, \tag{3}$$

where γ_{LV} is the surface tension of lubricant and R_{pore} represents the average pore radius. In order to have significant amounts of lubricant extracted from a porous reservoir, the thermal expansion needs to overcome the Laplace pressure.

As mentioned earlier, the internal lubricant of the oil-containing samples cannot be thrown out by the centrifugal effect at a rotational speed up to 3000 rpm. That is because the centrifugal force generated by the rotation cannot overcome the Laplace pressure formed with the internal pores. However, the internal lubricant be easily spilled out upon heating. This is turns out to be a beneficial feature for the application of bearing retainer [18,25].

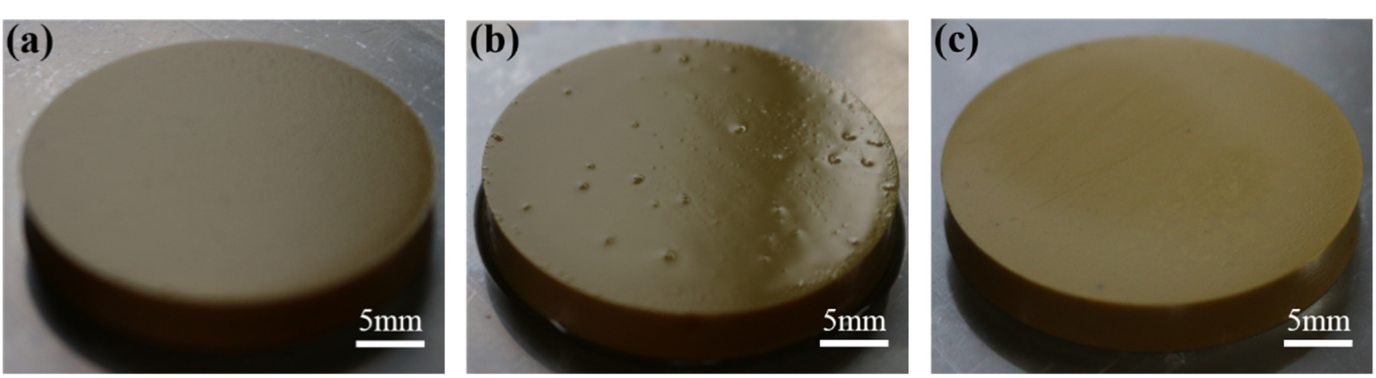

Fig. 2. Images of oil-spilling process of oil-containing sample. (a) Before heating; (b) Heated to 80 °C; (c) cooled down to 20 °C.

Under normal circumstances, the porous PI retainer absorbs and stores the lubricant and the lubricant does not come out under normal operation conditions. When the lubrication system failed and the rolling bearings experience starved lubrication, the internal lubricant can be released due to the significant temperature rise caused by aggravated friction. The released lubricant can also be sucked back when the temperature drops which ensures the maximum utilization of the lubricant.

2.3. Friction and lubrication tests

2.3.1. Friction test

The friction property of porous PI was investigated by using a ring-on-disk conformal contact friction wear tester MMW-1 (Jinan Lanbo Corp., China) at room temperature. The lower (stationary) specimen was made of PI material in the shape of a disk (30 mm in diameter, 3.2 mm in thickness). The upper (rotating) specimen was made of 316 stainless steel in the shape of a ring (28 mm in outer diameter, 14 mm in inner diameter) considering the fact that stainless steel is a typical bearing material because of its excellent antirust and anticorrosion properties. The stainless steel is much harder than the PI material, so the testing surface of the stainless steel was polished to obtain an average surface roughness Ra around 0.02 μm. PI specimens were tested in the states of non-oil-containing and oil-containing.

Fig. 3 presents the friction coefficients of non-oil-containing and oil-containing samples with different porosities under the rotational speed of 200 rpm (mean linear velocity of 0.22 m/s) and the load of 100 N, corresponding to the contact pressure of 0.2 MPa. The test time was 10,800 s and the mean value of friction coefficient was recorded. It can been seen that, with the increase of porosity, the friction coefficient of the non-oil-containing samples increased gradually from 0.23 to 0.37, whereas the friction coefficient of the oil-containing samples decreases from 0.18 to 0.09. With the same porosity, the friction coefficient of the oil-containing sample was significantly less than that of non-oil-containing sample. These results show that the oil-containing porous PI samples have a good anti-friction effect. Moreover, the higher the porosity is, the more effective the anti-friction effect appears to be.

Above results show that the friction property of the porous sample is determined by the internal structure of the porous PI and the lubricant contained inside. With the increase of porosity, the number of pores increases (see Fig. 1), which may lead to higher surface roughness and higher degree of stress concentration, exacerbating the friction. This is the reason why the friction

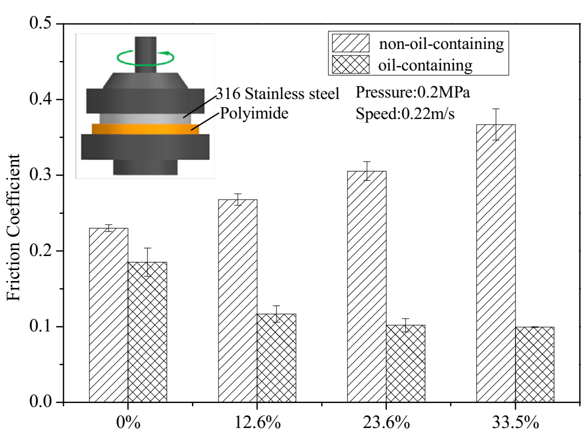

Fig. 3. The friction coefficients of oil-containing and non-oil-containing samples with different porosities.

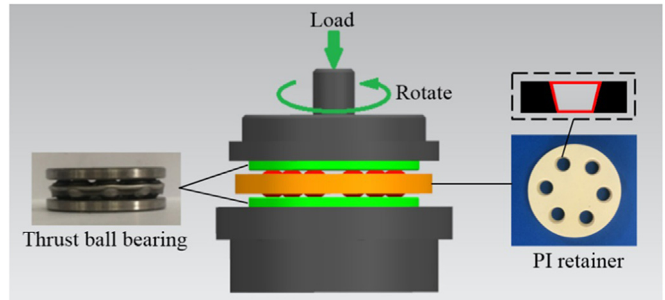

Fig. 4. Schematic diagram of bearing lubrication tester.

coefficients of non-oil-containing samples increase with the increase of porosity. On the other hand, the higher the porosity of the sample is, the higher the oil content is, and the better lubrication can be effectively achieved. This latter effect is the dominant factor that determines the friction in the oil-containing sample cases, resulting in the decreased friction coefficients with the increase of the porosity.

2.3.2. Bearing lubrication test

Since the above friction tests showed positive results, the lubrication tests were further conducted to confirm the lubricating effects of oil-containing porous PI as the retainer of rolling bearings. The friction tester MMW-1 was modified as shown in Fig. 4 to perform the bearing tests. The bearing model 51101 (HARBIN Bearing Corp., China) was selected as the basic testing specimens, and their retainer were replaced with that made of PIs. The original bearing has ten balls as the rolling elements. In order to minimize the influences of positioning and fabrication error, only six tapered holes are evenly fabricated on the PI retainer to hold the steel balls forming line contact. The PI retainers owing the porosities of 0% (compact), 12.6%, 23.6%, 33.5% were tested and labeled as A, B, C and D, respectively. Before each test, the bearing parts was ultrasonically cleaned in acetone, rinsed with ethanol and finally blow-dried with nitrogen. After the cleaning, both the compact and porous retainers were immersed in the lubricant for 12 h in a vacuum degassing chamber. The lubricant on the surface of each retainer was wiped off by cotton cloth to create the conditions of starved lubrication, in which only residual oil on and in the retainer could work for lubrication. Experiments were then carried out under the axial load of 500 N and rotational speeds of 800 rpm and 1200 rpm (mean surface velocities of 0.8 and 1.2 m/s) at room temperature. Thermocouples were fixed on the outer surface of the stationary ring. Because it is far from the contact position of the ball and race, the temperature obtained is that of stationary ring influenced by the thermal conductivity of the positioning jig. After the test, the specimens were cleaned ultrasonically in acetone. The micro morphologies of the worn surface were observed with a surface mapping microscope (BRUKER Corp., USA) and optical microscope (KEYENCE Corp., Japan).

Fig. 5 presents the evolution curves of the friction moment and the temperature (raceway surface) of the thrust ball bearing under different rotational velocities.

For the bearing A with the compact PI retainer, as shown in Fig. 5(a), at rotational speed of 800 rpm, the friction moment stabilized around zero at short times and the temperature gradually increased about 15 °C. When the running time reached 9700 s, the friction moment began to increase dramatically and became extremely unstable and the temperature increased rapidly by 25 °C within 1000 s. At the same time, the friction sound became sharp, and a large amount of wear debris was produced. It was believed that the lubrication failure occurred from the beginning of this period, and sliding happened between the roller

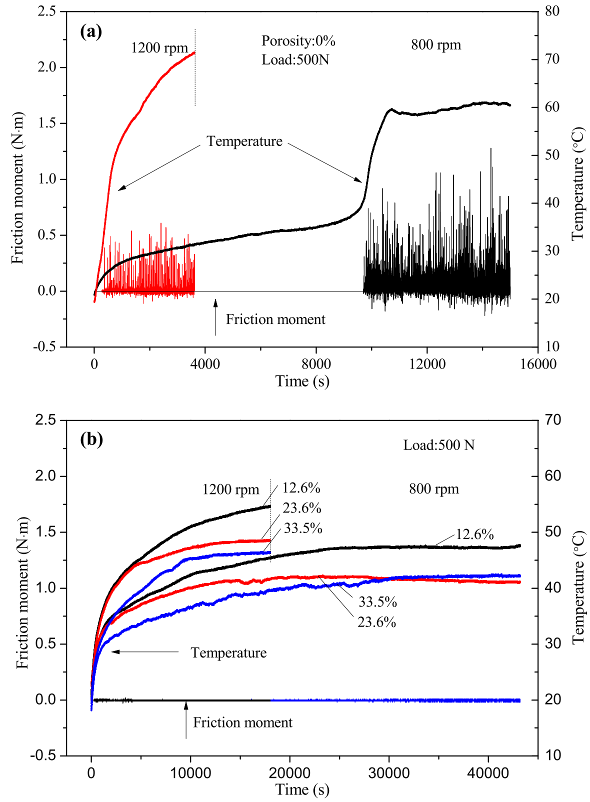

Fig. 5. Evolutions of friction moment and temperature curves of bearing. (a) Bearing A; (b) Bearing B, C, D.

and the raceway. Hence, the tests were terminated at the time shown in Fig. 5. The observation shows a lot of wear debris were embedded in bearing raceway surface as shown in Fig. 6 (a) corresponding to the severe adhesion wear.

When the rotational speed was 1200 rpm, the friction moment became extremely unstable after just 300 s and the temperature increased from 20 to 70 °C continuously within 3600 s. It was clear that the lubrication failure occurred more quickly than the case of 800 rpm. Of course, the surface residual lubricating oil can provide transient lubrication for bearing. However, with the increase of the rotational speed, the time of maintained lubrication was shortened dramatically. The reason should be that the surface residual oil is more easily to be consumed and thrown away due to the larger centrifugal force at high rotational speed.

For the bearing B, C and D with the porous PI retainers, as shown in Fig. 5(b), whether the rotational speed was 800 rpm (for 12 h) or 1200 rpm (for 5 h), the friction moment always maintained low values around 0, which are so small that it is hard to compare the differences of the retainers with different porosities, indicating that there was no occurrence of lubrication failure in these experiments. The temperatures were relatively stable during the test. Generally speaking, the lower the porosity of retainer is, the higher the temperature of bearing rose. Particularly, the range of the temperature rise of the bearing C and D were smaller than that of the bearing B. The experiments lasted 12 h at 800 rpm and 5 h at 1200 rpm, then, terminated because the bearing system of the tester became hot. By the observation on the tested specimen, only some slight wear was found on the raceway surface of Bearing B, C and D. Relatively, the wear width of the bearing B was found to be wider than those of bearing C and D, as shown in Fig. 6 (b, c, d). The wear widths of bearing C and D were found similar.

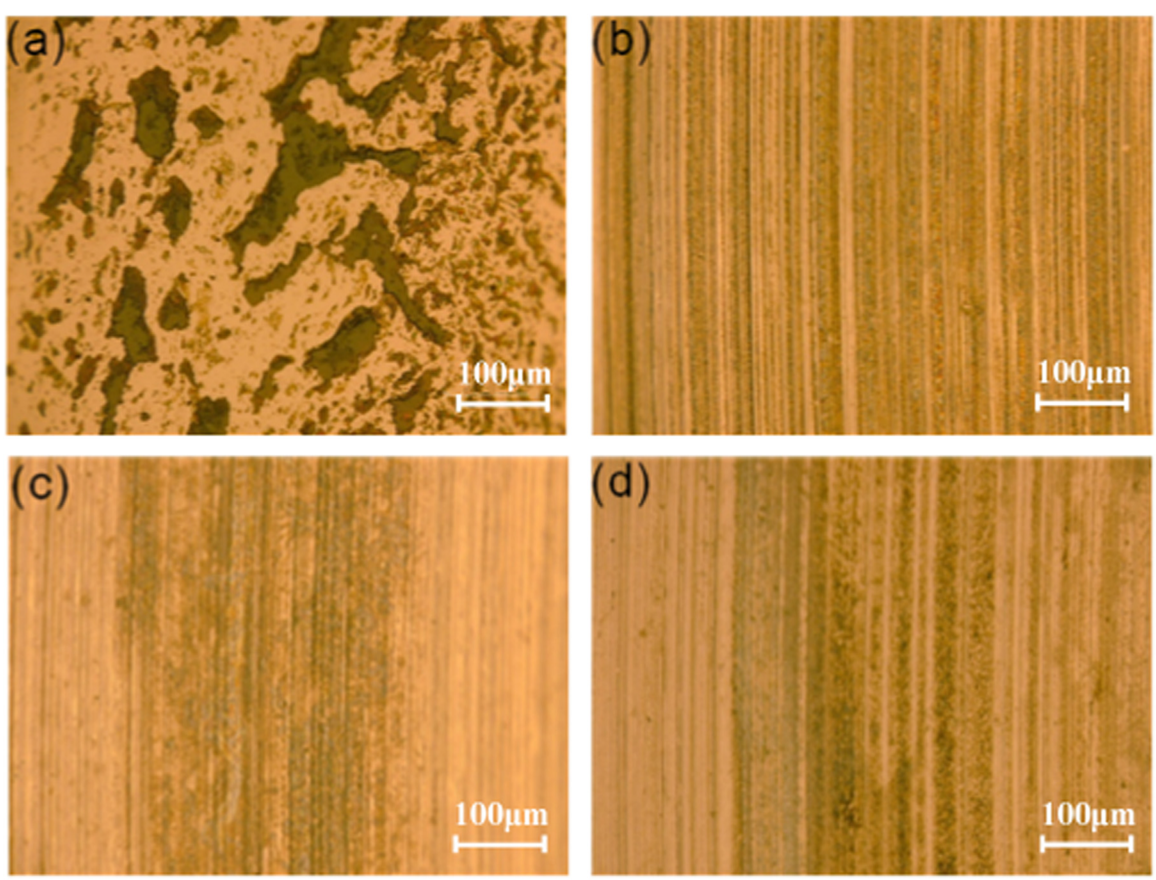

Fig. 6. Optical images of wear tracks of bearing raceway surface. (a) Bearing A; (b) Bearing B; (c) Bearing C; (d) Bearing D.

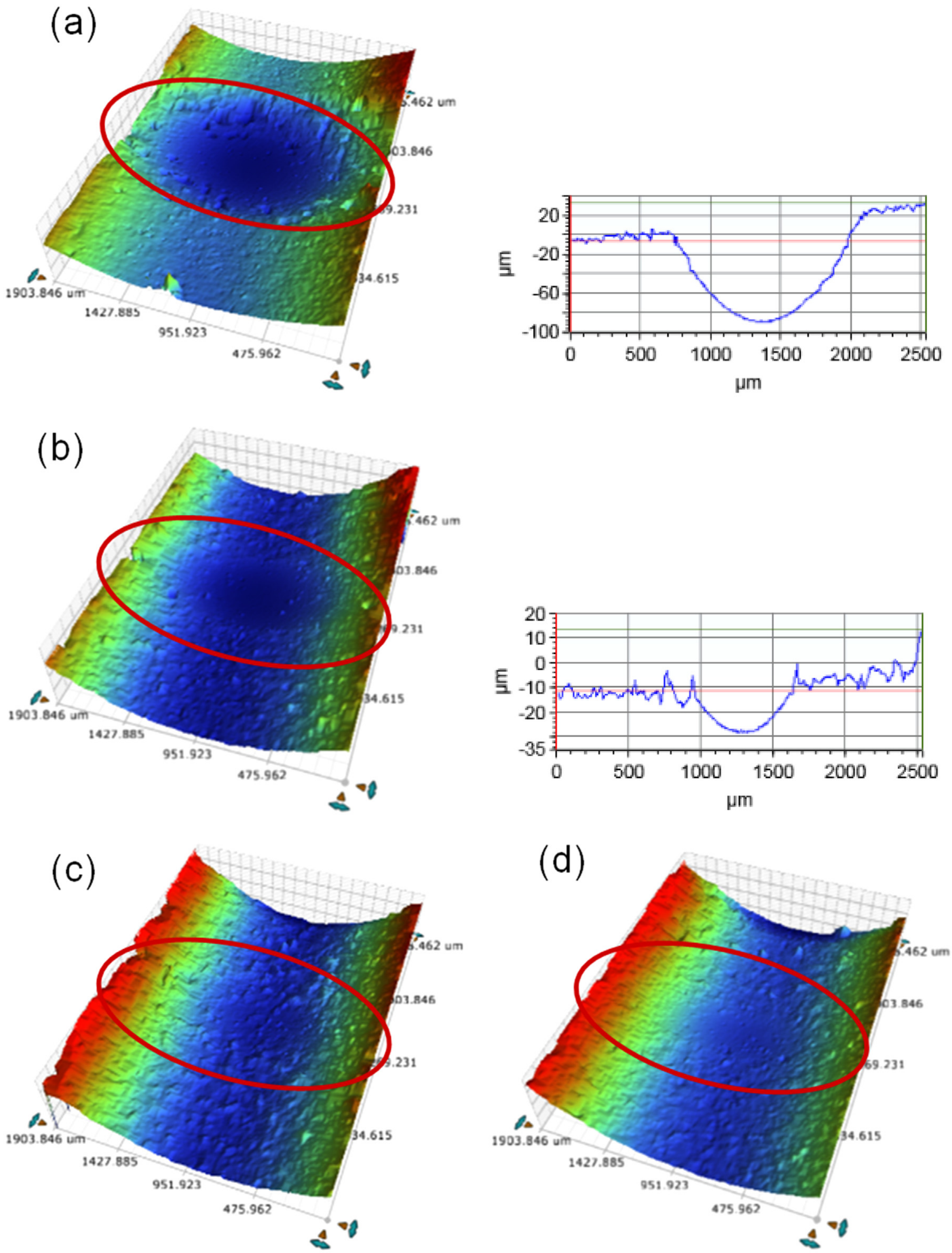

Fig. 7. Three-dimensional (3D) morphologies of wear tracks of retainers with different porosities. (a) 0%; (b) 12.6%; (c) 23.6%; (d) 33.5%.

Fig. 7 presents three-dimensional morphologies of wear tracks of retainers with different porosities. After 12 h of operation at the speed of 800 rpm, it can be seen clearly that the compact retainer was worn out a lot with depth near 100 µm (see Fig. 7(a)). However, the wear scar of the retainer with the porosity of 12.6% was shallower (see Fig. 7(b)) and the wear depth was around 15 µm. In the case of 23.6% and 33.5% porosities, there was only a slight wear on the retainers (see Fig. 7(c, d)).

The bearing lubrication tests as described above were repeated two times. The same testing procedure was also applied to an angular contact bearing. All the results are consistent with those presented above.

Therefore, it can be concluded that oil-containing porous PI retainer can release the internal lubricant steadily, providing a good lubrication to thrust ball bearing for cooling and friction reduction. And, the capability of resisting the abrasion of the retainer was also improved due to the internal lubricant. These three kinds of oil-containing retainers all performed reasonable lubricating effects. However, it should be noted that the lubrication performances of the retainer with the porosities of 23.6% and 33.5% were better than that of the 12.6% porosity in terms of temperature rise, friction and wear.

The current work presented some preliminary results. Further systematic full-life experiments using professional bearing testing apparatus under different load and speed conditions are definitely needed.

3. Conclusions

The purpose of this work was to propose and test a method that uses porous, oil-containing polyimide (PI) to improve the tribological performance of thrust-type, rolling bearings when under starved lubrication conditions. The properties of lubricant retention, method of supply, and sliding friction characteristics of the porous PIs having a range of porosity were investigated. The main results can be summarized as follows:

1) Porous PI has an ability to absorb liquid lubricant due to its distinctive porous structure.
2) Thermal effects rather than effects from centrifugation showed a primary influence on the properties of the oil being supplied. This characteristic benefits rolling bearings that are forced to work under starved lubrication. As PI porosity increased, the oil content ratio and the oil supply increased. That in turn resulted in better oil retention and reduced spillage.
3) Compared with compact PI retainers, porous retainers containing oil supply lubricate more steadily and improve performance in terms of increased life, enhanced cooling, and decreased friction and wear.

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