Chapter 7

Lubrication and Friction of Porous Oil Bearing Materials

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Abstract

In order to address poor lubrication of porous bearings due to the seepage flow of oil into the porous medium, multi-layered sintered composite bearings have been developed. Multi-layered bearings achieve a combination of high strength and good lubrication. Lubrication model of the porous multi-layer materials in polar coordinates was established based on Darcy's law. And the effect of surface Darcy flow and porous structure on the lubrication capacity were discussed by using the finite difference method. In the end, the tribology experiments of the multi-layer materials were presented on the end face tribo-tester to verify the simulation results. Results show that the lubrication performance of the multi-layer materials is better than that of the single layer materials. With the decrease of the surface porosity, the lubrication performance becomes better in the given range of surface layer. Also, it can be significantly improved if considering the surface Darcy flow. Within a certain range, the effects of surface Darcy flow on lubrication performance are more obviously with higher speed. There is a good agreement between the numerical analysis and the measurement. Research work provides a theoretical basis for analysis and design of multi-layer sintering bearing material.

Keywords: lubrication, friction, porous bearing, multi-layer materials, Darcy law

1. Introduction

Oil bearings with porous matrix have been widely used in industrial applications for its low manufacturing cost and oil self-lubricating properties [1]. As the counterpart picks up speed, the oil impregnated in the porous bearing exuded to the surface and the hydrodynamic oil film formed. Therefore, the oil storage capacity and lubrication performance have an important influence on the operating characteristic of oil bearing [2]. Over the past decades, a considerable number of theoretical models have been proposed on the lubrication characteristic by several researchers. The hydrodynamic theory of porous journal bearings was studied originally by Morgan and Cameron, who gave a solution for a short bearing based on Darcy model [3]. Later, Darcy's equations were extensively used in the study of the lubrication characteristic of oil bearing. The unsteady state, non-Newtonian effect and rough surface were coupling to the lubrication model to improve the numerical accuracy [4–9]. These studies were all focused on single-layer bearing materials, without considering the change porosity in the thickness direction. Meurisse [10] and Usha [11] found that reducing the porosity can prevent the oil leaking into the porous medium and improve the bearing strength and hydrodynamic capacity. But the decreased porosity leads to the decrease of oil content and then will deteriorates the self-lubrication performance. Therefore, it can be concluded that the coexistence of high strength and good lubrication characteristics of the porous bearing are difficult to achieve. This is the biggest problem that oil bearing has encountered in the industrial application. Hence, adjusting the permeability of bearing reasonably is the key to improve the lubrication property. Based on the above studies, Naduvinamani [12] and Rao [13] discussed the effect of the multi-layer structure parameters on the lubrication property, which promoted the theoretical development of the oil bearing. This multiple-layer structure is useful, as it would not only increase the load capacity of the bearing because of reduced oil seepage into its wall but would also help to bring oil between the surfaces, thereby improving the bearing performance when saturated with oil Inadequately. But for now, there is no systematic research on the multi-layer oil bearing materials compared with the single-layer sintered materials. Especially, most researchers ignored the surface Darcy flow to simply the boundary condition in the previous work. It did not coincide with the homogeneity and isotropy hypothesis, which will undoubtedly have a bad effect on the analysis accuracy. In this paper, the multi-layer oil bearing composites with different porosities were made to achieve the unification of high strength and good lubrication property. Hydrodynamic lubrication model of the porous bearing in polar coordinate system was established based on Darcy's law. The effect of surface Darcy flow and porous structure on the lubrication property were also discussed. In the end, the tribology experiments of the multi-layer materials were presented on the end face tribotester to verify the simulation results.

2. Lubrication model of the multi-layer sintered material

The physical configuration of the multi-layer bearing system is shown in **Figure 1**. As shown in **Figure 1**, the porous disk bearing ($\phi 34 \times 4$ mm) prepared by powder metallurgy is fixed. And the counterpart rotates at the angular velocity ω. T_1 and T_2 are the thicknesses of the surface and bottom layers. Similarly, k_1 and k_2 are the permeability of the two layers respectively. The o-x-y-z coordinate system is built on the surface of the porous bearing. Assuming that the counterpart surface is smooth. While the bearing surface has a sinusoidal roughness. The fluid film thickness h can be shown as

$$h = h_0 + \delta_0 \sin(2b\pi r) \sin(c\theta) \tag{1}$$

where the minimum film thickness h_0 equal to 10 μm, and the height of the roughness asperity δ_0 equal to 2 μm. The characters b and c represent rough peaks in radial and circumferential directions, respectively.

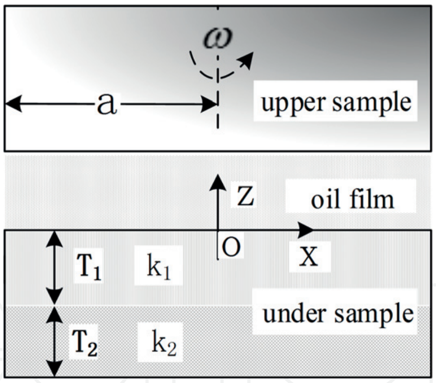

Figure 1. Two rotary parallel disc samples.

If take b equal to 2 and take c equal to 8, the film thickness is show in **Figure 2**.

Suppose the porous matrix is homogeneous and isotropic. That means the permeability is equal in any coordinate direction. The flow in porous matrix is governed by the Darcy's law.

$$U_0 = \frac{k_1}{\eta}\frac{\partial p}{\partial x}; V_0 = \frac{k_1}{\eta}\frac{\partial p}{\partial y}; W_0 = -\frac{k_1}{\eta}\left(T_1 + \frac{k_2}{k_1}T_2\right)\left(\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2}\right) \tag{2}$$

where η is the fluid viscosity, and p is the fluid pressure in porous matrix.

Owing to the fluid continuity in the porous bearing, the pressure p satisfies the Laplace equation

$$\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2} = 0 \tag{3}$$

Integrating the continuity Eq. (3) over the fluid film thickness and using the Eq. (2) as the velocity conditions, the general Reynolds equation can be obtained. By the coordinate transform technology, the Reynolds equation under the polar coordinate shown as

$$\frac{\partial}{\partial r}\left[r\lambda\frac{\partial p}{\partial r}\right] + \frac{\partial}{r\partial\theta}\left[\lambda\frac{\partial p}{\partial\theta}\right] = -6\eta\omega r\frac{dh}{d\theta} \tag{4}$$

where $\lambda = h^3 - 6hk_1 - 12k_1T_1 - 12k_2T_2$. And the surface Darcy flow in the three coordinate directions are all considered.

Similarly, the Reynolds equation without surface Darcy flow shown as

$$\frac{\partial}{\partial r}\left[r\xi\frac{\partial p}{\partial r}\right] + \frac{\partial}{r\partial\theta}\left[\xi\frac{\partial p}{\partial\theta}\right] = -6\eta\omega r\frac{dh}{d\theta} \tag{5}$$

where $\xi = h^3 - 12k_1T_1 - 12k_2T_2$.

As we all know, the internal powder particles are sintered at high temperature during the preparation of the oil bearing by powder metallurgy technology. The pores between the spherical particles are connected with each other to form the porous channels of the oil bearing, which is consistent with the modeling idea of the Kozeny–Carman equation. So the

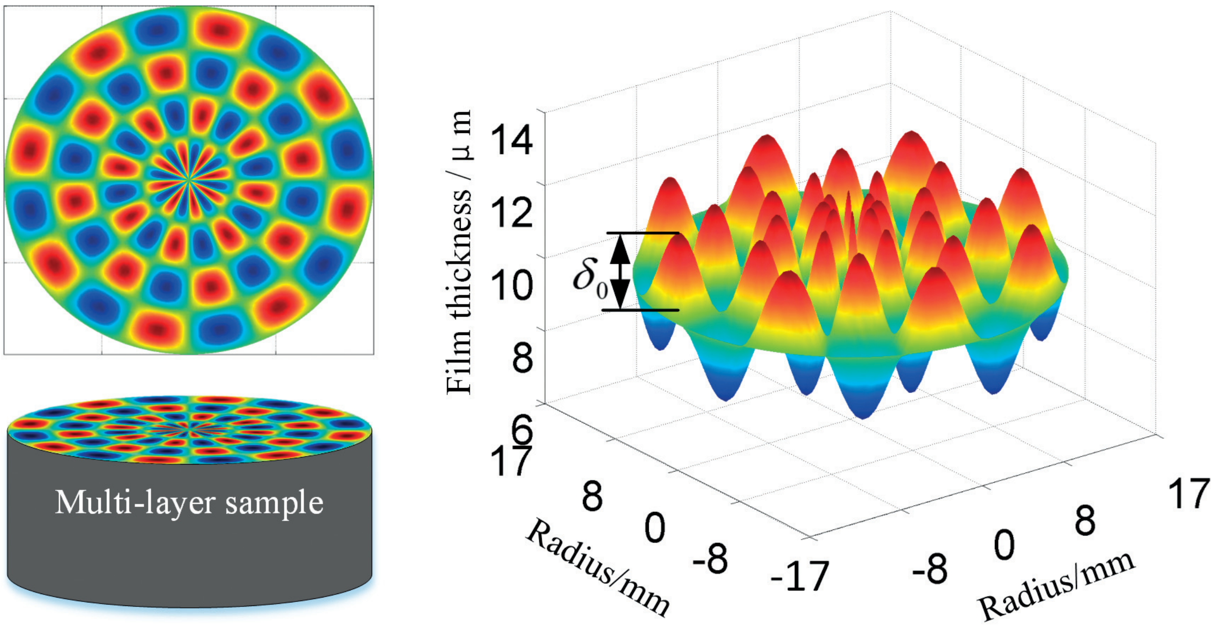

Figure 2. Film thickness.

relationship between pore structure and fluid pressure drop is often represented by Kozeny–Carman equation. Supposing that the porous bearing material is composed of tiny spherical particles with an average diameter of Dc, the permeability of the bearing can be described as

$$k_i = \frac{D_c^2 \varphi_i{}^3}{180(1-\varphi_i)^2} \tag{6}$$

where φ_i is the porosity of surface and substrate layers of the porous bearing.

The boundary condition shown as.

$$p|_{r=a} = 0; p_{\theta=0} = p_{\theta=2\pi} \tag{7}$$

where a is the outer radius of the disc bearing.

3. Results and analysis

In the present study, the lubrication model of the multi-layer porous bearing under polar coordinate system was established. The combined effects of the roughness, surface Darcy flow and porous structure on the lubrication performance have been studied. The following data given as: φ_i = 8 or 10%, $D_c = 1 \times 10^{-4} \sim 5 \times 10^{-4}$m, T_i = 0.002 m, η = 0.02 Pa · s.

3.1. Effect of surface Darcy flow on lubrication property

Figure 3 shows the effect of the surface Darcy flow on the hydrodynamic pressure. The pressure distributions with surface Darcy and without surface Darcy flow are shown in **Figure 3(a)** and **(b)**, respectively. The effect of surface Darcy flow on pressure distribution under different speeds are shown in **Figure 3(c)** and **(d)**. As can be seen from **Figure 3**, the

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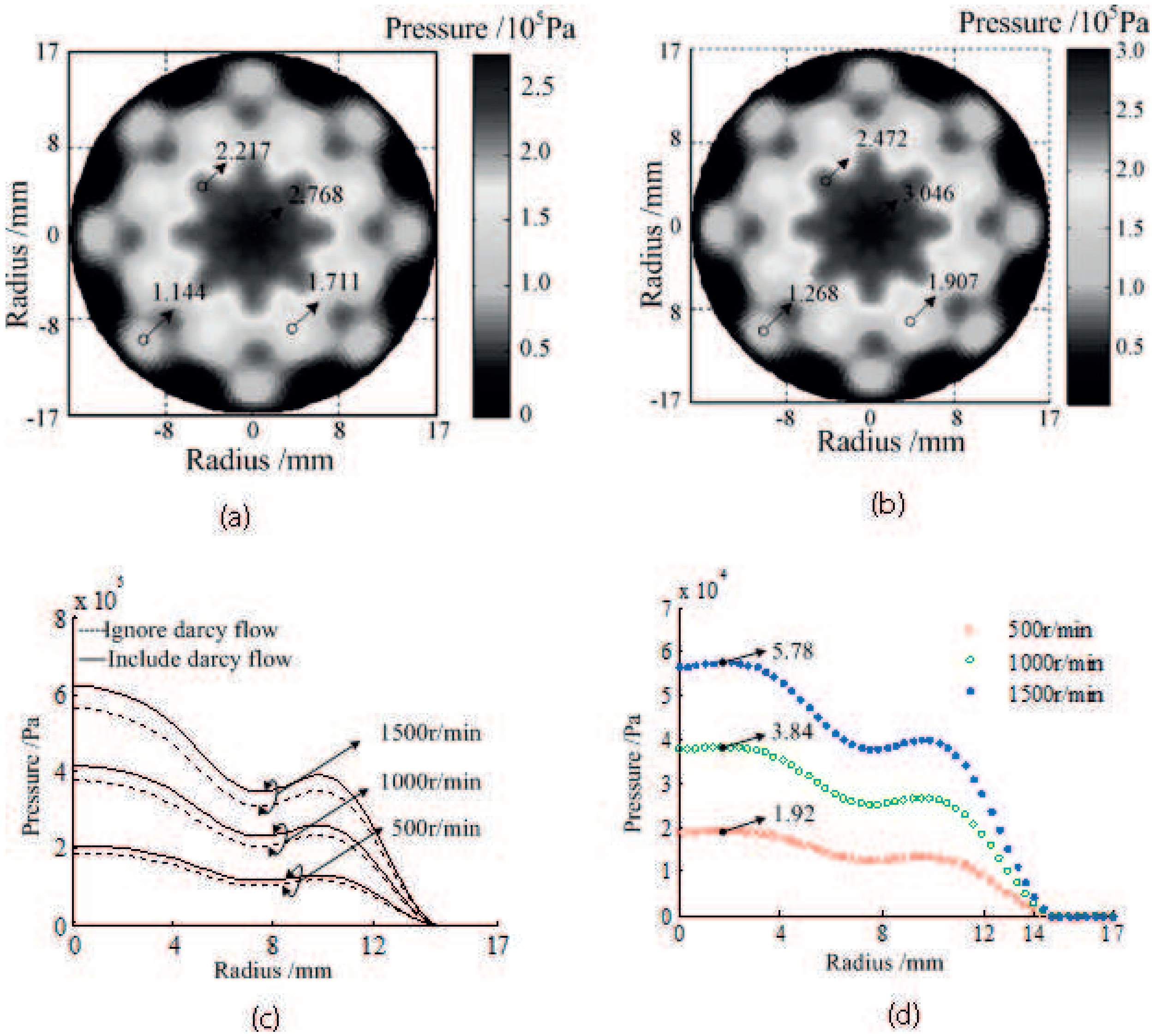

Figure 3. Effect of surface flow on pressure and its amplification in varied speeds. (a) Pressure with no surface flow (b) Pressure with surface flow (c) Pressure distribution (d) The pressure amplification.

pressure also presents a sine form, similarly to the film thickness distribution. The maximum pressure occurs at the center of the porous circle surface, and the minimum occurs at the outer circle. In addition, the oil film pressure increases with the increase of speed, and the pressure is higher if take the rough surface Darcy flow into consideration in every instantaneous speed. As shown in **Figure 3(d)**, the pressure amplification increases with the increase of speed along the radius direction. And it is more obvious that the effect of the surface Darcy flow on the pressure amplification with the increase of speed. The maximum pressure amplifications in three speeds are 1.92×10^4, 3.84×10^4, 5.78×10^4 Pa, respectively.

Figure 4 illustrates the variation of the load capacity and friction coefficient with the speeds. It is observed that the surface Darcy flow has obvious significance to the lubrication property. The property turns better when considering the surface flow. And its effect becomes obvious with the increase of speed. For example, when the speed is 1500 r/min, the load capacity caused by surface Darcy flow increases by 11.64%. Moreover, the lubrication property of single

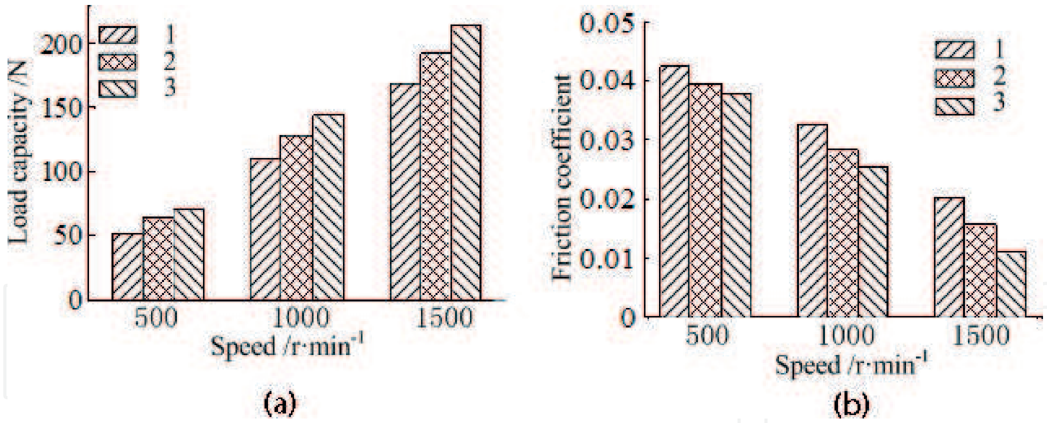

Figure 4. Effect of surface Darcy flow on the friction coefficient in different speeds. (a) Carrying capacity (b) Friction coefficient. Note: 1 denote monolayer material ignored Darcy flow; 2 denote multi-layer material ignored Darcy flow; 3 denote multi-layer material included Darcy flow.

and double layer oil bearings is improved with the increase of velocity. And the property of the multi-layer bearing is better than that of the single layer. In the single layer oil bearing, the oil driven by the hydrodynamic pressure penetrates into the porous medium easily, which weaken the oil thickness and the lubrication property. In the multi-layer oil bearing, the dense surface could prevent the fluid seepage into the porous bearing. Therefore, a thicker lubricant film can be formed between the friction pairs. And the multi-layer bearing with dense surface has better property than that of the single layer bearing.

3.2. The experimental verification

Figure 5 shows the variation of the dimensionless load capacity and friction coefficient with the aperture for different porosities of the two layers. It is observed that negatively increasing values of the dimensionless load capacity increase the aperture of the two layers, whereas positively increasing values of the friction coefficient increase the aperture of the two layers. Thus raising the aperture of the two layers has a negative effect on the lubrication performance. Moreover, the lower surface porosity is beneficial to improve the lubrication performance when the total

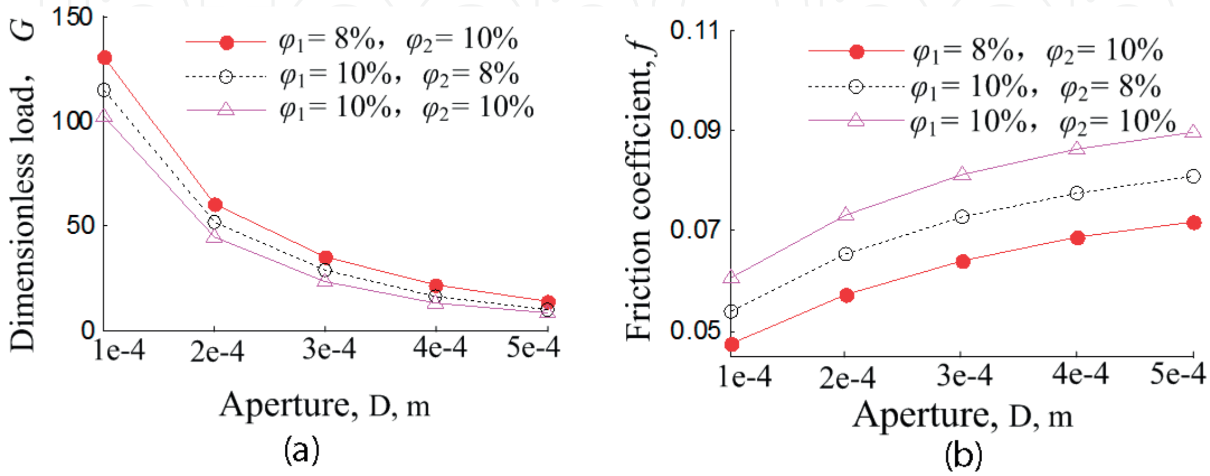

Figure 5. Effect of pore structure on oil slick bear capacity and friction coefficient.

porosities of the bearing are constant. On the one hand, when the total porosities of the bearing are larger, lubricant between the contact surfaces is more likely to seepage into the porous matrix. So that the oil film lubrication performance is poor. On the other hand, when the total porosities of the bearing are constant, the lower surface porosity can prevent the oil leaking into the porous matrix. Therefore the oil will be kept in the contact surfaces and the lubrication performance will be improved.

The Fe-C-Cu-based multi-layer bearing materials were prepared by powder metallurgy method. The wax-based lubricant as a densification agent was added into the surface layer to Increase the density. And an appropriate amount of TiH_2 as a pore-forming agent was added into the bottom layer to increase the oil content properly. The porosities were measured by drainage method. And the porosity of the bottom layer was about 20%, the porosity of surface layer changed within 10–20%. Note that the multi-layer bearing becomes monolayer when the porosities of the two layers are equal.

The tribological properties of the porous samples were tested on a face-to-face contact tribometer under oil lubrication condition. The initial load is 50 N for 10 min as run-in period. And then the load will be added 50 N every 10 min. And the total test time is 30 min. When the experiment tested with sufficient oil supply, the oil bearing materials can work in hydrodynamic lubrication state under the proper speeds and loads. This lubrication state is consistent with the numerical simulation. When the load exceeds a certain limit, the friction coefficient rises sharply. The test machine has a slight noise and vibration, which shows that the oil film cracks. And scratches and adhesion maybe existed in the friction surface. The limit load of the oil film rupture is the load capacity of the oil film.

The results of the friction test are shown in **Figure 6**. As shown in **Figure 6**, the friction coefficients of the multi-layer samples are significantly lower than that of the single layer sample (when the surface porosity is 20%) under the fluid lubrication condition. When the surface porosity is 10%, the friction coefficient of the multilayer material is the smallest. And the friction coefficients gradually increased when the surface porosities changed from 10–20%. The multi-layer materials with dense surface layers have better lubrication property than the single layer materials. The reason is that the dense surface can prevent the oil flow into the

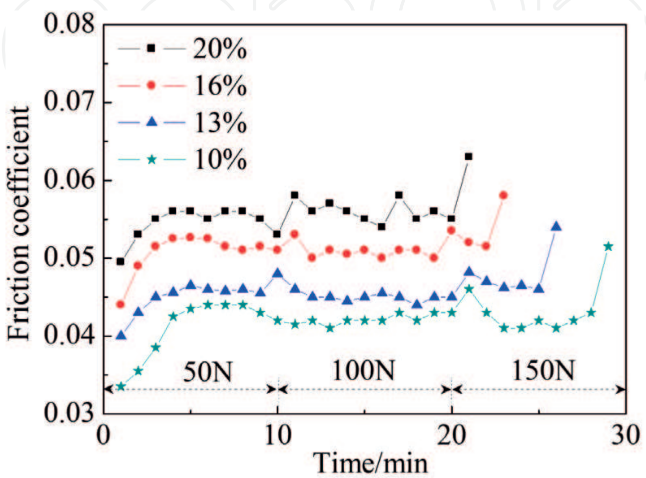

Figure 6. Friction coefficients of samples in variational load under fluid lubrication condition.

porous material, which could ensure a thicker oil film. When the surface layer has a higher porosity, the lubricant is not easy to exist between the friction pairs. So the lubricant is not sufficient. And the lubrication property is poor. In summary, when design the composite sintered material under the condition of fluid lubrication, the low surface porosity can effectively improve the material lubricating property. These experimental results are consistent with the results of the numerical simulation.

4. Conclusions

(1) The lubrication performance of the multi-layer materials is better than that of the single layer materials. Also, it can be significantly improved if considering the surface Darcy flow. Within a certain range, the effects of surface Darcy flow on the lubrication performance are more obviously with higher speed.

(2)The lower permeability surface is beneficial to improve the lubrication property of the multi-layer porous bearing when the total porosity is certain. There is a good agreement between the numerical analysis and the measurement. Therefore, when design the multi-layer oil bearing, the surface porosity should be reduced as far as possible if the oil content is guaranteed. This work is beneficial for the analysis of the tribological property and the structural design of multi-layer bearing.

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