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Influence of Texture Parameters on Lubrication Performance of Surface Textured Bearings

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Keywords: journal bearing, micro textures, rotational speed, viscosity, friction characteristics.

ABSTRACT

As an important supporting part of rotating machinery, bearing is widely used in rotating machinery and equipment. In order to explore the influence of working conditions on the texture bearing, the simulation analysis and experiment are used. By three-dimensional micro-texture journal bearing model considering cavitation effect, the influence of rotational speed and viscosity on the oil film pressure, bearing capacity, friction coefficients of texture bearing is studied. Simulation results are verified by different working conditions in experiment. The results show that the higher the viscosity of lubricating oil is, the better the lubrication performance will be. As the rotational speed increases, the friction coefficient of the bearing first decreases and then increases.

INTRODUCTION

According to the traditional tribology theory, the smoother the contact surface of the friction pair is, the better its friction performance will be and the more effective the anti-friction effect will be. Studies have proved that the improvement of the smoothness for the friction pair surface cannot improve effectively the performance of the friction pair, and even worsen the wear and increase the processing cost under some working conditions (Schneider et al. 1984). As an effective technology to improve the lubrication and friction properties of friction pairs, surface micro-texture technology has gradually become a hot topic in the field of mechanical friction (Joshi,2018; Shinde et al.,2017). Scholars (Yin, 2016; Lu et al.,2016) have studied the influence of texture shapes, texture parameters on of micro-texture on the dynamic and static characteristics of bearing. Hua et al. (2018) gained that oil film pressure on the micro-texture surface of cylindrical roller bearings increases with the increase of load and rotational speed. The effect of surface micro-texture on the working performance of journal bearings under transient conditions was studied by fluid-structure interaction method (Lin et al. 2018). Zhang et al. (2018) studied the effect of micro-texture structure parameters and eccentricity angle on lubrication performance of misaligned bearings. Rahmani et al. (2018) studied the micro-texture of rectangle and triangle, and obtained the best texture depth.

In Numerical computation, Nacer et al. (2015) used the finite difference method to study the friction performance of different surface texture geometries rotational speeds. Kango et al. (2012) used finite difference method to study the effect of different surface texture forms on bearings. Rao et al. (2014) established a theoretical model of coupled stress-fluid lubrication for sliding bearings with partial micro-texture based on narrow groove theory. In experiment, micro-texture can contribute to lubricate and retain solid lubricants (Tang et al., 2017; Gajrani et al., 2017; Urbaniak et al., 2015). Chang et al. (2019) used ultra-high molecular weight polyethylene as material, and processed three new micro-texture shapes on the surface of material. Dong et al. (2017) studied the influence of three different texture positions on bearing vibration and rotor stability. Gropper et al. (2018) optimized numerically to improve the minimum film thickness, friction torque and maximum temperature of bearing performance parameters utilizing an interior-point algorithm.

Theoretical and experimental results show that micro-texture can improve the lubrication performance of friction pairs, but the optimized

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surface texture parameters depend on the working conditions and structural parameters. After the oil film cavitation occurs, the gas and liquid distribution in the oil film cavitation zone will change, which will affect the oil characteristics of bearing. In the manuscript, the effect of rotational speed and viscosity on the friction coefficient and bearing capacity of textured bearings is studied by theory and experiment considering cavitation phenomenon, which has great engineering significance to improve oil film performance and optimize the working performance of bearings.

SIMULATION MODEL

The establishment of simulation model

Figure 1 shows the distribution and coverage of surface micro-texture in journal bearings, the texture location is at the exit of convergence zone. In order to illustrate the size of micro-texture in the diagram, the size of micro-texture is enlarged appropriately, the geometrical parameters and shape of micro-texture are shown in Fig. 2. The computed parameters are shown in Table 1.

Table 1. Oil film parameters of micro texture

Name	Symbol	Numerical value
Bearing Width	B	50mm
Bearing radius	R	25mm
Radius of axle	r	24.95mm
Clearance ratio	Ψ	0.002
Initial offset angle	φ	50°
Eccentricity ratio	ε	0.6
Eccentricity distance	e	0.03mm
Length of micro-texture unit	L	25mm
Depth	h	0.02mm
Width	w	0.3mm
Axial distribution rate	L/B	0.5
Coverage area	/	45°
Number of micro-textures	N	30

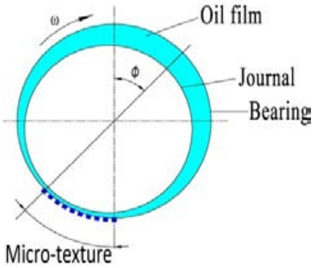


Fig. 1. Two-dimensional sketch map of micro-texture journal bearing

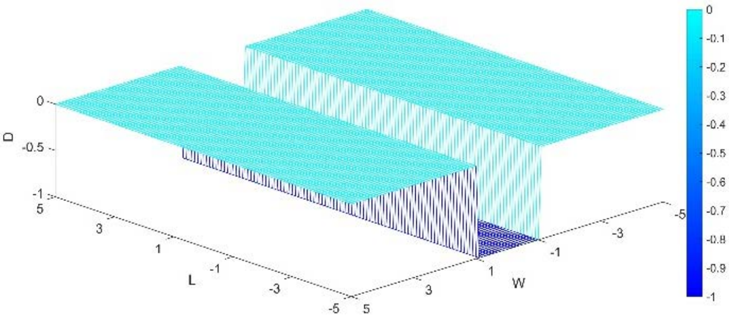


Fig. 2. Schematic diagram of micro texture geometric parameters

Establishment of cavitation model

Cavitation is the phenomenon of steam bubbles inside a liquid medium under certain conditions, which will affect the characteristics of oil film. It is also important to study the oil film distribution considering cavitation for micro-textured journal bearings. There are three multiphase flow models in Fluent, VOF model (Volume of Fluid) is not suitable for the calculation of cavitation, Eulerian model has higher requirement for computer and poor convergence, Mixed two-phase is used in the manuscript.

The three-dimensional model of journal bearing is established by Gambit software, and the mesh is divided. The environmental pressure is 101325Pa, and the cavitation pressure is 2367.8Pa, the oil inlet pressure is 10KPa; the two end of oil film are pressure outlet and the pressure is atmospheric pressure; the inner surface of the bearing is fixed, the axle surface is rotating wall surface, and the rotation direction is clockwise.

The existence of micro-texture on the surface of journal bearing, Navier-Stokes equation is chosen.

$$\frac{\partial p}{\partial t}+\frac{\partial}{\partial x_i}(pu_i)=0 \tag{1}$$

$$\frac{\partial}{\partial t}(pu_i)+\frac{\partial}{\partial x_j}(pu_iu_j)=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}(\mu\frac{\partial u_i}{\partial x_j})+pF_i \tag{2}$$

The oil film bearing capacity of micro-textured journal bearing can be obtained by integrating the oil film pressure on the inner surface of bearing with the area：

$$F_x=\int_{-B/2}^{B/2}\int_0^{2\pi}p(\theta,z)\cos\theta Rd\theta dz \tag{3}$$

$$F_y=\int_{-B/2}^{B/2}\int_0^{2\pi}p(\theta,z)\sin\theta Rd\theta dz \tag{4}$$

$$F=\sqrt{(F_x^2+F_y^2)} \tag{5}$$

Where p is the oil film pressure, u is the fluid velocity, i , j, represent respectively the order in the x and y directions, F is the oil film bearing capacity, F_x is the horizontal oil film force, F_y is the vertical oil film force, R is the radius of micro-textured journal bearing, B is the width of journal bearing, t is time, θ and z represents the circumferential coordinates and axial coordinates.

DESIGN OF EXPERIMENT SCHEME

The main experimental equipment is MMW-1A universal friction and wear tester as shown in Fig. 3, and it is produced by Jinan Yihua Tribology Testing Technology Co. Ltd. The main engine power of tester is 2.5 kW and maximum spindle speed is 2000 r/min. Friction simulation tests between different friction pairs are carried out by changing the rotational speed, friction pair material, the lubrication state.

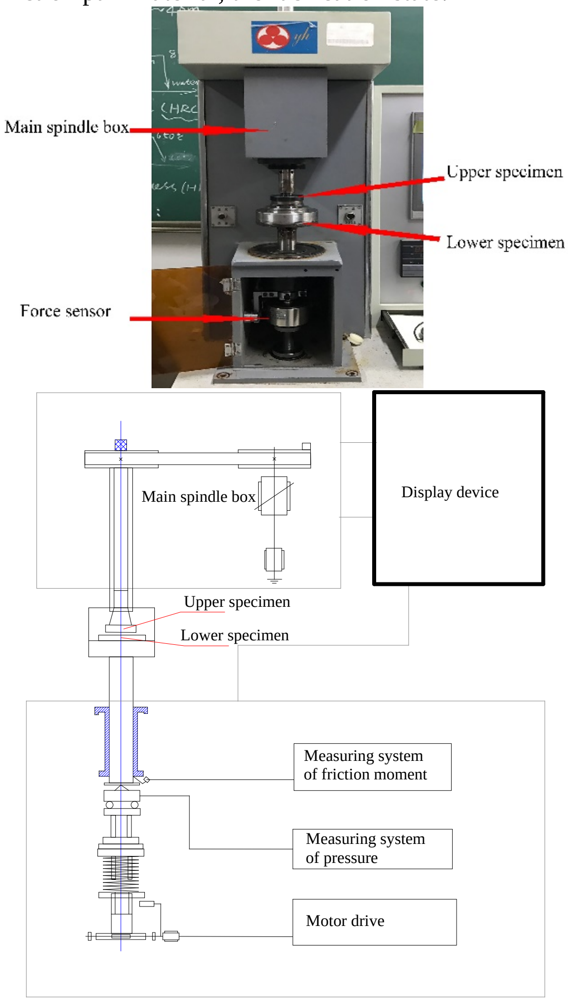
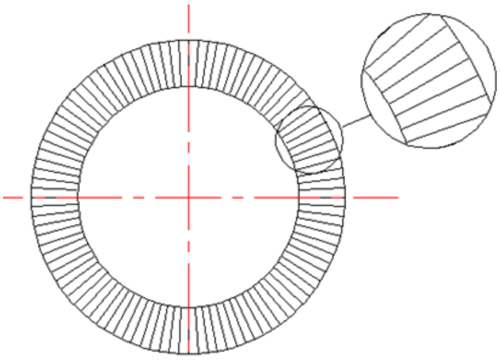


Fig. 3. MWW-1A universal friction and wear tester



(a) Sketch map of groove micro texture friction pairs

(b) Physical map of groove micro texture friction pairs
Fig. 4. Friction texture of groove micro texture

The micro-texture preparation of the friction pair is the micro-texture shape evenly distributed on the lower surface of the workpiece by laser engraving. Fig. 4 (a) shows groove-like micro-texture schematic diagram, Fig. 4 (b) shows micro-texture physical diagram. The experimental parameters are shown in Table 2.

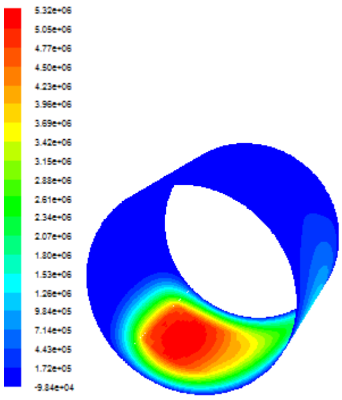
Table 2. Parameters of friction test

Name	Symbol	Numerical value
Experimental materials	/	45# steel
Width	d_1	0.1mm
Depth	h	0.05mm
Number	N	100
Test time	T	30min
High viscosity lubricating oil	η_1	68#
Low viscosity lubricating oil	η_2	5#
Experimental load	/	100N

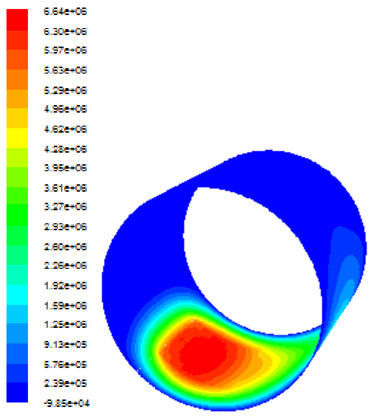
ANALYSIS OF SIMULATION RESULTS

Effect of rotation speed on properties of micro textured bearings

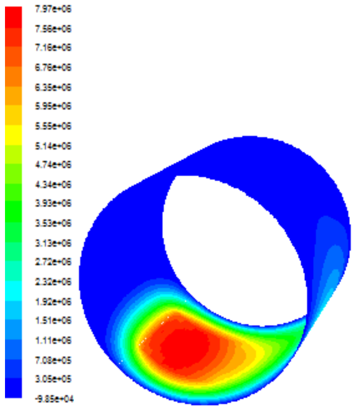
Fig. 5 shows the oil film pressure distribution cloud diagram of micro-textured bearings at different rotational speeds when the cavitation effect is taken into account. The oil film pressure has a positive pressure zone in the convergence zone of the oil film, and the oil film cavitation occurs in the divergence zone due to the cavitation effect. The pressure cloud diagram shows that the maximum oil film pressure is 5.316MPa at 400 rad/s, 6.643MPa at 500 rad/s and 7.967MPa at 600 rad/s, the maximum oil film pressure of micro-textured journal bearings increases gradually with the increase of rotational speed; but the location of the greatest oil film pressure region does not change distinctly.



(a) n=400rad/s



(b) n=500rad/s



(c) n=600rad/s

Fig. 5. Cloud map of oil film pressure distribution at different rotational speeds

Fig. 6 shows the circumferential distribution of oil film pressure of micro-textured bearings at different rotational speeds in the axial mid-section position (Z = 25mm) considering cavitation effect. Fig. 7 shows the distribution of oil film pressure at different rotational speeds in the minimum convergence gap of the micro-textured bearing considering cavitation effect. From Fig. 6, it can be seen that the circumferential pressure distribution of oil film exists a positive pressure zone, which are consistent with the distribution in pressure cloud diagram. The greatest positive pressure of micro-textured bearings appears near 210^o at different rotational speeds, cavitation region appears near 256^o-353^o. Compared with the smooth bearing, the overall position of the positive pressure zone for micro-textured bearings is closer to the convergence gap outlet, and the position of the cavitation zone is closer to the divergence gap inlet, which reduces the generation of oil film cavitation and improves the overall stability and bearing capacity performance.

Fig. 7 shows that the oil film pressure of micro-textured bearings is symmetrically distributed in the axial direction, the maximum axial pressure appears in the middle location of axial direction and decreases gradually from the middle to both ends. The oil film pressure decreases rapidly when it is near the end of the axis. This is due to the existence of leakage at the end of the bearing and the end close to the oil sealing edge of the bearing. The axial rotational speed increases from 300 rad/s to 600 rad/s, and the maximum axial pressure increases from 3.87 MPa to 7.97 MPa; with the increase of axial rotational speed, the distribution of the axial pressure of the micro-textured journal bearings increases obviously.

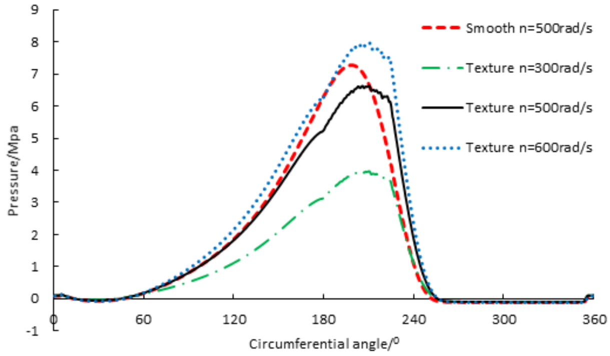


Fig. 6. Distribution diagram of oil film pressure along the circumferential direction

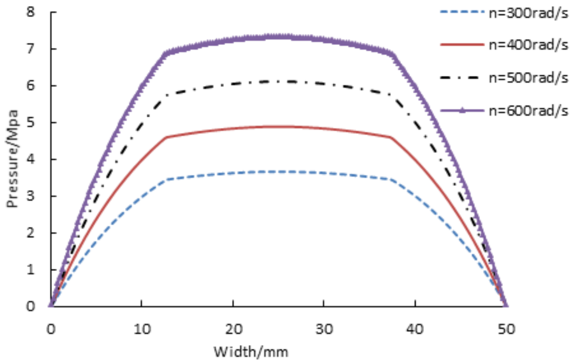


Fig. 7. Axial distribution of oil film pressure at different rotational speeds

Figs. 8 and 9 show the variation of bearing capacity, friction coefficient of oil film at different rotational speeds. The oil film bearing capacity of journal bearings with micro-texture is larger than smooth bearings, the friction coefficient of micro-textured bearings is smaller than that of smooth bearings. The bearing capacity of micro-texture with cavitation effect is lower than without cavitation effect, and that of smooth bearings with cavitation effect is larger than that without cavitation effect. The bearing capacity of smooth and micro-textured bearings increases with the increase of rotational speed. For example, the bearing capacity increases from 1528.3N to 9511.7N when the rotational speed of micro-textured journal bearings increases from 100 rad/s to 600 rad/s without considering cavitation effect. The oil film friction coefficient of smooth and micro-textured bearings decreases gradually with the increase of rotational speed. The micro-texture can improve the lubrication and friction performance of oil film, and rotational speed has obvious influence on lubrication performance of bearing.

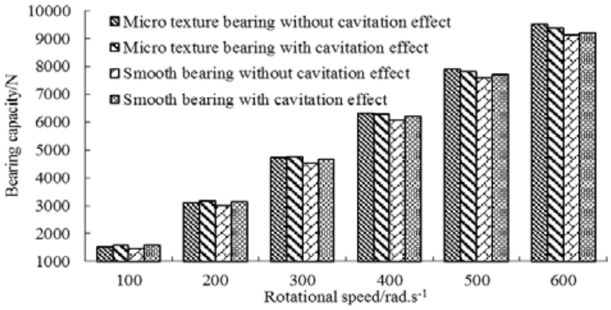


Fig. 8. Bearing capacity at different rotation speeds

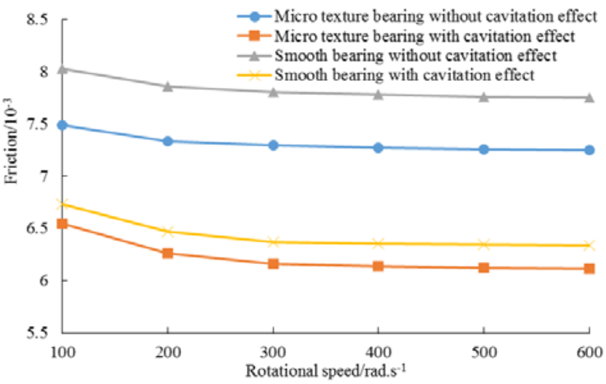


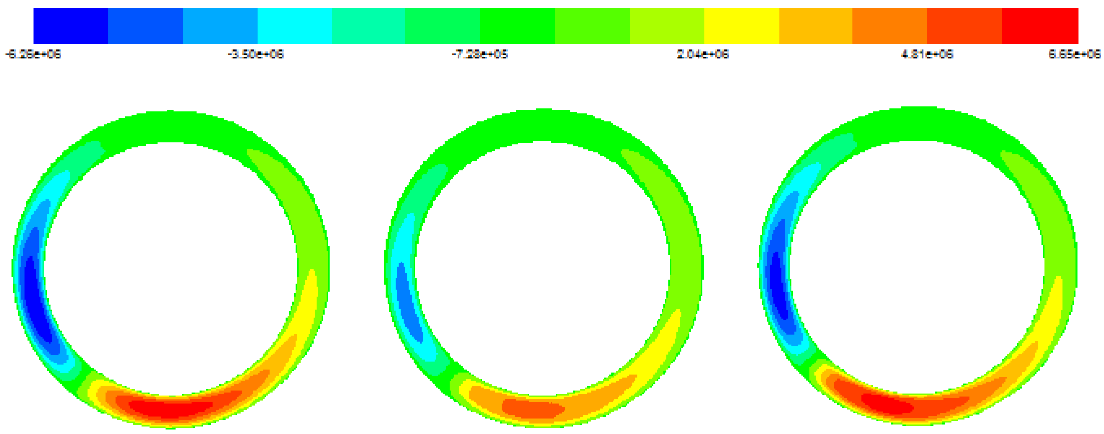
Fig. 9 Friction coefficient at different rotation speeds

Effect of viscosity on properties of micro textured bearings

Fig. 10 shows the distribution of oil film pressure distribution under different viscosities. It can be seen that the pressure distribution position of micro-textured bearings and smooth bearings on the pressure cloud diagram has no obvious difference at the same viscosity, and the maximum pressure value of micro-textured bearings is lower than that of smooth bearings; at different viscosities, the positive and negative pressure regions and values of oil film increase with the increase of lubricant viscosity. For example, the oil viscosity of micro-textured bearings increases from 0.015 Pa. s to 0.02 Pa. s, and the maximum positive pressure of oil film increases from 4.45Mpa to 5.93Mpa. This is because that with the increase of oil viscosity, the viscous shear force between oil films increases gradually, and the squeezing effect between oil films is obvious; hydrodynamic pressure effect is more obvious, the peak pressure of the oil film also increases significantly, the oil film bearing capacity improves, the influence of the oil film bearing capacity and friction coefficient will be analyzed in detail in Figs. 11 and 12.

Fig. 11 shows the variation of bearing capacity under different lubricating oil viscosities, bearing capacity of micro-textured bearings is greater than that of smooth bearings, and the higher the viscosity, the more obvious the increase of bearing capacity of micro-textured bearings is. The bearing capacity of micro-textured bearings and smooth bearings increase with the increase of lubricant viscosity, which is because the increase of the viscosity of lubricating oil improves the viscous shear force between oil films, and hydrodynamic pressure effect increases obviously.

Fig. 12 shows the oil film friction coefficient under different viscosities. The oil film friction coefficient of micro-textured bearings is smaller than that of smooth bearings. With the increase of viscosity, the friction coefficient of micro-texture and smooth bearings decreases gradually, which is consistent with the analysis of bearing capacity. Properly increasing the viscosity can improve effectively the load-bearing performance of oil film and optimize bearing friction performance.



(a) Smooth bearing, 0.02Pa.s (b) Texture bearing, 0.015Pa.s (c) Texture bearing, 0.02Pa.s

Fig. 10. Cloud map of oil film pressure distribution under different viscosities

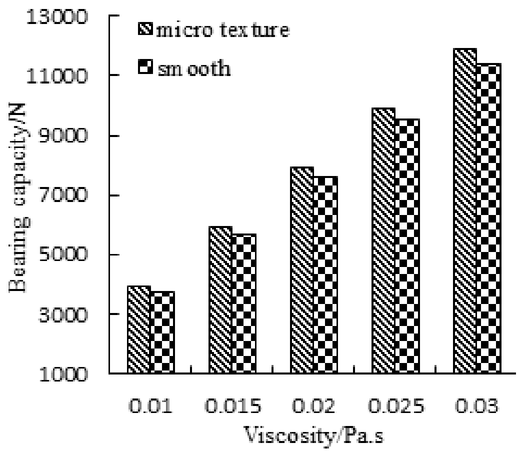


Fig. 11. Bearing capacity at different viscosities

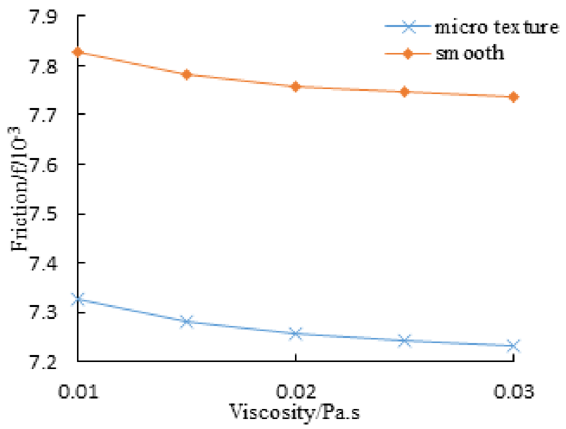


Fig. 12. Friction coefficient at different viscosities

Table 3 shows the cavitation parameters of oil film under different lubricating oil viscosity when cavitation effect is included. It can be seen that under the same viscosity, the number of cavitation, cavitation volume ratio and cavitation area ratio of micro-textured bearings are smaller than those of smooth bearings, which shows that micro-texture effectively inhabits the generation of cavitation effect, reduces the region where cavitation occurs, and is conducive to improving the stability of bearings; with the increase of lubricating oil viscosity, the cavitation effect of micro-textured bearings and smooth bearings enhance gradually, the number of cavitation increases gradually, the cavitation area increases gradually, but the increase of lubricating oil viscosity is not conducive to the improvement of the overall performance of bearing oil film. Therefore, when the improvement of bearing performance is considered, it is necessary to combine actual working conditions to choose reasonably the lubricating oil and the effect of cavitation on the bearing performance is avoided greatly.

Table 3. Cavitation parameters of oil film at different viscosities

Viscosity Pa.s	Number of cavitation		Cavitation Volume ratio /%		Cavitation area ratio/%	
	Smooth bearing	Texture bearing	Smooth bearing	Texture bearing	Smooth bearing	Texture bearing
010	22069	20656	13.65	12.88	14.50	13.77
0.015	24969	23807	16.79	16.22	15.09	14.18
0.020	26720	25545	18.79	18.20	15.65	15.27
0.025	27921	26767	20.25	19.62	19.64	19.13
0.030	28801	27653	21.56	20.65	20.45	19.94

ANALYSIS OF EXPERIMENT RESULTS

Effect of rotational speed on the properties of friction pairs

Fig. 13 shows the variation of friction coefficient at high viscosity lubrication oil and different rotational speeds, Fig. 14 shows the average friction coefficient at stable wear stage. In Fig. 13, the friction coefficient of smooth and micro texture specimens reduce gradually with the increase of rotating speed, the average friction coefficient of Fig. 14 can more clearly see the decrease trend of friction coefficient. Fig. 14 shows that the friction coefficient of micro-textured specimens is smaller than that of smooth specimens when rotational speed is less than 120r/min, but greater than that of smooth specimens at 120r/min and 150r/min. Although the increase of rotational speed will enhance the dynamic pressure effect and reduce the surface friction coefficient, the wear of micro-textured specimens is more prone to occur and particles that cannot be stored in time in micro-textured pits are more likely to damage the friction surface at high rotational speed; moreover, the higher the rotational speed, the more obvious the thermal effect is, the reduction of viscosity is not conducive to the entrapment and storage of wear debris, so the micro-texture specimens cannot show effective friction reduction effect compared with smooth specimens at higher rotational speeds. There will be a reasonable range of rotational speed for micro-texture friction pairs.

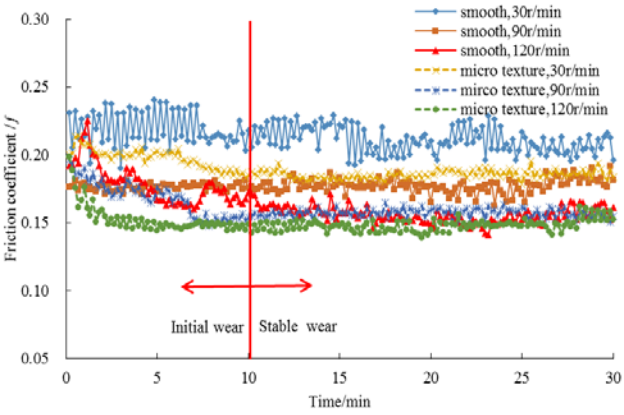


Fig. 13. Friction coefficient at different rotational speeds

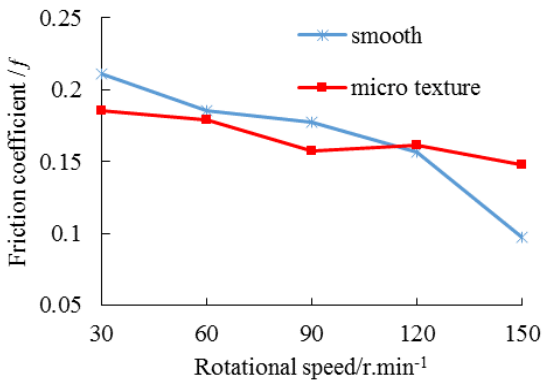


Fig. 14. Average friction coefficient at different rotational speeds

Effect of viscosity on properties of friction pairs

Fig. 15 shows the friction coefficient of friction pairs under different viscosities. For low viscosity lubricant, there is no obvious difference between the friction coefficient of texture friction pair and smooth friction pair in the initial wear stage, but the friction coefficient of texture friction pairs decreases continuously and the friction coefficient of smooth friction pairs increases slightly in stable wear stage. For high viscosity lubricant, the friction coefficient of smooth friction pair is basically unchanged with the change of time, but its friction coefficient of texture friction pair decreases continuously, especially in the stable wear stage, its friction coefficient is much lower than that of smooth texture. The effect of low viscosity lubrication on reducing friction coefficient is less than high viscosity lubrication, which is consistent with the previous theoretical analysis and change trend of average friction coefficient in Fig. 16. Because the oil film of low viscosity lubricant is easy to be destroyed by the direct contact of micro-rough convex peak, which weakens the dynamic pressure effect formed by surface micro-texture and the formation of stable oil film; for high viscosity lubricant, a stable oil film with small shear strength can be formed between the upper and lower work pieces, the oil film can avoid the direct contact of rough convex peaks of the friction matrix and reduce effectively the friction coefficient of friction pair.

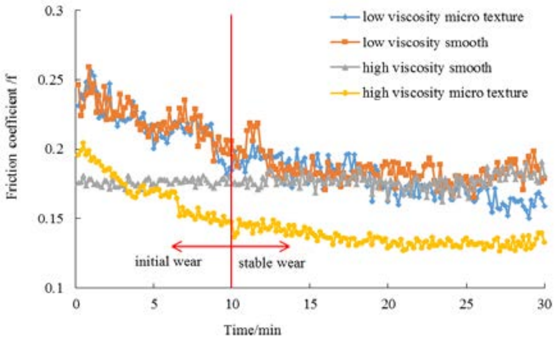


Fig. 15. Friction coefficients at different viscosities

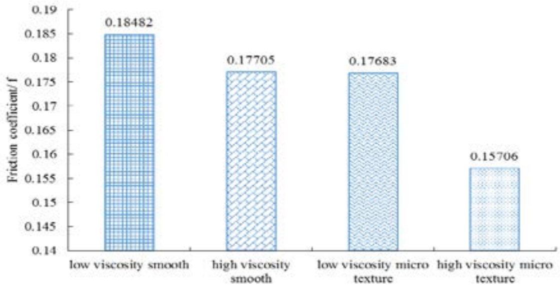


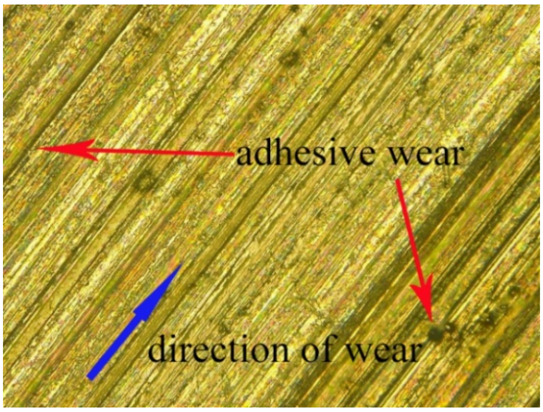
Fig. 16. Average friction coefficient at different viscosities

Analysis of surface wear

Fig. 17 shows the surface of smooth specimens before and after wear by enlarging 500 times at 60 r/min and low viscosity lubricant. Fig. 18 is the texture specimen before and after wear under different lubrication conditions and rotating speeds. Comparing Fig. 17 with Fig. 18, the wear marks on the surface of the specimens appear along the rotational direction, all of which are plough-groove-like wear marks; but the depth of wear marks on the textured surface is shallower than smooth specimens, and the number of ploughs is relatively small, which shows that the dynamic pressure effect of surface micro-texture and the oil storage effect on the wear table play an effective role in reducing wear.

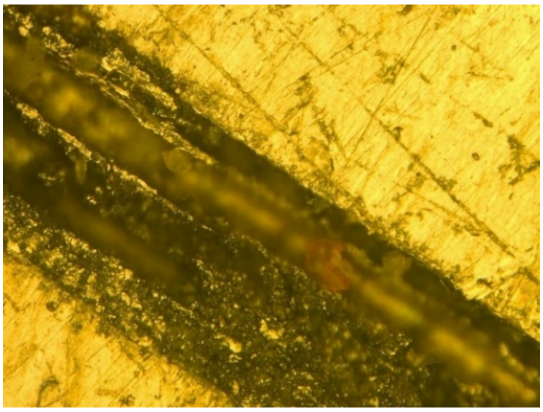
Comparing with Fig. 18 (b) and (c), the wear of texture specimens is more serious at 60 r/min, the number of plough groove-like wear marks is more and the wear marks are wider; the wear depth of specimens is greater at 150 r/min; which is consistent with the above theoretical analysis, abrasive wear is more likely to occur and particles that cannot be stored in time in micro-texture pits are more likely to damage the friction surface at higher speed. Compared with Fig. 18 (b) and (d), at high viscous lubrication, the wear condition of the specimens is lighter, the number of wear marks is relatively small, and the wear depth is relatively shallow.

(a) Specimen before wear

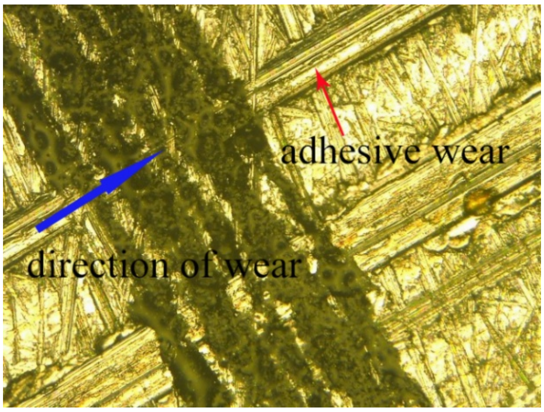


(b) Specimens after wear

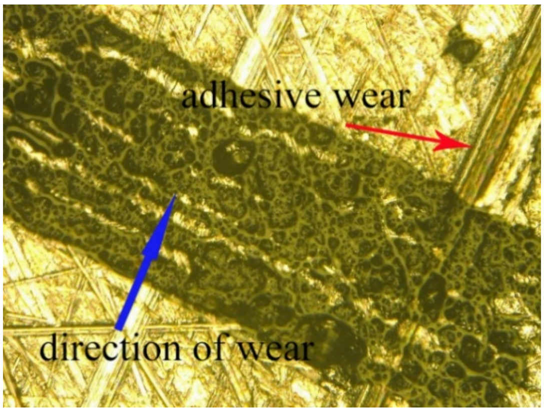
Fig. 17. Comparison of wear behavior for smooth specimens



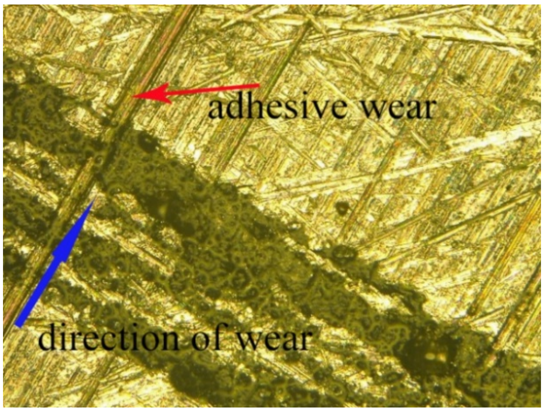
(a) Texture specimen before wear



(b) 60r/min, texture specimen after wear under low viscosity lubrication



(c) 150 r/min, after wear under low viscosity lubrication



(d) 60r/min, after wear under high viscosity lubrication

Fig. 18. Comparison of texture specimens before and after wear

CONCLUSIONS

The influence of rotational speed and viscosity on oil film pressure, cavitation characteristics, bearing capacity, friction coefficients of textured bearings considering cavitation is studied by simulation calculation and verified experimentally by universal friction and wear tester.

(1) For three-dimensional micro-texture journal bearing using mixed two-phase model, the bearing capacity of textured bearings is greater than that of smooth bearings, and the friction coefficient of textured bearings is smaller than smooth bearings; the higher the viscosity, the more obvious the texture effect is. There is only one positive pressure zone in the convergence zone of oil film considering cavitation for micro-texture journal bearing, and there is no obvious difference for the maximum pressure zone with smooth bearings. With the increase of rotational speed, the maximum pressure of bearing oil film increases gradually; with the increase of viscosity, the bearing capacity of textured and smooth bearings increases gradually.

(2) The friction pair of ring contact is made of 45#, the friction and wear experiments are carried out. The results show that the friction coefficient for smooth and textured specimens decreases gradually with the increase of rotational speed. At lower rotational speed, the friction coefficient of micro-textured specimens is smaller than smooth specimens, at higher rotational speed, the friction coefficient of texture specimens is higher than smooth specimens, there is a rotational speed range. The friction coefficient for texture and smooth specimens decreases with the increase of lubricant viscosity, and the friction coefficient of high viscosity decreases much more than low viscosity.

(3) Both theoretical and experimental studies show that, with the increase of rotating speed, the bearing capacity of the textural bearing increases, and the average friction coefficient first decreases and then increases compared with the smooth bearing, there is an optimal value. With the increase of viscosity, the friction coefficient of textured bearing decreases continuously. Only reasonable choice for rotating speed and lubrication viscosity, the reduction of friction can be realized effectively.

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