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Original scientific paper

Research on Anti-Wear Properties of Nano-Lubricated High-Speed Rolling Bearings under Various Working Conditions

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Abstract: Under high-speed and light-load conditions, rolling bearings often suffer from skid damage and wear. Nano-lubrication could inhibit the wear failure of mechanical parts. Therefore, in this manuscript, nano-lubrication technology is adopted to improve the anti-wear performance of rolling bearings. Nano-mixed oil with different particle sizes and concentrations of silica nanoparticles are prepared. Based on an improved rolling bearing test rig, the friction coefficient, wear depth, and real-time temperature rise under different operating conditions are studied, and the friction and anti-wear mechanisms of the nano-lubricated high-speed rolling bearings are obtained.The results show that the wear failure of the light-load rolling bearings decreased by using nano-lubricated mixture oil. There is no direct correlation between the friction coefficient and wear depth in the rolling bearings. Moreover, the use of nano-lubrication can effectively suppress the wear of rolling bearings, especially in the absence of sufficient oil.This study can provide an effective support for nano-lubrication and its application in anti-wear of rolling bearings.

Keywords: friction; high-speed rolling bearings; nano-lubrication; nanoparticles; wear

1 INTRODUCTION

Research on high-speed rolling bearings has been pursued extensively. Jones [1] solved the simple analysis of the bearing motion law. Harris and Mindel [2] evaluated the dynamic performance of rolling bearings. Dowson and Higqinson [3] were among the first to present numerical results for these contacts, studying the theory of contact lubrication, and achieving advances in the calculation of friction in bearings. Upadhyay [4] conducted rolling bearing failure analysis. Nguyen [5] aimed at proposing an integrated generalized discriminant analysis method for bearing fault diagnosis. Ambrozkiewicz [6] established a 2-DOF model and studied the influence of radial clearance on ball bearing dynamics. Cheng [7] studied the load distribution and contact of rolling bearings. In the actual operation of high-performance rolling bearings, skid damage often occurs, which affects their service performance. Zhang [8] conducted an experimental study on the influence of roller slip ratio on the friction performance of a cylindrical roller-bearing and inner ring friction pair at different roller speeds. Harris [9] established a nonlinear equilibrium equation for the roller, cage, and inner ring. Li [10] investigated the process of dynamic lubrication failure of the contact pairs of rolling bearings when the slip rate and temperature were changed. Cao [11] proposed an analytical model for the study of roller slippage under maximum loads at different accelerations. Skid damage and wear directly affect the life of rolling bearings; therefore, reducing wear is a crucial issue.

Wear is a process in which the surface material of objects that are in contact is constantly removed during the relative motion. The problem of wear of rolling bearings in practical applications has attracted considerable attention. By reducing the wear of the bearings, their service life can be extended, and the maintenance costs can be reduced. Wen [12] described the progress of research on material wear theory and anti-wear technology. Xu [13] concluded that adhesive wear is closely related to the materials of the friction pairs and the working parameters. Yuan [14] established a mapping model for obtaining information related to bearing wear surface and abrasive particle. Lu [15] analysed the lubrication performance of bearings operating under the condition of point contact with the spent oil, which could provide a reference for future research on reducing wear by improving lubrication performance.

Nanoscale lubrication has received much attention from researchers as a method for reducing the wear of materials. Common lubrication methods include grease lubrication [16], oil lubrication [17], and water lubrication [18]. Owing to its advantages of high temperature resistance and good lubricity, oil-based lubrication has been widely used and has achieved obvious results. Peña-Parás [19] conducted experimental studies by dispersing nanoparticles of different particle sizes in PA_{O2} oil. Hwang [20] dispersed nanoparticles in mineral oil to systematically study the effects of particle size and shape on their frictional properties. Kalyani [21] analysed the mechanism of the influence of particle size on the tribological behaviour of paraffin-based oil under boundary conditions. Rabaso [22] showed that nano-lubricating oils effectively reduce the friction and wear of disc friction pairs.

Research has shown that when used as lubricating additives, nanoparticles have a special effect on reducing friction, anti-wear, and extreme pressure. TiO2 nanoparticles show excellent tribological performance (Wang [18]; Peña-Parás [19]; Katainen [23]; Zhu [24]; Jaiswal [25]; Xue [26]; Sabareesh [27]). In recent years, with the rapid development of nanoscience and nanotechnology, nanomaterials have gradually become important when choosing lubricant additives, and are expected to play a more important role in the field of friction and wear [25]. The effects of particle size and shape on the frictional properties of mineral oil with various carbon-based particles were systematically analysed [20, 28]. Many organic compounds, such as those containing phosphorus, sulfur, halogens, nitrogen, and oxygen, have been used as anti-wear and extreme-pressure lubrication additives. Similar behaviour has been observed in measurements of Zn0.92Mg0.08O particles in paraffin oil, which have shown that smaller sizes provide better anti-wear properties. Scholars have improved the efficiency of machines by using various additives to reduce wear [21, 29, 30]. Lubricants with inorganic fullerene (IF) nanoparticles can effectively reduce friction and wear under boundary lubrication conditions [22, 31]. Previous research indicates that the lubrication performance of MoS2 nanoparticles was dependent not only on the quantity, morphology, size, but also on the contact surfaces [22]. Peña-Parás [32] studied the friction and wear characteristics of CuO- and Al_2O_3- based synthetic nano-lubricants. Liu [33] analysed the friction and wear characteristics of copper nanoparticles as additives. Many studies on nanoparticles have chosen TiO_2 as an additive, which has special anti-friction and anti-pressure effects. However, as a new and environmentally friendly additive, SiO_2 nanoparticles cannot be ignored, which offer the advantages of high controllability and dispersion [23, 34]. Peng [35] studied the tribological properties of liquid paraffin wax prepared with SiO_2 nanoparticles as the additive. Huo [36] prepared a monodispersed nano-SiO_2 additive with ethyl orthosilicate as a raw material, and measured the tribological properties of the prepared nano-SiO_2 as a 500SN base oil additive. Zhang [37] studied the tribological properties of silica as a semi-fluid fat additive.

As a nano-additive, SiO2 nano-lubrication can reduce the wear of contact pairs, but there is limited application where SiO_2 nano-lubrication is used for rolling bearings. As a key component of aeroengines, the performance of high-performance rolling bearings directly affects the overall performance of the engine. In the cases of frequent starting and stopping, abnormal load, etc., the lack of oil lubrication can occur easily, which has a significant influence on the subsequent working stability of the rolling bearings, and thus affects their life and reliability. Skid damage and wear failure of rolling bearings are aggravated due to lack of oil lubrication. Nano-lubrication can inhibit the wear failure of mechanical parts. Based on the literature reviewed, insufficient attention has been paid to the relationship between the nano-lubrication and anti-wear properties of high-speed rolling bearings. Therefore, the focus of this study is to explore the use nano-lubrication technology to improve the anti-wear performance of rolling bearings.

2 TEST PREPARATION

2.1 Improved Test System

To check the performance of the roller bearing, a computer-controlled testing rig is used to enable the bearing load, speed, and temperature to be varied, as shown in Fig. 1. An HRB NU210 roller bearing is selecting as the test sample. The testing rig, which used a cantilever structure, had the characteristics of high speed, heavy load, and multi-purpose applications. The test is stopped upon failure, which is automatically identified.

The test rig is composed of main body and software parts with measurement and control system. Main body of the test rig is cantilever structure. The test rig featured a stepping motor for loading, a high-power electric spindle with drive selection, and other advanced technologies. During the test, the temperature data is collected by PT100 temperature sensor, the load data is collected by PT9552 pressure sensor, the friction torque data is collected by GB-DTS-G50 torque sensor, the spindle speed data is collected by CZ-400 sensor.

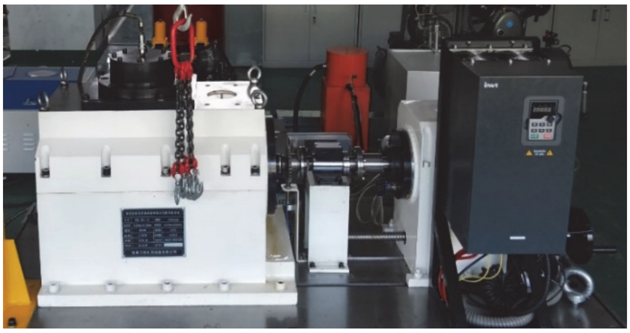


Figure 1 High-speed rolling bearing testing rig

The high-speed rolling bearing testing rig is improved. The oil supply device of the testing rig is improved to close the original oil inlet and oil return path. In the experiment, a WG600F intelligent industrial peristaltic pump, which is suitable for large-flow transmission and liquid separation, is incorporated into the oil supply device. It can realize the basic functions of positive and negative flow, start and stop, and flow regulation. One end of the peristaltic pump-independent oil supply system is connected to the rolling bearing testing rig to supply oil to the bearing, and the other end is connected to the prepared nano-lubricating oil supply container. The flow rate of the oil supply is adjusted through the human-machine interface to achieve the required conditions for the lubrication by the spent oil.

The performance of rolling bearings is tested under various conditions, such as a lack of oil lubrication, high speed, and light loads. In the cases of starting and stopping, abnormal oil break, etc., the lack of oil lubrication can occur easily, which has a significant influence on the subsequent working stability of rolling bearings, and thus affects their life and reliability.

2.2 Preparation of Nano-Mixed Oil

(1) First, the base oil is added to the reactor and the stirrer is turned on; 2.5% SiO_2 nanopowder with a particle size of 50 nm is added to the base oil, which is then stirred for 5-10 min to obtain the nano-mixed oil with a specific ratio. Mobil DTE 24 is adopted as the base oil.

(2) Pure oil without nanoparticles is used as the experimental control. Mobil DTE 24 is used as the pure oil.

3 RESULTS AND DISCUSSION

3.1 Design of Experimental Scheme

In this study on the preparation of nanoparticles based mixed oil, the effect of nano-lubrication on rolling bearing friction and wear mechanism are studied by adjusting the oil supply quantity, speed, and load conditions. Based on the single factor control variable method, different values of the coefficients of friction, wear mechanism, and the influence of temperature variation are studied.

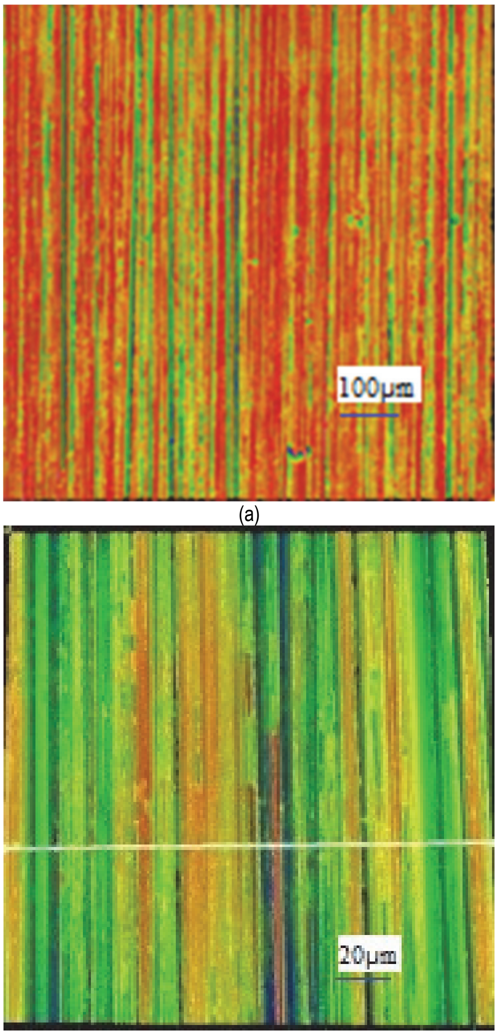
Experiments are conducted to explore the effects of different working conditions on the friction and wear of rolling bearings by changing the load, rotating speed, and the amount of lubricating oil. The extent of wear and the friction coefficient upon addition of the nano-lubricants are analysed to reveal the variations in friction and wear mechanism of rolling bearings coupled with different nanoparticles and on the rough surfaces of friction pairs.

The mechanisms of friction reduction and life extension of high-speed rolling bearings under different working conditions and solutions are investigated.

3.2 Bearing Surface Topography Test

A Talysurf CCI2000 white light interference surface profilometer is used to measure the bearing surface topography, surface roughness, and key dimensions with high precision, based on the coherence correlation interferometry interference principle.

The bearing 3D topography test results are shown in Fig. 2a and Fig. 2b.

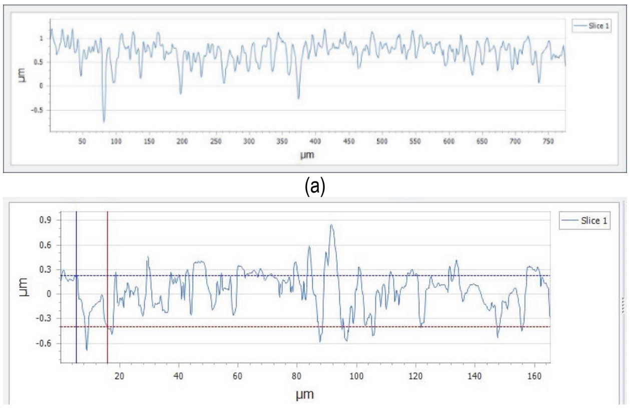


(a)

(b)

Figure 2 3D topography: (a) 3D topography of the bearing surface before the test; (b) 3D topography of the bearing surface after the test

As shown in Fig. 2a, the surface roughness parameters of the inner ring of the bearing are *Sa* = 0.178 μm, *Sq* = 0.244 μm, and *Sz* = 3.731 μm. After the test, the surface roughness of the inner ring of the bearing is Sa=0.199μm; *Sq* = 0.246μm; *Sz* = 1.936μm. The value of Sa increases from 0.178 μm to 0.199 μm before and after the experiment, and the increment is very small, indicating that the overall wear of the rolling bearing by using the nano-mixed oil is extremely light. However, the value of *Sz* decreases from 3.731 μm to 1.936 μm before and after the experiment, indicating that the bearing wear surface became relatively smooth by using thenano-mixed oil.



(a)

(b)

Figure 3 Surface roughness curve: (a) Surface roughness curve of bearing before test; (b) Surface roughness curve of bearing after test

The typical surface roughness curve is shown in Fig. 3, where the surface roughness is mostly in the range of 0 to 1 μm. By comparison, it is found that the line surface roughness of the bearing increases after the test, and the distribution of the line surface roughness after the test is slightly less uniform than that before the test.

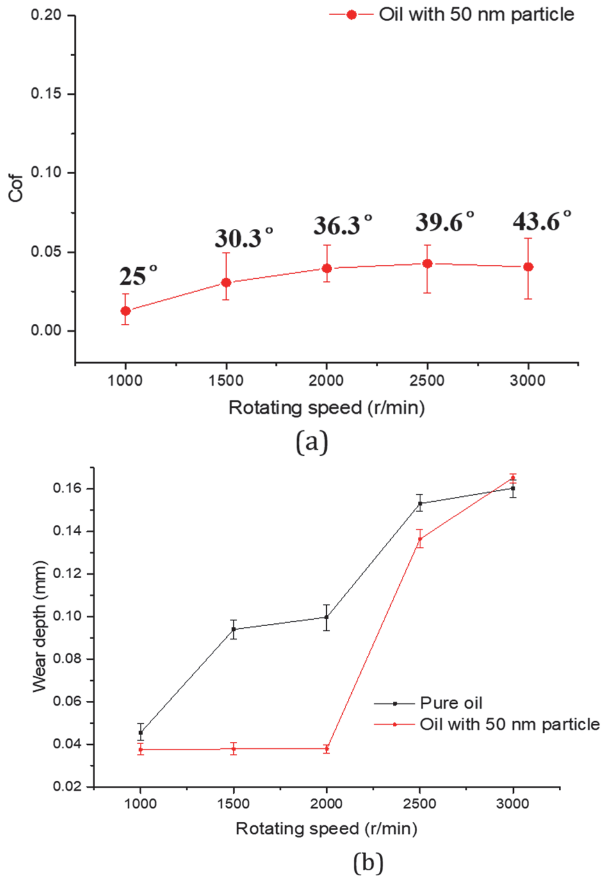
3.3 Friction and Wear of Nano-Lubricated Rolling Bearings under Various Speeds

The mechanism of the influence of speed on the tribological properties of nano-lubricated rolling bearings is investigated. The experimental results are presented in Fig. 3. The test conditions are as follows: load, 1000 N; time, 10 min; and oil supply, 25 ml/min. A mixture of lubricating oil containing 50 nm silica particles at a concentration of 2.5% by mass is selected for the experiment.

As shown in Fig. 4a, the friction coefficient of the curve with the addition of the nanoscale mixture first increases with increase in the rotational speed and then decreases. The results showed that the friction coefficient increased with increase in the rotational speed up to 2500 r/min. Simultaneously, with a continuous increase in the rotational speed, the thermal effect becomes more apparent beyond a speed of 2500 r/min, which increases the temperature of the lubricating oil. As shown in Fig. 4a, under specific working conditions, the temperature of the lubricating oil is approximately 25 °C for a rotational speed of 1000r/min, the temperature is about 43.6 °C with the rotational speed of 3000 r/min, which indicates that the temperature shows an increasing trend with increases in the rotational speed. This leads to a decrease in viscosity of the lubricating oil, which reduces friction to a certain extent. Thus, the friction coefficient decreases. The experimental results show that skid has a significant effect on the performance of bearings under light-load conditions, and the increase in the friction coefficient after adding nanoparticles can reduce the degree of skid to a certain extent.

As shown in Fig. 4b, when the speed is 1000 r/min, the wear depth of the rolling bearing with nano-mixed oil is 0.0374 mm. When the speed reaches 2000 r/min, the wear depth of the rolling bearing is 0.038 mm. When the rotational speed further increases to 3000 r/min, the wear depth of the rolling bearing is 0.165 mm. It is shown that with an increase in the rotational speed, the wear amount also increases. Compared with the pure oil test, the wear depth of the bearing with lubricating oil containing 50 nm silica particles is reduced, reflecting its anti-wear effect.

For practical problems such as skid and wear in the use of light-load rolling bearings, the study shows that the use of nano-mixed lubricating oil can increase the friction and reduce the skid accordingly, thereby effectively reducing the degree of wear in rolling bearings.



(a)

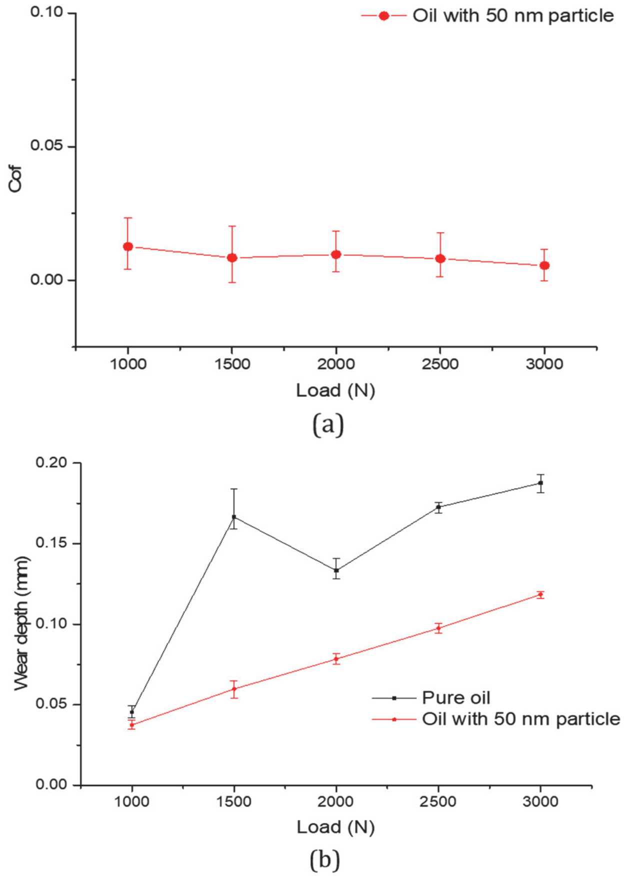
(b)

Figure 4 Friction coefficient and wear under various speeds: (a) friction coefficient; (b) comparison of wear depth between pure oil and nano-lubrication

3.4 Friction and Wear of Nano-Lubricated Rolling Bearings under Various Loads

The influence mechanism of different rotational speeds on the tribological properties of nano-mixed lubricating rolling bearings is also investigated. The experimental results are presented in Fig. 4. The test conditions are: speed, 1000 r/min; time, 10 min; and oil supply, 25 ml/min. A mixture of lubricating oil with 2.5% by mass of 50 nm silica particles is used in the experiment.

Fig. 5a shows the friction coefficient of the 50 nm particles under different loads. The results show that the friction coefficient generally decreases with an increasing load, except that the friction coefficient increases slightly as the load increases from 1500 to 2000 N. As the load increased, the oil film pressure gradually increased, and the 50 nm SiO_2 particles in the oil are pressed through the gap in the bearing surface morphology. The friction coefficient is greatly affected by oil pressure; thus, the friction coefficient increases. As the influence of the oil film pressure increases, the friction coefficient reaches a maximum and does not increase further. At this time, the load continues to increase and the other conditions remain unchanged. It can be concluded that the friction coefficient decreases with increasing load.



(a)

(b)

Figure 5 Friction coefficient and wear under various loads: (a) friction coefficient; (b) comparison of wear depth between pure oil and oil with nanoparticles

Fig. 5b shows a comparison of the wear depth of pure oil and oil with 50 nm particles under different loads.The test results show that the wear depth of rolling bearing is 0.0374 mm when the load is 1000 N. When the load increases to 2000 N, the wear depth is 0.784 mm. When the load continues to increase to 3000 N, the wear depth of the rolling bearing is 1.37 mm. The results show that the amount of wear increases with increasing load. The study shows that the wear depth of rolling bearings increases with increasing load and the comparison proves that the wear degree of bearings is effectively reduced after adding nano-mixed oil.

3.5 Friction and Wear of Nano-Lubricated Rolling Bearing under Various Oil Supply

Finally, the influence mechanism of different rotational speeds on the tribological properties of nano-mixed lubricating rolling bearings is studied. The experimental results are presented in Fig. 5. The test conditions are: speed, 1000 r/min; load, 1000 N; and time, 10 min. A mixture of lubricating oil with 2.5% by mass of 50 nm silica particles is used in the experiment.

Fig. 6a shows a comparison of the variation of the friction coefficient of 50 nm particles under different lubricating oil supplies of 5, 15, and 25 ml/min. The results show that the friction coefficient of the nano-lubricated rolling bearing is 0.015 when the oil supply is 5 ml. The friction coefficient of the rolling bearing is 0.014 when the oil supply reaches 15 ml. When the oil supply further increases to 30 ml, the friction coefficient decreases to 0.012. It is concluded that the friction coefficient of the bearing decreased with an increase in the oil supply. A small oil supply reduces the lubrication effect and reduces the friction coefficient of the contact surface to a certain extent.

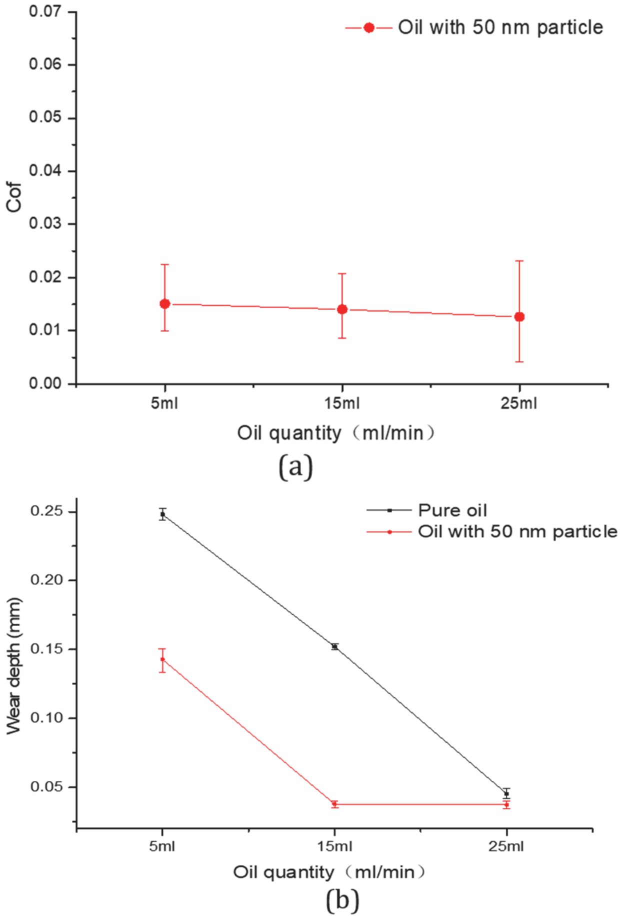


Figure 6 Friction coefficient and wear under various oil supply: (a) friction coefficient; (b) comparison of wear depth between pure oil and oil with nano-lubrication

As can be seen in Fig. 6b, when the oil supply is 5 ml, the bearing is in the stage of depleted oil, and the wear increases owing to the increased wear depth due to the lower oil supply. When the oil supply is increased to 15ml, the wear quantity decreases gradually, and when the oil supply is sufficient at 25 ml, the wear quantity is the minimum. By comparing the results of the pure oil and nano-lubricating oil, it can be seen that the bearing wear due to the nano-lubricated mixture oil is less than that of pure oil for an oil supply of 5 ml, and the difference decreases as the oil supply increases. Compared with pure oil, the wear depth of the bearing with lubricating oil containing 50 nm silica particles is reduced, which indicates that the nano-lubricated mixture oil can reduce wear to some extent. The results show that it has a sufficient anti-wear effect under starved lubrication conditions.

4 CONCLUSIONS

In this study, an improvement was made to a high-speed rolling bearing test rig, and a specific ratio of oil mixed with silica nanoparticles was tested. Based on the control variable method, factors such as speed, load, oil supply, and other factors were investigated to determine the change in the laws of friction and wear under high-speed rolling bearings, to study the anti-wear mechanism on rolling bearings, and subsequently improve and enhance the performance of rolling bearings.

(a) Silica nanoparticles with a particle size of 50 nm could provide good lubrication to the bearing and reduce the wear of the bearing to a certain extent.

(b) The friction coefficient first increased and then decreased with a gradual increase in the rotational speed of the bearing, which was simultaneously affected by the coupled factors of skid and increasing temperature. The wear increased with increasing speed.

(c) The friction coefficient decreased with an increase in load. Simultaneously, the wear increased with an increase in the load, and the degree of wear of the bearing was effectively reduced after the addition of the nano-mixed oil.

(d) The study shows that nano-lubrication can effectively inhibit the wear failure of rolling bearings under the condition of starved lubrication, and its effect is greater than that under the condition of full oil supply.

Further research can be focused on the tribological characteristics of nano-lubricated high-speed rolling bearings considering the interaction between different nano-particles and the rough surface.

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