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Tribological Characteristics of Nano-Lubricated High-Speed Rolling Bearings Considering Interaction between Nanoparticles and Rough Surface

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Abstract: The embedding situation between various nanoparticles and rough surfaces affects the lubrication characteristics of rolling bearings. If not properly handled, this can easily lead to wear damage of rolling bearings. Therefore, the friction and wear mechanism of nano-lubricated high-speed rolling bearings under various nanoparticle embedded states is studied in this manuscript. Mixed oils containing different sized SiO_2 nanoparticles and dispersants are prepared, and then the tribology test of nano-lubricated high-speed rolling bearings considering the interaction between various nanoparticles and the rough surfaces is conducted. The friction and wear properties such as coefficient of friction, wear volume and real-time temperature rise of high-speed rolling bearings under different embedding conditions are revealed, and the anti-wear mechanism of the nano-lubricated high-speed rolling bearings is obtained. The results show that compared to the complete non-embedded state, the complete embedded state of different nanoparticles effectively improves the anti-wear effect of the bearing. When the nanoparticle mixed oil is added, the bearing still has good anti-wear performance under the conditions of high speed and lack of oil. As for the light loaded rolling bearing adopted with nano-mixed oil, the coefficient of friction is appropriately increased, as well as the skid reduced, while the wear of the rolling bearing is effectively reduced. This research will provide theoretical basis and important reference for nano-lubrication and its application in aviation rolling bearings.

Keywords: lubricating oil; nanoparticles; high-speed rolling bearing; friction; wear

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1. Introduction

As lubrication additives, nanoparticles can play a special role in reducing friction and anti-wear. TiO_2 nanoparticles show excellent tribological properties [1–6]. Hwang and Kalyani dispersed various carbon-based particles in mineral oil to systematically study the effect of particles size and shape on friction properties [7,8]. Many organic compounds such as phosphorus, sulfur, halogens, nitrogen and oxygen have been used as anti-wear additives. Additives with active elements are adsorbed on the contact surface of the metal, and formed a tribochemical film under lubrication conditions. Kalyani, Zhou and Tomala improved machine efficiency by reducing wear and friction [9–11]. Rabaso and Rapoport adopted inorganic fullerene (IF) nanoparticles in lubricants, which proved to be effective in reducing friction and wear under boundary lubrication conditions [12,13]. Pena-paras studied the effects of CuO and Al_2O_3 nanoparticles on the tribological properties and the load capacity of the PAO 8 and GL-4 oils, respectively [14]. Liu investigated the mending effect of copper nanoparticles on contact surfaces; the results showed that copper nanoparticles do display an excellent mending effect [15]. Lee found that nanoparticles dispersed in mineral oil played an important role in the lubrication enhancement of nano-oil; the friction coefficient of the disc specimen immersed in the nano-oil was significantly lower than that of the disc specimen immersed in the mineral oil. [16]. Hu prepared nanoparticles and conducted the experiment, and the results showed that addition of nanoparticles improved the wear resistance and load bearing capacity, while reducing the coefficient of friction of 500 SN base oil [17]. As a common nanoparticle, SiO_2 has been valued by researchers because of its advantages of good controllability and dispersion and narrow distribution range. Wang and Zhu investigated the tribological properties and anti-wear mechanism of the water-based lubricants with SiO_2 nanoparticles [18,19]; nevertheless, the interaction between surface roughness and nanoparticles has not been explored in depth. Peng's aim was to study the tribological properties of liquid paraffin with SiO_2 nanoparticles as additives, and the results indicate that the optimal concentrations of SiO_2 nanoparticles in liquid paraffin is associated with better tribological properties than pure paraffin oil [20].

In previous research, less attention has been paid to the tribological properties of friction pairs under the coupling effect of surface roughness and nanoparticle size. Pena-paras studied the friction and wear mechanism of a sliding block under the interaction of TiO_2 nanoparticles and surface roughness [2]; however, the object of this study is slider, which cannot be directly applied to rolling bearing. García developed a grinding lubricant containing nano particles as the main additive; the analysis on slitting knives determines that nano particles weight percentage in the oil-based lubricant was the only significant influence in the study [21]. Uysal investigated the effects of nano particles on surface roughness and cutting temperature during MQL (minimum quantity lubrication) milling of AISI 430 stainless steel, and the results showed that the MQL method was beneficial for reducing cutting temperature and surface roughness values [22].

Based on the literature reviewed, insufficient attention has been paid to the relationship between the SiO_2 nanoparticles and surface roughness of high-speed rolling bearings. The embedding situation between various nanoparticles and the rough surface will affect the tribological characteristics of rolling bearings. Therefore, the tribological mechanism of nano-lubricated high-speed rolling bearings under various nanoparticle embedded states has been studied in this manuscript.

2. Materials and Methods

2.1. Preparation of Nano-Mixed Oil

2.1.1. Preparation of 50 nm Particles Mixed Oil

SiO_2 particles with a size of 50 nm and a mass fraction of 2% were added to Mobil DTE 24 base oil, and then 1.5% T154 dispersant was added. An electric mixer was used to stir the nano-mixed oil for 8 min. Nano-mixed oil with a specific ratio was prepared, which was used for the complete embedding experiment.

2.1.2. Preparation of 10 μm Particles Mixed Oil

SiO_2 particles with a size of 10 μm and a mass fraction of 2% were added to Mobil DTE 24 base oil, and then 1.5% T154 dispersant was added. An electric mixer was used to stir the nano-mixed oil for 8 min. Nano-mixed oil with a specific ratio was prepared, which was used for the complete non-embedding experiment. The preparation process is shown in Figure 1.

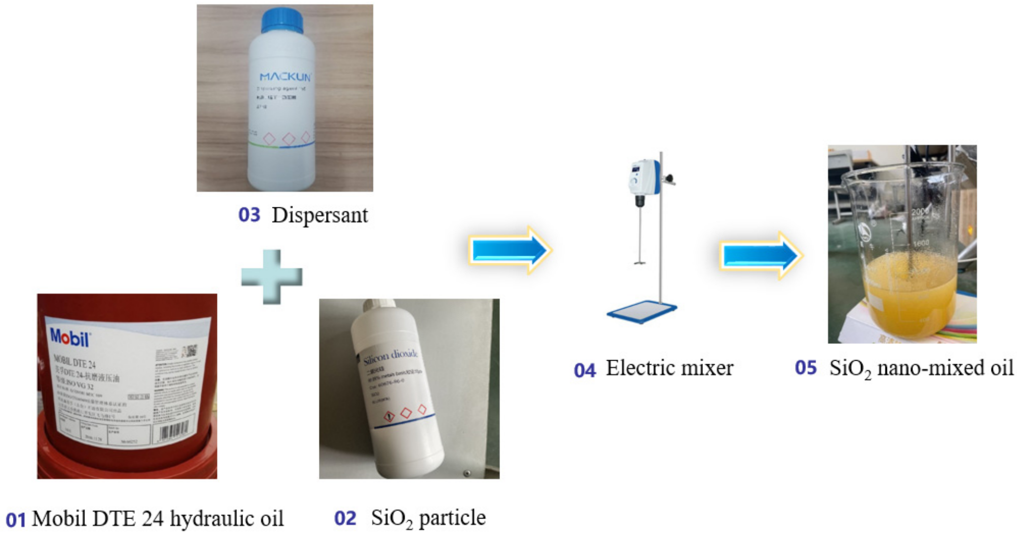

Figure 1. Preparation process of nano-mixed oil.

2.2. Bearing Microtopography

HRB NU210 roller bearing (Harbin Bearing Manufacturing Co., Ltd., Harbin, China) was adopted as the test sample, which is shown in Figure 2. A Talysurf CCI2000 white light interference surface profilometer was used to measure the bearing microtopography, and the measurement results are shown in Figure 3.

Figure 2. Rolling bearing.

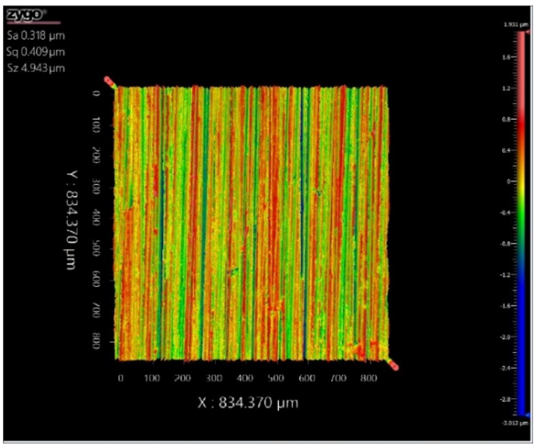

Figure 3. Surface microtopography of the roller bearing.

2.3. Experimental Design

Based on the 50 nm and 10 μm SiO_2 particle mixed oil, the experimental research of nano-lubricated rolling bearing was carried out for the completely embedded and completely non-embedded conditions, respectively; the effect of different nano-mixed oil with a specific ratio, surface morphology and operating conditions on the coefficient of friction and wear mechanism of high-speed rolling bearing under various embedding states was explored, and then the mechanism of reducing friction and increasing life of high-speed rolling bearings was obtained.

The complete embedding state in this experiment was shown in Figure 4a, and in this case, the nanoparticles were far smaller than the surface roughness, which results in the nanoparticles being completely embedded in the rough surface. The completely non-embedded state is shown in Figure 4b, and in this case, the nanoparticle size was much larger than the surface roughness, which causes the nanoparticles to completely float on the rough surface. The test conditions are shown in Table 1.

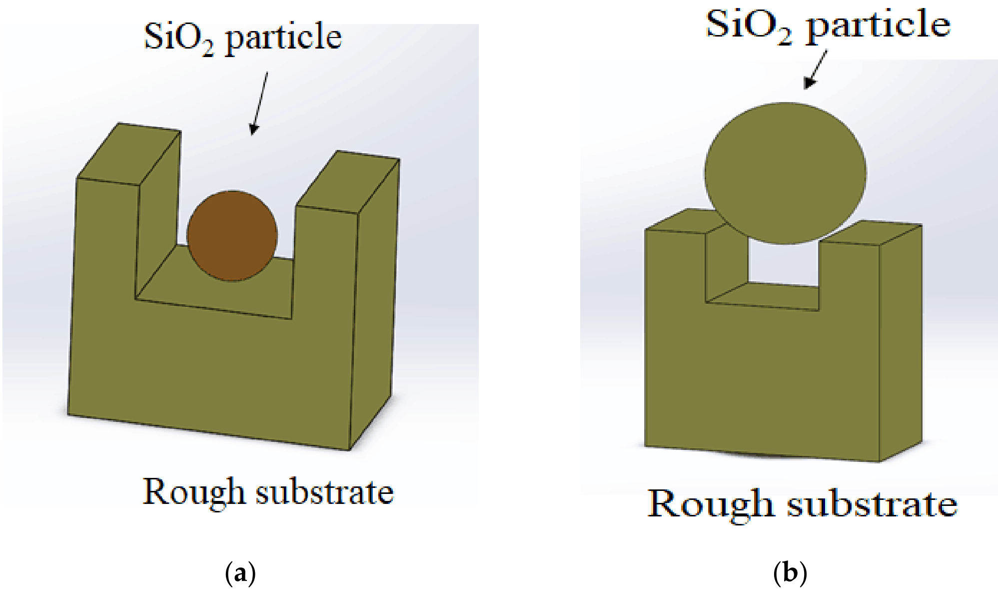

Figure 4. Embedding conditions: (**a**) complete embedded case; (**b**) complete non-embedded case.

Table 1. Test conditions.

Test No.	Radial Load (N)	Rotating Speed (r/min)	Oil Quantity (mL/min)
1	800	3000	6
2	1600	3000	6
3	2400	3000	6
4	3600	3000	6
5	4000	3000	6
6	4000	1000	6
7	4000	1500	6
8	4000	2000	6
9	4000	2500	6
10	4000	3000	12
11	4000	3000	18
12	4000	3000	24
13	4000	3000	30

3. Results and Discussion

3.1. Friction and Wear of Nano-Lubricated Rolling Bearings with Various Oil Supply under Different Embedded States

The influence mechanisms of nano-mixed lubricant with 50 nm particle sizes on the tribological properties of rolling bearings were studied experimentally. The experimental results are presented in Figures 5 and 6. Test conditions: speed was 3000 r/min, load was 4000 N, time was 10 min. The nano-mixed oil with 2.5% 50 nm SiO_2 particles and 1.5% dispersant was used in this experiment.

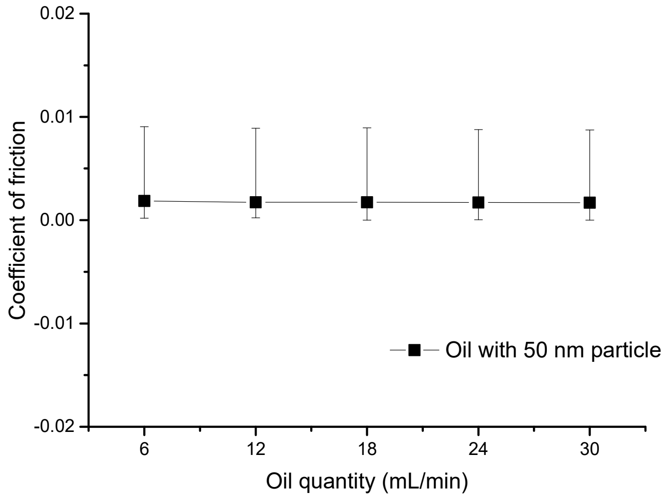

Figure 5. Variation law of coefficient of friction under different oil quantities.

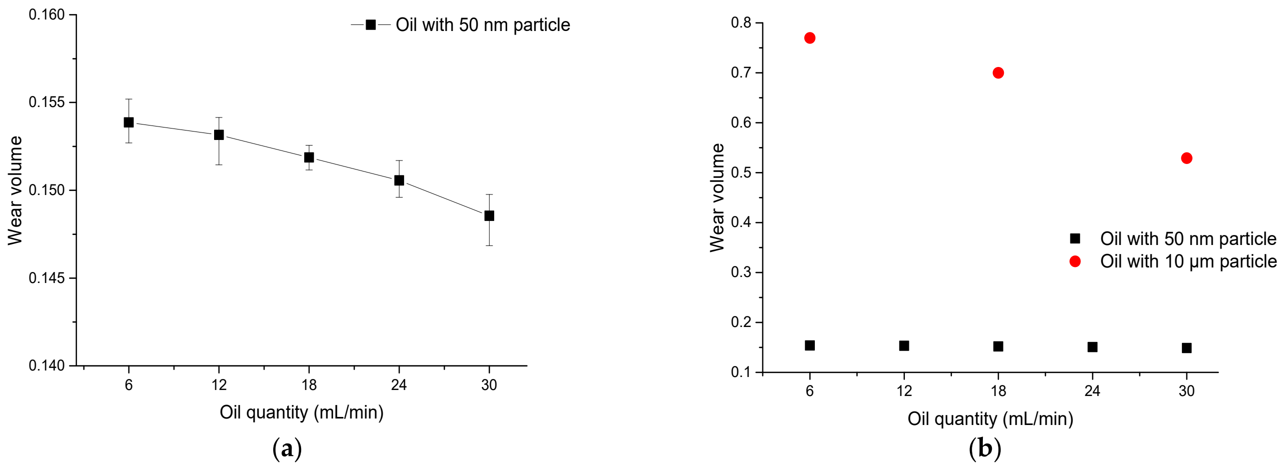

Figure 6. Variation law of wear under different oil quantity: (**a**) wear volume of the complete embedded under various oil supply; (**b**) comparison of wear volume under different embedded conditions.

Figure 5 shows the variation law of coefficient of friction of rolling bearing lubricated with 50 nm particle mixed oil under different lubricating oil quantities, ranging between 6–30 mL. The results show that the coefficient of friction of rolling bearings decreases with the increase of oil quantity. In this case, the reduction in oil quantity produces relatively less lubrication, and therefore increases the coefficient of friction of the contact surface to a certain extent.

In Figure 6a, when the oil quantity is 6 mL, the rolling bearing is in the stage of lack of oil, and the wear is aggravated due to the small amount of oil. When the oil quantity increases to 30 mL, the wear decreases gradually. The results show that with an increase in the oil quantity, the wear amount decreases.

Figure 6b shows that the comparison of wear volume of rolling bearing lubricated with 50 nm mixed oil and 10 μm mixed oil under different embedded conditions. Rolling bearing lubricated with 10 μm particles mixed oil easily fails; therefore, only three tests of the oil quantity of 6, 18 and 30 mL/min are conducted here. The results show that the 50 nm mixed oil has a greater effect on wear reduction than the 10 μm mixed oil. The results also indicate that when nanoparticles are fully embedded in the rough surface, bearing lubrication has an excellent effect, and its anti-wear effect is far greater than the case when nanoparticles are completely floating on the rough surface.

3.2. Friction and Wear of Nano-Lubricated Rolling Bearings with Various Speed under Different Embedded States

The influence mechanisms of nano-mixed lubricant with 50 nm particle sizes on the tribological properties of rolling bearings are studied experimentally. The experimental results are presented in Figures 7 and 8. Test conditions: load is 4000 N, time is 10 min, oil quantity is 6 mL/min. The nano-mixed lubricant with 2.5% 50 nm SiO_2 particles and 1.5% dispersant was used in this experiment.

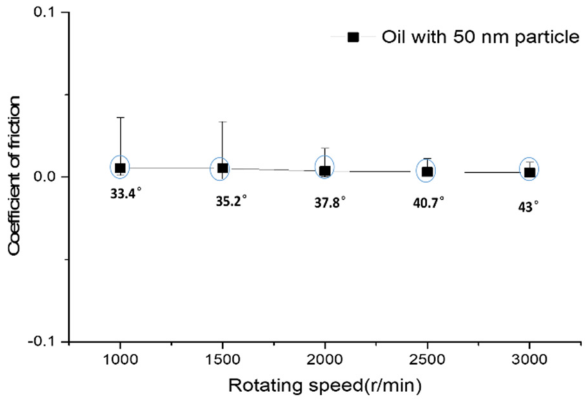

Figure 7. Variation law of coefficient of friction under different speeds.

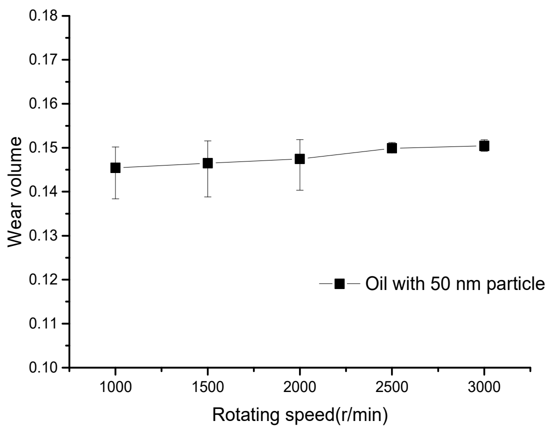

Figure 8. Variation law of wear under different speeds.

Figure 7 shows that the coefficient of friction of rolling bearings decreases with the increase of rotating speed. It can be seen from Figure 7 that the temperature of the bearing inner ring increases with the increase of rotational speed. In this case, the load reaches a large value of 4000 N, so the effect of the skidding factor on the coefficient of friction of rolling bearings is non-significant; conversely, the effect of the temperature on viscosity becomes significant. The viscosity decreases with the temperature increases, and further changes the lubricant film, resulting in a decrease in coefficient of friction of rolling bearings.

As shown in Figure 8, under specific working conditions, the wear volume is approximately 0.14544 mm under the rotational speed of 1000 r/min, the wear volume is about

0.15043 mm under the rotational speed of 3000 r/min, which indicates that the wear volume shows an increasing trend with increases of the rotational speed. Rolling bearing lubricated with 10 µm particle mixed oil easily fails; therefore, only one test was conducted here. Test conditions: load is 4000 N, speed is 3000 r/min, and oil quantity is 6 mL/min. In this case, the test result of wear volume is 0.77 mm, which is much larger than the wear volume of rolling bearing lubricated with 50 nm particles mixed oil. When 50 nm nanoparticles are added, due to the smaller size of the nanoparticles, the nanoparticles are completely embedded in the surface gap of rolling bearing, which reduces the wear of the high-speed rolling bearing and shows good anti-wear performance.

3.3. Friction and Wear of Nano-Lubricated Rolling Bearings with Various Loads under Different Embedded States

The influence mechanisms of nano-mixed lubricant with 50 nm particle sizes on the tribological properties of rolling bearings were studied experimentally. The experimental results are presented in Figures 9 and 10. Test conditions: rotating speed was 3000 r/min, time was 10 min, oil quantity was 6 mL/min. The nano-mixed lubricant with 2.5% 50 nm SiO_2 particles and 1.5% dispersant was used in this experiment.

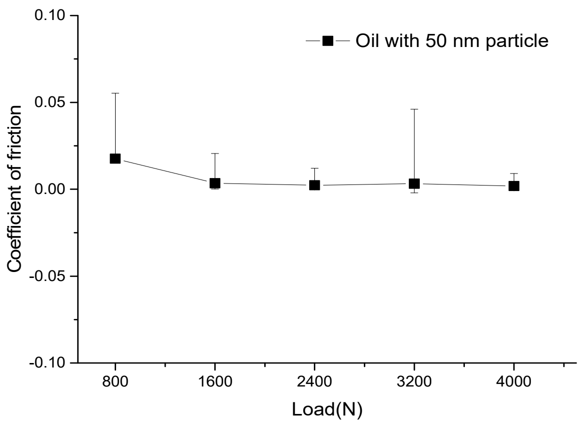

Figure 9. Variation law of coefficient of friction under different loads.

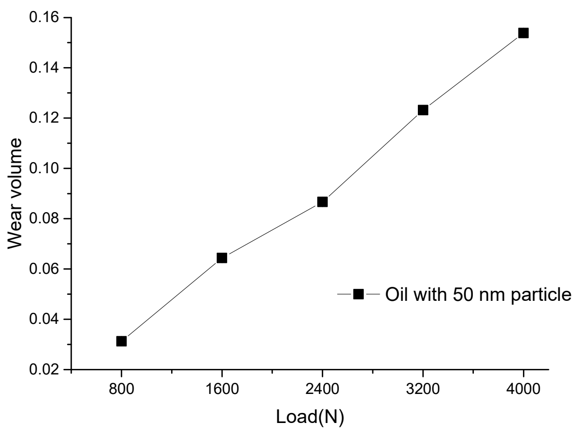

Figure 10. Variation law of wear under different loads.

Figure 9 shows the variation law of coefficient of friction of rolling bearing lubricated with 50 nm particles mixed oil under different loads. The results show that the coefficient of friction of rolling bearings decreases in general with the increase of loads. The greater the load, the smaller the skid factor. As the load increases, the skid factor decreases, resulting in a decrease in the coefficient of friction of high-speed rolling bearings to a certain extent.

As shown in Figure 10, wear volume is approximately 0.31265 mm under the load of 800 N, and the wear volume is about 0.15386 mm under the load of 4000 N, which indicates that the wear volume increases continuously with increases of the load. Rolling bearing lubricated with 10μm particles mixed oil easily fails; therefore, only three tests of the loads of 800 N and 2400 N were conducted here. The experimental results show that the wear volume is 0.181 mm and 0.624 mm, respectively. This is much larger than the wear volume of rolling bearing lubricated with 50 nm particles mixed oil. When 10 μm particles are added, due to the larger size of the particles, the particles are completely floating on the rough surface, which increases the wear of the high-speed rolling bearing.

4. Conclusions

The specific ratio of SiO_2 nano-mixed oil was prepared, the tribology test of nano-lubricated high-speed rolling bearings considering the interaction between different nanoparticles and the rough surface was conducted, and then the friction and wear properties such as friction coefficient, wear volume and real-time temperature rise of high-speed rolling bearings under different embedding conditions were studied systematically.

(1) Different nanoparticle sizes and bearing surface roughness form different embedding states. Compared to the complete non-embedded state, the anti-wear effect of bearings can be effectively improved for the complete embedded state of the nanoparticles. The rolling bearing lubricated with 50 nm particles mixed oil still shows good wear resistance at high speed.

(2) As for the light load rolling bearing lubricated with nano-mixed oil, the coefficient of friction is appropriately increased, while the wear of the rolling bearing is effectively reduced.

(3) Rolling bearing lubricated with nanoparticles mixed oil still shows good anti-wear performance under the condition of lack of oil, which provides specific methods for reducing wear and extending the life of rolling bearings.

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