

Article

A Study on Micro-Pit Texture Parameter Optimization and Its Tribological Properties

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Abstract: In this paper, the effect of micro-dimple textures (produced by a laser) on the tribological properties of bearings is investigated. This study offers guidelines to reduce the friction torque of the bearing pair and addresses the problem of difficult start-ups after shutdowns. Micro-pits with different texture diameters and depths were machined on the surface of journal bearings. Then, the impact of several different texture parameters on the tribological performance of the bearing pairs was studied using an orthogonal experimental design. Subsequently, the surface morphology of the bearings before and after the friction and wear test was observed using scanning electron microscopy (SEM) and energy-dispersive spectrometry (EDS). These observations were then used to determine the type/state of friction and wear, which also improves our understanding of how texture affects the service life of bearings. The results indicate that the bearings' micro-pit surface hardness follows an approximate parabolic spatial distribution that decreases along the micro-pit wall. Furthermore, the laser processing of surface textures was found to cause hardening in certain areas, and the chemical composition of elemental carbon and oxygen at the inner surface of processed bearings increased by 31.1% and 7.9%, respectively. Moreover, abrasive wear was identified as the primary form of wear. The textured surface's antifriction mechanism primarily functioned to trap particles, which acted as a secondary lubrication source and altered the lubrication states by serving as a medium for supplied lubricants. The results confirm that a suitable selection of texture parameters can not only effectively reduce the friction coefficient without shortening the service life of the bearing pair but also facilitate the smooth start-up of the rotor-bearing system.

Keywords: surface texturing; journal bearing; tribological properties; parameter optimization



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1. Introduction

With advancing technology, higher demands are being placed on rotating machinery that operates under extreme conditions. As a critical component, the entire system is affected by the tribological performance of journal bearings. In order to improve the tribological properties of bearings under such conditions, researchers have devoted considerable time and effort [1,2]. Traditional tribology theory holds that the smoother the surfaces that contact each other, the smaller the friction and wear [3]. Several studies found that the tribological properties of friction pairs can be improved by designing and performing surface texturing [2,4–6]. Surface texturing, also known as surface micromachining, is an attempt to reduce friction and wear on a material's surface through special machining methods or treatments.

Specifically, surface texturing alters the tribological performance of journal bearings (bearings that support rotating shafts), which was shown to impact their reliability and service life [7]. Therefore, it is highly desirable to study the impact of surface textures

on the tribological performance of hydrodynamic journal bearings. General surface texturing types include circles [2,8–10], ellipses [8,11], squares [9,11,12], diamonds [8], and triangles [9,11,13]. In addition, circular micro-pit textures are primarily used to study the tribological properties of surface textures because they are easy to process and simple to manufacture. In this paper, circular pit textures were chosen to study the effect of surface texture on the tribological properties of bearings. Slawomir et al. [14] found that a texture density of 9% resulted in the lowest friction coefficient under higher temperature conditions. Niketh et al. [15] showed that the friction coefficient decreased under dry friction and lubrication conditions. The friction coefficient of a mixed-texture surface decreased by 20.37% under dry friction conditions and by 30.43% under water lubrication conditions. Li et al. [16] prepared a novel kite-shaped texture and found that the friction coefficient was inversely proportional to the angle under lower surface densities ($S_p = 5\sim 10\%$). The friction coefficient increases inversely with the angle for higher surface densities ($S_p = 20\sim 30\%$). Schnell et al. [17,18] compared the tribological properties of three different surfaces under water lubrication conditions and found that grooved surfaces could reduce friction by 29%. Zhang et al. [19] machined three textures with different shapes on the surface of 42CrMo-alloy steel and analyzed the tribological characteristics of the microstructure through experiments. The group also found that the wear resistance of machined alloy steel improved compared to the unprocessed surface. Annadi et al. [20] reported that, in general, the higher the texture density, the better the antifriction effect. However, when the texture density is too high, the adverse effects of stress concentration and surface roughness on tribological properties become more pronounced—materials with a texture area density of 0.3 and texture depth of 10 μm exhibit better tribological properties. Hu et al. [21] found that the wear rate of the original silicon carbide surface can be reduced by more than 28 times under a load of 5 N. Wozniak et al. [22] discovered that under lubrication conditions, the friction coefficient can be reduced by 26%, and the wear volume can be reduced by 29%. Guo et al. [23] studied the tribological properties of TB6 (Ti-10V-2Fe-3Al) alloy, which was improved using laser surface texturization under dry friction as well as oil-deficient lubrication conditions. Their research indicates that the optimal low-shear coatings (LSCs) and diamond-like structures (DSs) can significantly reduce the coefficient of friction (CoF) by 66% under dry friction conditions and by 61% under oil-deficient lubrication conditions. Zhao et al. [24] used a friction tester to study the tribological properties of textured gear alloy in a dry friction state. Their experimental results indicate that textured gear alloy has good tribological properties. In addition, the friction coefficient and wear rate can be reduced by more than 30% and 95%, respectively, which they attributed to the dynamic pressure effect of texture and debris storage. Zhang et al. [25] showed that the friction coefficient of a grooved textured surface (depth $h = 0.4$ mm, width $w = 1.5$ mm, area ratio $S_p = 34\%$) was 12.7% lower than that of a non-textured surface. The wear resistance was 4.9 times higher than the non-textured surface. Hu et al., Xu et al., and Rapoport et al. [26–28] showed that both the friction and the wear of friction pairs could be effectively reduced by selecting a suitable texture–area ratio for a specific arrangement. Arslan et al. [29] studied the effects of texture diameter and depth on the tribological properties of diamond coatings under lubrication. Their study revealed that the micro-concave texture with the optimal diameter could capture debris and improve surface wear resistance significantly. Saeidi et al. [30] investigated how surface texture affects the wear and failure mechanism of gray cast iron under the reciprocating action in a starved lubrication state. The results indicated that two different wear and failure mechanisms existed in their friction and wear tests with different surface texture patterns. Zhang et al. [31] showed that a suitable surface texture shape was beneficial to improving the tribological properties. In addition, friction discs with a square texture arrangement exhibited superior tribological properties compared to those with a linear emission arrangement. While several studies have found that textured surfaces can improve the tribological performance of friction pairs, few investigations have focused on determining the optimal textured parameters and the tribological properties of bearings.

In this paper, we explore surface textures with various texture area densities, depths, and diameters that were created on bearing surfaces through laser processing. More specifically, the effect of laser forming on surface hardness was investigated, and the tribological properties of textured rotor–bearing systems with different texture parameters under various operating conditions were studied. We used friction and wear testing equipment and the orthogonal test method, and we examined the impact of the weights for each parameter on the friction coefficient. Subsequently, the optimal parameter combination to reduce friction and wear was identified. Furthermore, the surface morphology and wear trace composition of the bearings were analyzed in more detail to better understand their friction and wear mechanisms. Overall, this study provides a design direction to help overcome the problems associated with restarting rotor–bearing systems after a shutdown.

2. Experiments

2.1. Preparation

Brass has many desirable properties, such as high strength, good plasticity, and high toughness, as well as excellent friction-reducing properties. In addition, it is widely used in journal bearings around the world. Therefore, brass was the material of choice in this study. The specifications of the processed samples were area = 100×100 mm, surface hardness = 266.5 HV, and inner surface roughness (R_a) $\approx 1.6 \mu\text{m}$; the other surface roughness (R_a) was $3.2 \mu\text{m}$. A BY-BDB three-dimensional fiber laser texturing machine was used to create the surface texture. The surface texture machine used a 200 W diode-pumped short pulse Nd: YAG laser (1064 nm) with a repetition frequency below 50 kHz and a pulse width and power instability below 5 ms and $\pm 3\%$, respectively. Micro-pit arrays were processed by securing the sample in a three-jaw chuck, with a laser beam from a laser launcher device targeting the inner surface. The chuck's rotation drove the sample to turn in a regular manner, which enabled the precise texturing of the micro-pit surface—see Figure 1.

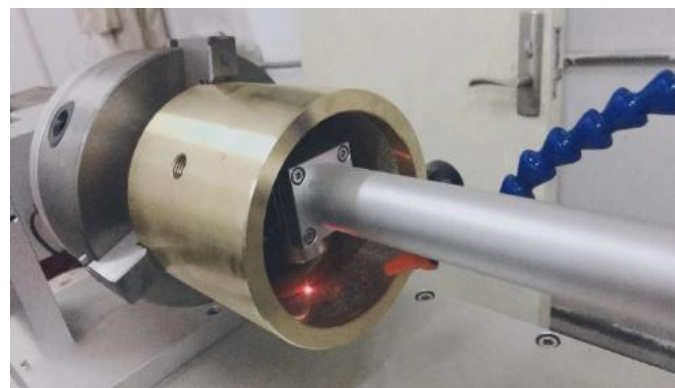


Figure 1. Surface texture machining.

The textured surfaces were polished sequentially using 800#, 1200#, and 1500# metallographic sandpapers. Then, the textured surface was cleaned with acetone solution for 10 min. In addition, the JSM-5610LV scanning electron microscope (SEM) and a German NanoFocus 3D surface profilometer analyzer were used to observe the surface micro-indentation texture produced by the BY-BDB laser texturing machine, and a typical 3D morphology map of the micro-pit was obtained.

2.2. Friction and Wear Test

In this paper, the friction and wear test (type: LYB-Bearing, manufacturer: Luoyang Aobote Intelligent Equipment Co., Ltd., Luoyang, China) was performed using a bearing test bench. The friction and wear tester, depicted in Figure 2, operates with a surface-to-surface contact mode. The bearing was installed in the testing machine (spindle surface hardness = HRC55–58), which was attached to a V-shaped table, and a hydraulic cylinder

below the fixed table applied the load. The friction and wear test of the bearings was conducted through the rotation of the spindle.

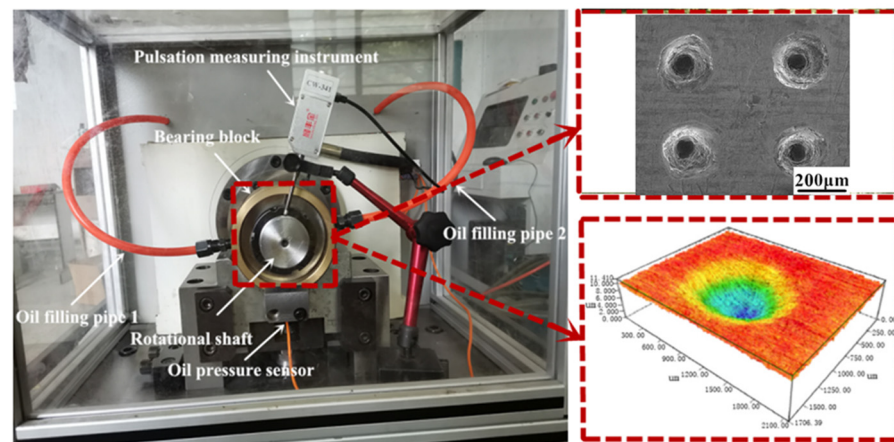


Figure 2. Setup to test the tribological properties.

Great Wall JUSTAR J400 15w-40 lubricating oil was selected for the test, with its parameters listed in Table 1. The test lasted 30 min and was conducted at room temperature (25 °C) with a relative humidity of 60%. The normal load and rotational speed were 4 kN and 600 rpm, respectively.

Table 1. Performance parameters of the lubricant.

Parameters	Units	Values
Flash point	°C	230
Viscosity in 100 °C	$10^{-6} \text{ m}^2/\text{s}$	15.66
Density	kg/m^3	900
Pour point	°C	−39
Viscosity grade	–	40

The tribological properties after surface texturing are determined by many parameters such as area ratio, diameter, and depth. Thus, it was necessary to determine the order of parameters affecting the tribological properties. In this work, orthogonal experiments were used to establish the order of influencing factors.

2.3. Design of the Orthogonal Experiment

According to the design scheme, the textured parameters—area density ratio, diameter, and depth—were determined using an orthogonal experimental method and are represented by A, B, and C, respectively. The factors influencing the tribological properties were analyzed using this design, as shown in Table 2.

Table 2. Factor level list of the orthogonal test.

Level	Factors		
	A	B	C
1	20	100	10
2	25	300	25
3	35	500	40

The range analysis of the orthogonal test design of the textured surface friction coefficient is shown in Table 3. In Table 3, the factors affecting the friction coefficient are ranked based on their impact from highest to lowest as follows: density ratio, diameter, and depth.

This ranking is represented by $R_{\text{area density ratio}} > R_{\text{diameter}} > R_{\text{depth}}$. Moreover, the texture parameters with the lowest friction coefficient are $S_p = 20\%$, $d = 300 \mu\text{m}$, and $h_p = 25 \mu\text{m}$.

Table 3. Range analysis of the orthogonal test design.

No.	Factors			COF
	A	B	C	
0	0	0	0	0.12760
1	20	100	10	0.07050
2	20	300	25	0.05320
3	20	500	40	0.07012
4	25	100	25	0.07870
5	25	300	40	0.06451
6	25	500	10	0.07736
7	35	100	40	0.11280
8	35	300	10	0.08023
9	35	500	25	0.08115
K ₁	0.087	0.0760	0.0721	
K ₂	0.066	0.0710	0.0811	
K ₃	0.076	0.0825	0.0764	
R	0.010	0.0050	0.0043	
Rank			A > B > C	
Optimum		$S_p = 20\%$, $d = 300 \mu\text{m}$, $h_p = 25 \mu\text{m}$		

The main effects plot, which illustrates the impact of geometric parameters of the textured surface on the friction coefficient, is shown in Figure 3. In Figure 3, the optimal combination scheme of geometric parameters for the textured surface is shown as level 1 for factor A, level 2 for factor B, and level 2 for factor C. This corresponds to the combination $A_1B_2C_2$ under the selected parameters.

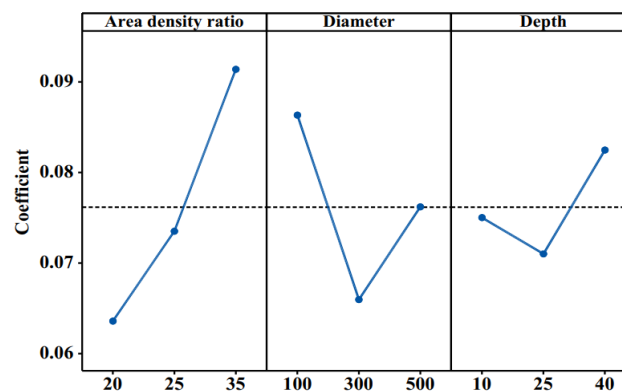


Figure 3. Mean main effects plot for the three variables (area density, diameter, and depth).

3. Hardness Analysis of Laser Machining

3.1. Analysis of the Surface Hardness

The HVS-1000AT/EOS100B automatic microhardness measurement system was selected for hardness measurements. The cross-sectional specimens' hardness measured by the measurement equipment is based on a microhardness tester, high-power microscope observation, and a special laser measurement method. The loading pressure used in the measurement was 1000 g, and the unloading pressure after the loading time was 10 s. The effect of laser machining on microhardness is shown in Figure 4. The figure indicates that the surface hardness was significantly enhanced by ablation.

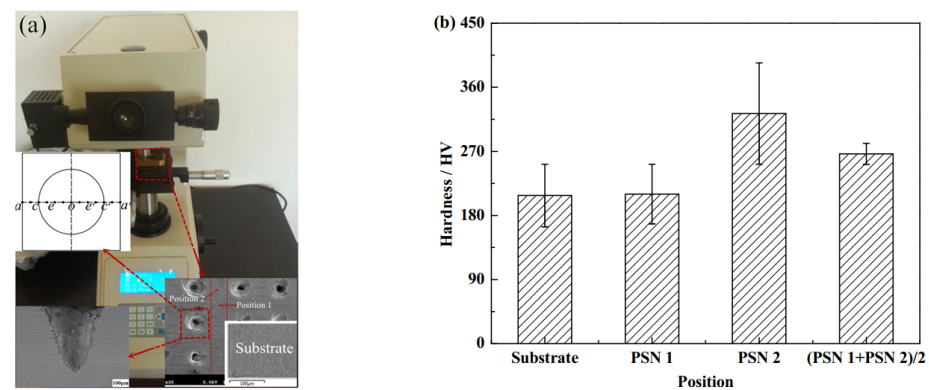


Figure 4. Measurement location and surface hardness. (a) Measurement location. (b) Surface hardness.

Moreover, the surface hardness of position 2 was increased by 50%, which was closer to a micro-dimple. The reason for this is that position 2 was located in the heat-affected zone of the laser micro-pit. Hence, surface hardening occurred, and the hardness in this zone was clearly higher than that of the substrate.

A micro-dimple results from local thermal ablation. When a high-energy laser is used to modify the surface, it rapidly ablates the material at high power density and forms a molten pool of liquid in the irradiated area. The heat-affected zone was subjected to melting heat, which triggered the phase transition of the microstructure. Micro-pits then rapidly underwent melting to condensation, and the rapid heating and cooling rate was much higher than the quenching rate of common surface heat treatments. The internal dislocation density in the quenching area of the micro-pit was relatively high, which ultimately facilitated the formation of a martensite structure. Therefore, the laser micro-pit had a hardening effect on position 2 of the heat-affected zone. Surface hardening occurred, which would play an essential role in reducing the friction and wear of hydrodynamic journal bearings. However, there was no clear change in position 1, which is further away from the ablated micro-pit. It could be concluded that no hardening occurred. Once friction and wear occurred on the surface of the journal bearing in the friction and wear test, friction and wear in this area would be given priority.

In a word, laser machining would cause hardening in the local area of the surface, but the scope was limited. The reason for this was that the surface hardness at the hardness measurement location 1 (see Figure 4a) was about 210 HV, while at location −2, it was about 323 HV, and the substrate was about 208 HV (see Figure 4b). Thus, the scope of the hardening caused by laser processing was limited.

3.2. Effect of Energy on Microhardness

The effect of pulse energy on microhardness is shown in Figure 5. In Figure 5a, the surface microhardness of the micro-pit shows a parabolic distribution in the horizontal a-a' direction. Surface microhardness values were different when the pulse energies were 1 J, 3 J, 5 J, and 7 J; the higher the energy, the higher the surface hardness. An increase in energy could improve the average surface hardness, and the hardness value of the center point o was the highest under laser ablation. The rapid increase in surface temperature, along with its significant variation, occurred due to the action of the stronger laser. This change enhanced the driving force for surface phase transformation. As a result, a martensitic structure formed during the solidification phase transformation. Thus, a higher hardness could be achieved locally, i.e., in some areas. Figure 5b shows that the hardness of micro-pits gradually decreased from the surface to the bottom along the depth direction, and the higher the energy, the greater the hardness. This also suggested that the increase in energy promoted the expansion of the heat-affected zone, and the hardness also improved significantly. In addition, the depth of the hardness-affected layer increased.

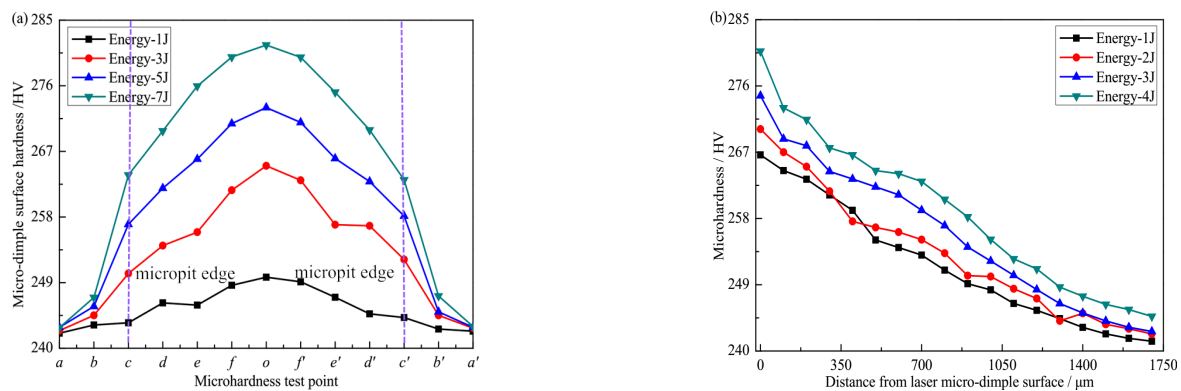


Figure 5. Variation in the micro-pit hardness for different energies. (a) Variation in hardness in a-a' direction. (b) Variation in hardness with depth direction.

3.3. Effect of Repetition Times

The distribution of microhardness across various repetition times is shown in Figure 6. In Figure 6a, the microhardness of a and a' in the heat-affected zone, under varying pulse repetition times, differ and are significantly higher than those of the matrix. The microhardness value increased as the testing position approached point o and reached the maximum at point o. The microhardness at the center point o of the material surface increased by 41%, 50%, 55%, and 59% compared to the matrix hardness values for 1, 2, 3, and 4 repetition times, respectively. However, the microhardness at the edges c and c', heat-affected zones a and a', and point o showed a gradual increase with increasing repetition number. In Figure 6b, the hardness of micro-pits with different repetition numbers decreased as the depth of the micro-pit wall increased. This is because the energy of the laser ablation process was transferred from the surface of the material to the interior and weakened gradually along the depth of the micro-pit. The power density of the laser was lower than the melting threshold of the material as the micro-pit approached a certain depth. In addition, the ablation phenomenon would not occur in the material interior. Therefore, the depth hardness was consistent with that of the substrate. The microhardness of the micro-pit measured 880 μm after one repetition and 1720 μm after four repetitions. Moreover, their maximum hardness increased by 28% and 50%, respectively, compared with the matrix hardness. This suggests that more repetitions can induce a deeper microhardness layer, and the microhardness can be improved significantly.

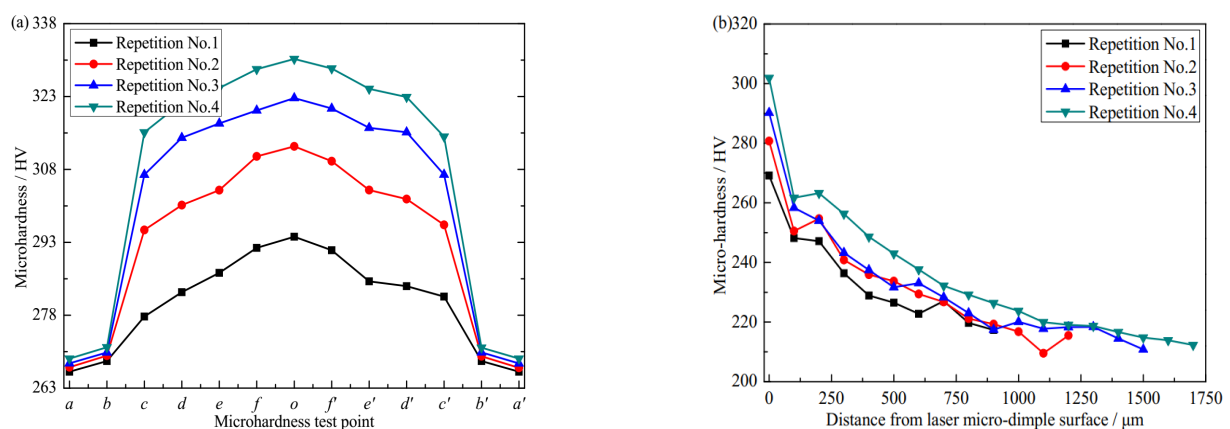


Figure 6. Distribution of hardness for various repetition numbers. (a) Hardness under various repetition times. (b) Relationship between hardness and depth.

3.4. Surface Composition Analysis

To further explore differences in the composition of the inner surface of a journal bearing after laser machining, the internal surface was analyzed using energy-dispersive spectroscopy (EDS) with a JSM-7800F field-emission scanning electron microscope. The composition analysis of a smooth inner surface and a textured inner surface is shown in Figure 7. As shown in Figure 7a, the main chemical elements of the inner surface of the smooth bearing were Cu, Zn, C, and O, ranked from high to low. However, the chemical composition of C and O of the inner surface after laser processing, shown in Figure 7b, increased by 31.1% and 7.9%, respectively. The primary reason for this is that the inner surface of the hydrodynamic journal bearing was subjected to transient laser beam energy, which caused both phase transformation and the hardening of the material's surface. The results of the surface texture analysis are consistent with the conclusion in Section 3.3, namely that the creation of the texture caused local hardening from the analysis, which eventually increased the content of the chemical elements C and O in the surface texture of the hydrodynamic journal bearing.

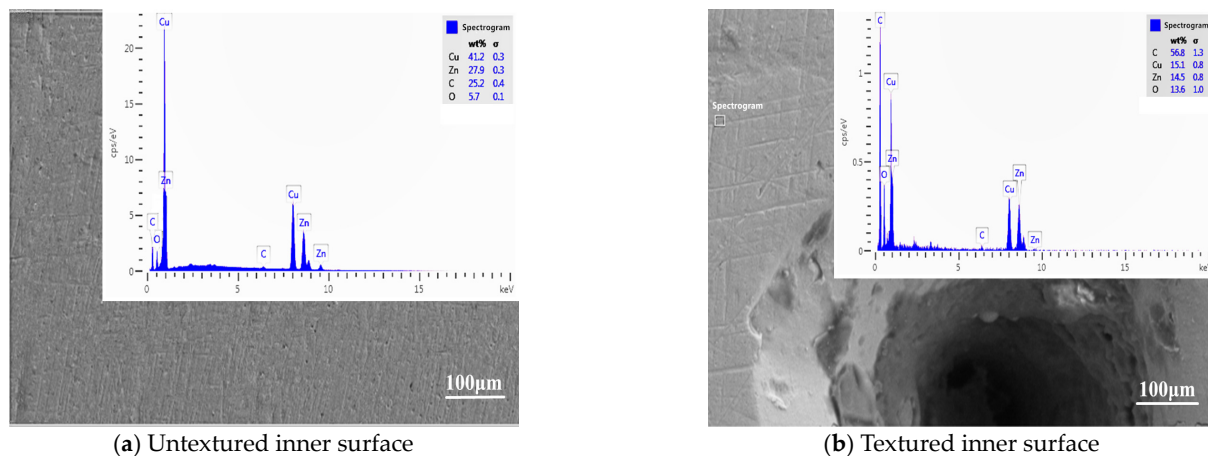


Figure 7. Surface composition of a journal bearing.

4. Tribological Characteristics

The variation in the friction torque of a textured bearing (area density ratio $S_p = 20\%$, diameter $d = 200 \mu\text{m}$, and depth $h_p = 35 \mu\text{m}$) versus time is shown in Figure 8. The figure shows many scratches at different positions, and varying widths and lengths are observed on the surface of the textured bearing. There are also many non-uniform scratches with different position distributions. This was likely due to the random distribution of wear particles generated by the peak friction between rough surfaces during the creation of the surface texture and the simultaneous presence of lubricating oil and spindle rotation. Furthermore, the different sizes and widths of scratches were caused by the inconsistent dimensions of wear particles generated by friction. In addition, the surface texturing micro-pits also captured some wear particles.

The variation in wear capacity with normal load is shown in Figure 9. As shown in Figure 9, the variation in the wear capacity of the textured bearing initially decreased and then began to increase as the normal load continued to rise, reaching its lowest point when the normal load was 4 kN. The reason for this behavior is likely that the bearing entered a hydrodynamic lubrication state when the applied loads varied between 2 and 4 kN. With increasing load (5~8 kN), the bearing might enter a mixed lubrication state. Moreover, the surface texture may not effectively store wear particles and produce a secondary dynamic pressure lubrication effect due to the increased number of loads, causing the friction to increase gradually. In addition, the maximum antifriction effect of textured bearings increased by 48% compared to untextured bearings when the load was 4 kN.

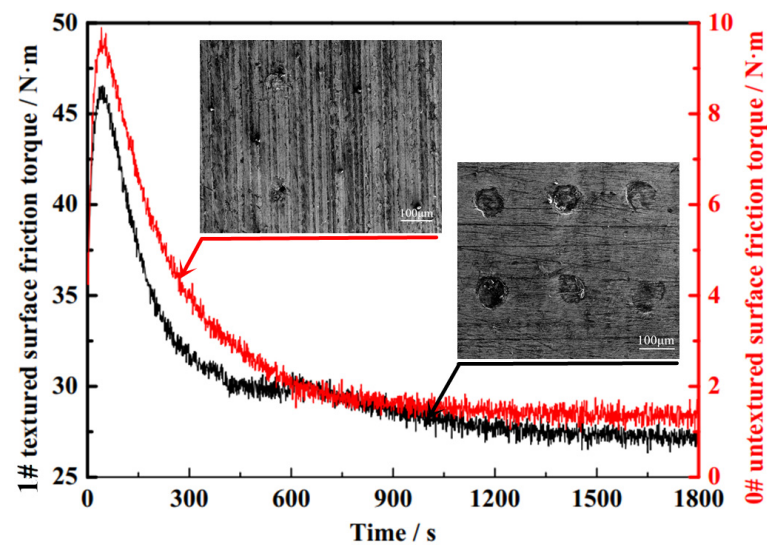


Figure 8. Friction torque variation versus time.

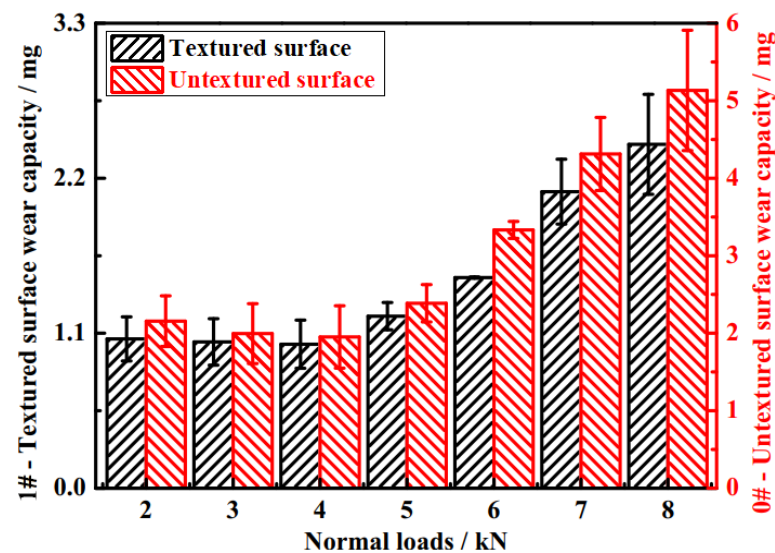


Figure 9. Variation in the wearing capacity versus load.

The variation in the wear capacity as a function of rotational speed is shown in Figure 10. When the rotational speed was 200–800 rpm, friction and wear on the textured surface were substantial, which suggests that the rotor–bearing system might have been in a boundary lubrication state. Furthermore, the interaction between rough peaks on the bearing surface was enhanced, which caused more rough protrusions on the bearing pair surface to participate in friction. Wear decreased gradually as the spindle speed operated in the range of 800–1100 rpm, while the bearing might have been in a mixed lubrication state. The gap between the spindle and bearing was infinitely close to the height of the rough peak, and the rough peak shared the external load. In addition, the oil film pressure and the friction and wear were caused by the deformation or shear of lubricating oil and rough peak. For the range of 1100–2000 rpm, wear increased gradually and slowly. The rotor–bearing system might have been in a hydrodynamic lubrication state, and the oil film separated the rotational shaft and bearing. The increased rotational speed caused the interfacial shear force of lubricating oil to increase, which led to the friction being intensified.

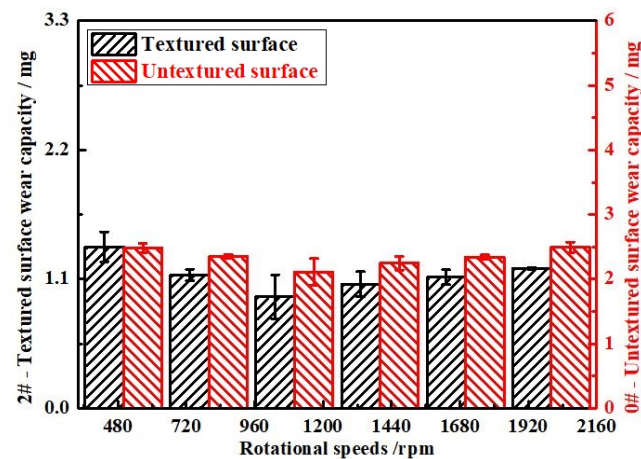
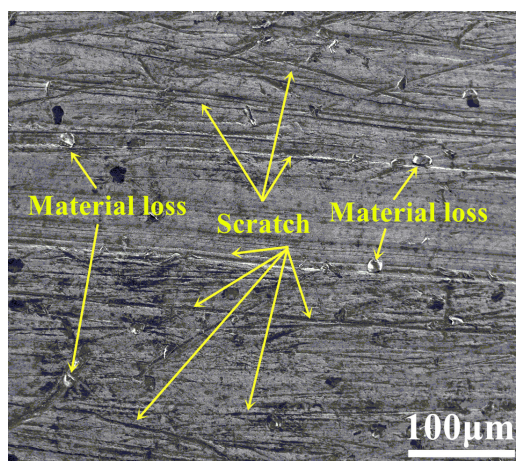
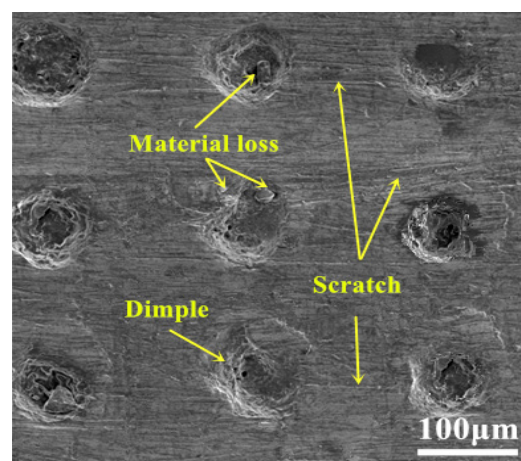


Figure 10. Variation in wearing capacity with speed.

The SEM images of the morphology of the bearing surface following the friction and wear test are shown in Figure 11. As shown in Figure 11a, obvious scratches occur on the untextured surface, and abrasive wear is more apparent. Because the untextured surface could not store lubricating oil and wear particles, microscopic cutting between bearing pairs was formed due to wear particles generated during the process of operation. This led to abrasive wear on the bearing surface. As shown in Figure 11b, the wear of the textured bearing was relatively low, the furrow was shallower and narrower, and the mechanism was abrasive wear and running-in wear. Abrasive particles were stored in micro-pits, which avoided the deterioration of the friction state of the contact surface somewhat, and the frictional heat and microscopic cutting of wear particles generated were reduced during the friction process. This was likely the reason that the surface texture bearing had fewer wear scratches and lower friction and wear. Moreover, the instantaneous heat generated during the surface texturing processing caused a phase transition on the material surface, and the wear resistance of the material surface was improved.



(a) Untextured SEM morphology



(b) Textured SEM morphology

Figure 11. SEM morphology of the bearing surface.

In order to analyze the difference after the friction and wear test and further clarify the friction and wear mechanism, the EDS system of the JSM-7800F field-emission scanning electron microscope was used to analyze the bearing surface. The EDS results of the bearing surface after the test are shown in Figure 12. As shown in Figure 12, the untextured bearing surface after the test mainly contained elements like Cu, Zn, C, O, and Fe. The most common element was Cu, which mainly came from the bearing substrate, followed by

C and O, which mainly came from lubricating oil that remained on the bearing surface. Moreover, Fe was detected on the untextured bearing surface, whereas no Fe element was found on the textured bearing surface. Thus, a substantial material transfer occurred during the friction process between the untextured bearing surface and the rotational spindle. Moreover, the hardness of the spindle material (GCr15 bearing steel) was significantly higher than that of the Cu-Zn alloy material. However, the Fe element was still transferred to the Cu-Zn alloy bearing surface, indicating that the rotational spindle experienced slight wear, while untextured surface wear was more severe than that for the textured surface.

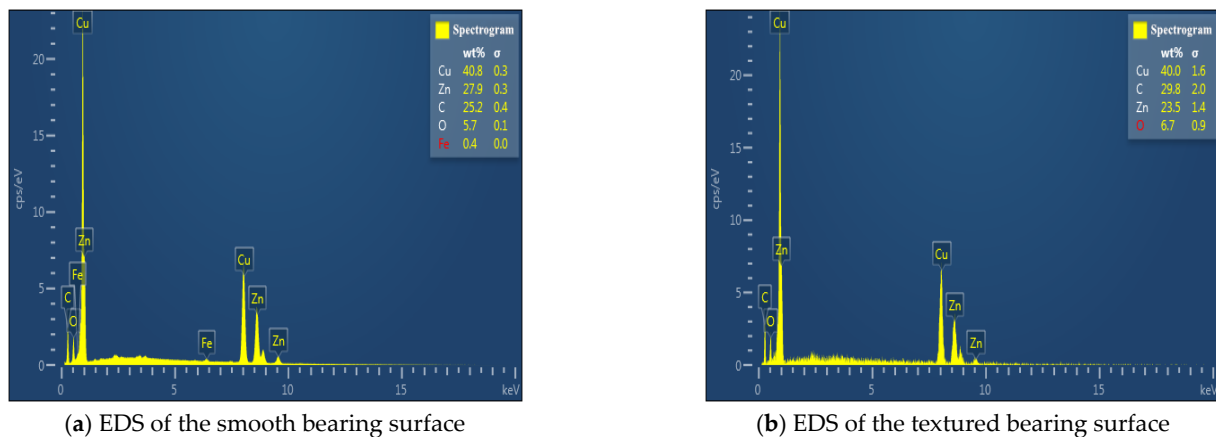


Figure 12. Surface EDS analysis results after the test.

5. Conclusions

A thorough experimental investigation of the effect of machining parameters on micro-pit morphology and its tribological properties was conducted. The most important conclusions can be summarized as follows:

- (1) The laser texturing of surfaces induced hardening in some areas, and it resulted in increased concentrations of carbon (C) and oxygen (O) elements on the inner surfaces of processed bearings by 31.1% and 7.9%, respectively. Moreover, it was found that the micro-pit surface hardness followed an approximate parabolic distribution and decreased along the micro-pit wall. This finding aids our understanding of hardness change during laser processing.
- (2) The optimal texture parameters to obtain the lowest friction coefficient were $S_p = 20\%$, $d = 300 \mu\text{m}$, and $h_p = 25 \mu\text{m}$. The antifriction properties of the investigated textured bearing could be improved by up to 48%. Suitable micro-pit texturing on the surface can effectively reduce friction, which provides a valuable approach for surface optimization design. In addition, it was found that the oil film boundary underwent a series of lubrication processes (from boundary lubrication to mixed lubrication and finally to dynamic lubrication) as the operating conditions changed.
- (3) The corresponding wear was abrasive wear, and the antifriction mechanism involved the synergistic effect of abrasive storage, a secondary hydrodynamic lubrication source, and a supplied lubricating medium to change the lubrication states. These outcomes provide valuable information for the optimization and control of bearing lubrication.

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Data Availability Statement: The data that support the findings of this study are available from the corresponding author.

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