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Thermal Dynamic Exploration of Full-Ceramic Ball Bearings under the Self-Lubrication Condition

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Abstract: A silicon nitride ceramic bearing has good self-lubricating characteristics. It still has a good operational status under the condition of a lack of oil. However, the temperature distribution of a silicon nitride ceramic bearing during its operation is unclear. To clarify the thermal distribution of a full-ceramic ball silicon nitride ceramic bearing under self-lubricating conditions, the changing trend of the rolling friction temperature between the rolling elements and channels with different accuracies is analyzed using the friction testing machine. The bearing heat generation model based on the silicon nitride material coefficient is established, and the life test machine measures the temperature of the bearing to verify the accuracy of the simulation model. The results show that the friction temperature between the ceramic ball and channel decreases with the increase in ceramic ball level. With an increase in the ceramic ball pressure and temperature, the friction temperature rises. Under self-lubrication, when the bearing bears a heavy load, the influence of the rotating speed on temperature rise tends to decrease. Under the condition of high speed, with the increase in load, the change range of temperature rise shows an upward trend. The important relationship between the bearing's heat and bearing's load and speed is revealed. It provides some theoretical guidance for the thermal analysis of a silicon nitride ceramic ball bearing under the self-lubricating condition to improve the service life and reliability of full-ceramic ball bearings.

Keywords: full-ceramic ball bearing; self-lubricating; ceramic ball; heat generation analysis; conduct heat; friction torque; temperature distribution



Citation: Tian, J.; Wu, Y.; Sun, J.; Xia, Z.; Ren, K.; Wang, H.; Li, S.; Yao, J.

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Lubricants **2022**, *10*, 213. <https://doi.org/10.3390/lubricants10090213>

Received: 31 May 2022

Accepted: 30 August 2022

Published: 6 September 2022

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1. Introduction

Engineering ceramic materials, such as silicon nitride (Si_3N_4), silicon carbide (SiC) and zirconia (ZrO_2), are widely used in high-precision fields such as the aerospace and military industries because of their excellent characteristics of wear resistance, corrosion resistance, high- and low-temperature resistance, high hardness, high strength, low density, low expansion coefficient and self-lubrication. Silicon nitride (Si_3N_4) stands out in engineering ceramics because of its higher hardness, wear resistance and light weight [1,2]. It is considered to be the best substitute for bearing steel. Full-ceramic bearings made of silicon nitride materials have the characteristics of high hardness, high wear resistance, being lightweight and high thermal stability. Therefore, full-ceramic ball bearings have great advantages in high-temperature, high-speed and acid corrosion environments [3,4]. Ordinary bearings must add lubricating oil and other media to improve their performance. Mohamed G. A. Nassef researched the superiority of graphene in enhancing the load-carrying capacity and damping of grease in rolling bearings [5]. The self-lubricating characteristic of silicon nitride helps to improve the operating characteristics of full-ceramic bearings in a poor oil state. However, due to the root problem of friction heat generation between materials, under the working conditions of a heavy load and high speed, the

friction heat generation between various components in a ceramic bearing is the main reason affecting the formation of a thermal field in the working process of the bearing [6]. The study is on the effect of grease level on mechanical vibrations associated with the damaged rolling bearings.

The formation of the thermal field is directly related to the service performance and service life of the bearing. Because the working state of the bearing is complex, the formation of the bearing thermal field is closely related to its running state [7]. The thermal state of the bearing comes from the friction between the moving pairs of the bearing. The load working state amplifies the heat source and the external environment assists in the increase or decrease in the heat source. The formation of this heat has a great impact on the service performance of the bearing [8]. Sun Jian analyzed the factors that affect the surface quality of silicon nitride ceramics. It has been found that between friction depth and speed, the latter factor has a greater impact on friction force and the quality of the surface [9]. Ma S. analyzed the radial load applied to the bearing; the peak impact force is more sensitive to the bearing's speed changes [10]. Kannel et al. studied the bearing's rolling element by taking the infinite surface heat transfer as the premise and obtained the calculation method of the contact surface temperature of the rolling element [11]. Hannon obtained the formula that the corresponding size change of the bearing is determined by the change in the bearing's temperature gradient, and put forward a new friction heat generation model of the rolling bearing by analyzing the relationship between the internal component temperature of the bearing and the friction heat generation power [12,13].

It can be seen from the above that many well-known scholars have conducted in-depth research on bearing heat generation and obtained many results. However, the thermal analysis of bearings is mainly focused on metal bearings, while the thermal analysis of full-ceramic bearings is still relatively rare. Many scholars are studying the dry friction characteristics of silicon nitride ceramics and analyzing the friction changes formed by cage materials and ceramic crystal structures [14,15]. In the application of the bearing, the main reason for its heat generation is the mutual movement between the inner and outer rings of the bearing and between the cage and the rolling element, in which the load and rotation speed have an important impact on its temperature [16]. The surface roughness and roundness of the bearing's rolling element have a certain influence on the running heat of the bearing. The amount of heat produced by this movement depends on several factors, including the degree of roughness and roundness of the ceramic ball's surface and the bearing's inner and outer ring channels [17]. The inclination of the bearing's outer ring also has an important influence on the heat generation of the bearing [18]. The temperature distribution of the entire ceramic bearing will also be impacted by the frictional characteristics between the cage and the rolling body. Based on Palmgren's empirical formula, a thermal dynamic analysis model is established for full-ceramic bearings under self-lubricating conditions [19]. It is difficult to test the bearing under high-speed and heavy-load conditions. At the same time, it is difficult to measure the temperature of each part of the bearing. Thus, the analysis and prediction of the thermal changes between various bearing parts are necessary. Therefore, the analysis of the friction between the rolling element and the groove of the ceramic bearing is the basis of bearing heat generation. The bearing's heat under a high speed and heavy load is analyzed through the heat generation model and the test of the ceramic bearing, which is helpful to predict the service performance of full-ceramic ball bearings.

2. Experimental Section

2.1. Experimental Materials

In order to better reveal the influence of ceramic ball level and friction state on the thermal state of silicon nitride under the condition of self-lubricating of full-ceramic ball bearing, the friction temperature between silicon nitride ceramic ball and inner and outer rings was explored. This experiment used a ceramic ball and ceramic block with a channel for experimental analysis. The friction and wear tests of silicon nitride ceramic balls

and silicon nitride ceramic blocks with different specifications were carried out. The characteristics of silicon nitride material are shown in Table 1. The level and specification of the ceramic ball are shown in Table 2.

Table 1. Material properties.

Density (g.cm ⁻³)	Young's Modulus (GPa)	Poisson's Ratio	Thermal Expansion Coefficient (10 ⁻⁶ /°C)	Specific Heat Capacity (J/(kg*K))	Fracture Toughness (MPa*m ^{1/2})	Compressive Strength (MPa)
3.07–3.21	(20 °C) 310	0.27	3.5–3.9 (20–1000 °C)	711.7	7–12	4500

Table 2. Ceramic ball level and specification.

Level	Roughness (μm)	Roundness (μm)
G3	0.009	0.07
G5	0.013	0.1
G10	0.18	0.24

2.2. Characterization Methods

The test was carried out by a friction and wear testing machine (MFT-500, Rtec Instruments, San Jose, CA, USA). The parameters used in the friction test are shown in Table 3. The test process and ball clamp status are shown in Figure 1. In the experiment, the friction and wear tester recorded the friction coefficient; at the same time, a FLIR thermal imager (FLIR Systems, Inc., Wilsonville, OR, USA; Accuracy is $\pm 1\%$) was used to detect and record the temperature. After the experiment, firstly, the detected temperature value was averaged. Then, the worn spherical surface was observed by a three-dimensional microscope (KEYENCE, Osaka, Japan). Next, the surface morphology of the Si₃N₄ ball after wear was analyzed by scanning electron microscopy (SEM) (FEL, Hillsboro, OR, USA), and the wear mechanism under different loads and rotation speeds was deduced. Then, based on the temperature and coefficient of the ceramic ball in the process of rolling friction, the bearing heat generation model was established. The model was used to predict the temperature rise state of full-ceramic bearings. Finally, the temperature change trend of the bearing is tested by the life test machine (Hangzhou Bearing Testing Center, Hangzhou, China). The test equipment of bearing is shown in Figure 2. The predicted bearing temperature is compared with the test temperature value to verify the correctness and accuracy of the model.

Table 3. Test grouping.

Group	The Precision of Silicon Nitride Ceramic Ball	Speed v (r/min)	Apply Load F (N)	Test Time (s)
N _i (i = 1 ... 8)	G3, G5, G10	500	5, 15, 25, 35, 45, 55, 65, 75	1800
F _i (i = 1 ... 9)	G3, G5, G10	100, 200, 400, 500, 600, 700, 800, 900, 1000	35	1800
G3, G5, G10	G3, G5, G10	500	35	1800

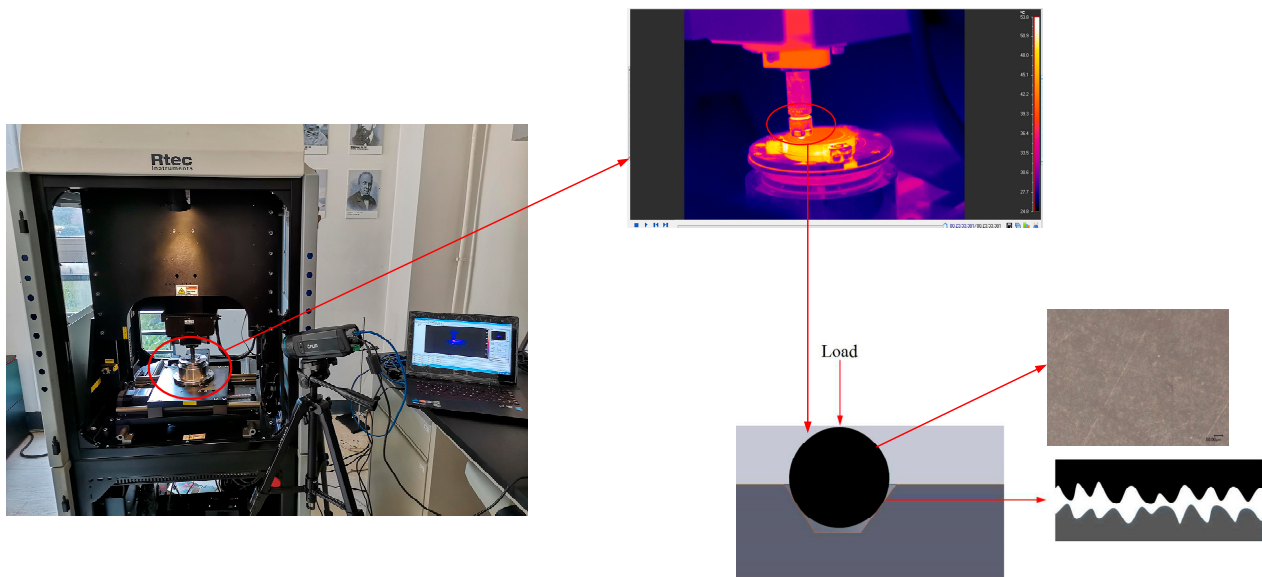


Figure 1. Friction experiment and the geometric contact of the roll with the channel.

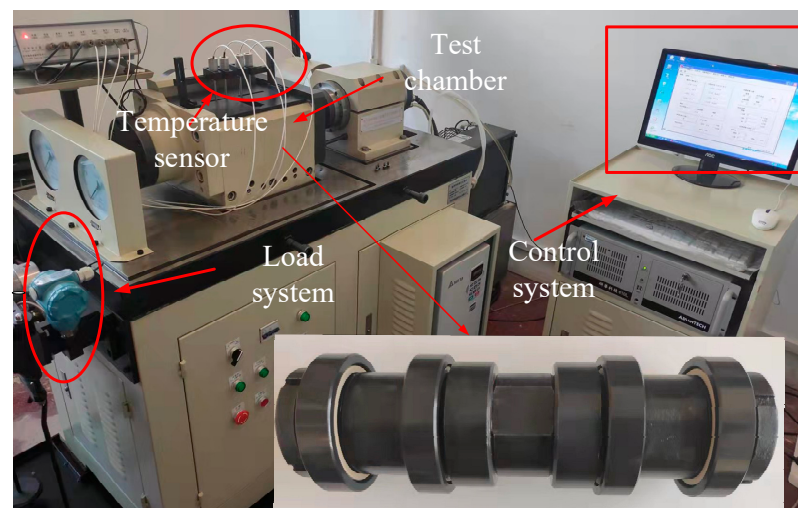


Figure 2. Bearing life strengthening testing machine.

3. Results and Discussion

3.1. The Analysis of Silicon Nitride Ceramic Ball Friction State

It can be seen from Figure 3 that the precision level of the ceramic ball is high and the friction temperature is low. The friction temperature of the G3 ceramic ball changes slightly. As the level of the ceramic ball decreases, the roughness decreases, and the friction temperature increases with the same load environment. This is due to the roughness increase, which leads to the increase in the friction force and temperature. Figure 3 shows the initial friction temperature of the ceramic balls is relatively high in the friction experiment process. With the progress of friction, the surface temperature fluctuates between 5 °C and 10 °C at G1 and G2, but the fluctuation range reaches about 40 °C at G10. Figure 4 shows that the friction coefficient of the three levels of ceramic balls is relatively high at the initial stage of friction. The coefficient of friction of the G3 level ceramic balls is relatively low, and the change is relatively smooth. The friction coefficient of the G10 ceramic balls is high, and the overall change is relatively large.

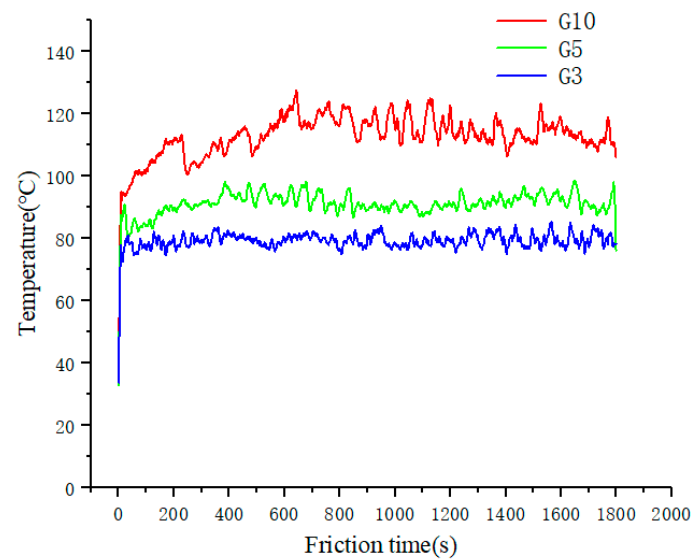


Figure 3. The friction temperature of the different level ceramic ball under the same conditions.

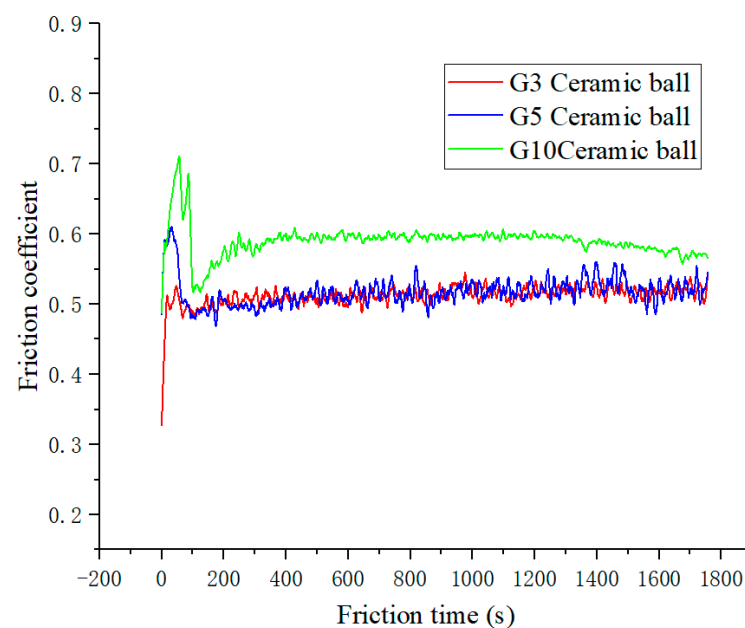


Figure 4. The friction coefficient of the different level ceramic ball under the same conditions.

The friction temperature changes with the transformation in the roundness of the ceramic ball. When the roundness of the ceramic ball is relatively high, the temperature formed by friction decreases, which means that the roundness of the ceramic ball is very high and the temperature rise conversion rate is relatively smooth. However, with the extension in friction time, the friction temperature of the ceramic ball with low roundness is relatively large.

Figure 5 shows that the temperature rise of the bearing in operation will increase with the increase in its load. The temperature rise of the ceramic ball bearings is relatively low, and the effect of load on the temperature rise tends to be linear. However, with the load increase, the temperature of the G10 ceramic ball changes significantly at the beginning, and then the temperature rise changes slowly. This is because the surface roughness of the G3 ceramic ball is relatively low and the surface is smooth. The friction force is small under the load condition and the friction temperature is low. However, the surface roughness of the G10 ceramic ball is high. In the initial stage of bearing load, it is affected by some

wave peaks on the surface, which increase the friction force. The decrease in friction force reduces the range of temperature rise.

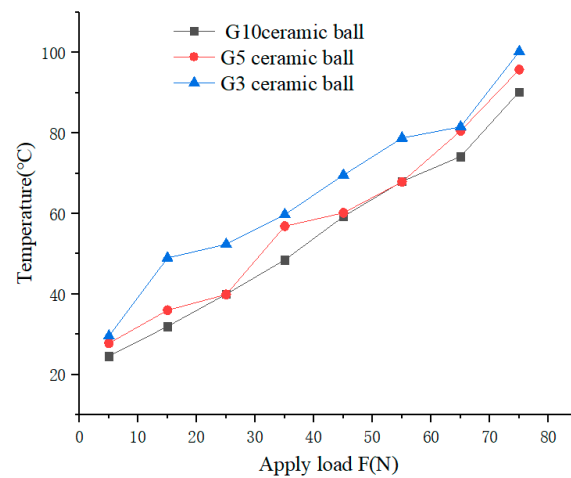


Figure 5. The change in the ceramic ball temperature under different pressures.

When the rotational speed increases, the bearing's temperature rises; however, as the level of the ceramic ball increases, there is less of a temperature shift, as shown in Figure 6. As the speed increases, the temperature of the bearing with G3 ceramic balls steadily rises. However, as the speed increases, the temperature rise of the bearing using G10 ceramic balls changes substantially. When the rotation speed of the bearings with G10 and G5 ceramic balls is 600 r/min, the temperature changes arrive at the turning point. When the speed is greater than 600 r/min, the temperature tends to slow down with the speed increase. This is because when the speed of the bearing's rolling body is low, the contact area between the rolling body and the raceway surface increases under the action of centrifugal force, leading to the aggravation of the friction phenomenon. Under certain load conditions, when the speed is greater than 600 r/min, partial peaks on the contact surface are reduced because of the centrifugal force of the friction force between the bearing's rolling element and the raceway contact surface. Thus the surface friction force is reduced. As a result, the effect of the speed on the temperature is reduced.

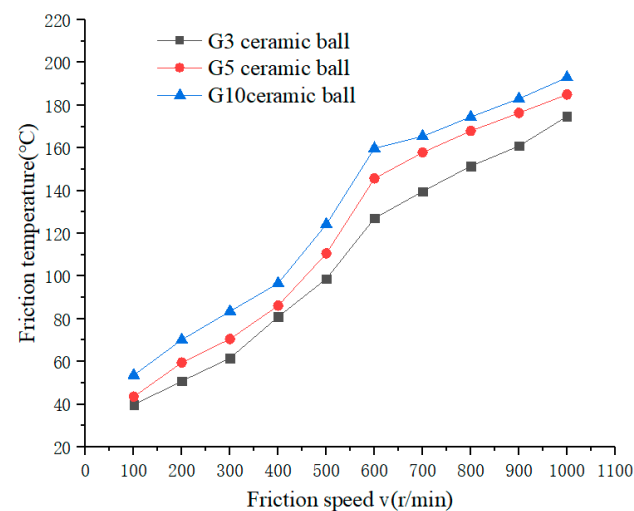


Figure 6. The temperature change of ceramic ball under different rotational speeds.

As shown in Figure 7, the surface roughness of the ceramic ball increases significantly. There are grind marks on the ball's surface after the friction experiment. The appearance of wear marks directly affects the friction and temperature. It can be observed from Figure 8b,c

that when the ceramic ball is under the same speed and pressure conditions, the friction marks on the surface of the G3 ceramic ball are relatively shallow and the wear marks of G5 and G10 are deeper. This is because the contact surface of a high-precision ceramic ball is relatively smooth and the friction is relatively small. The surface wear traces and the wear defects of the G10 ceramic ball are increased when the balls are under heavy-load conditions. μm

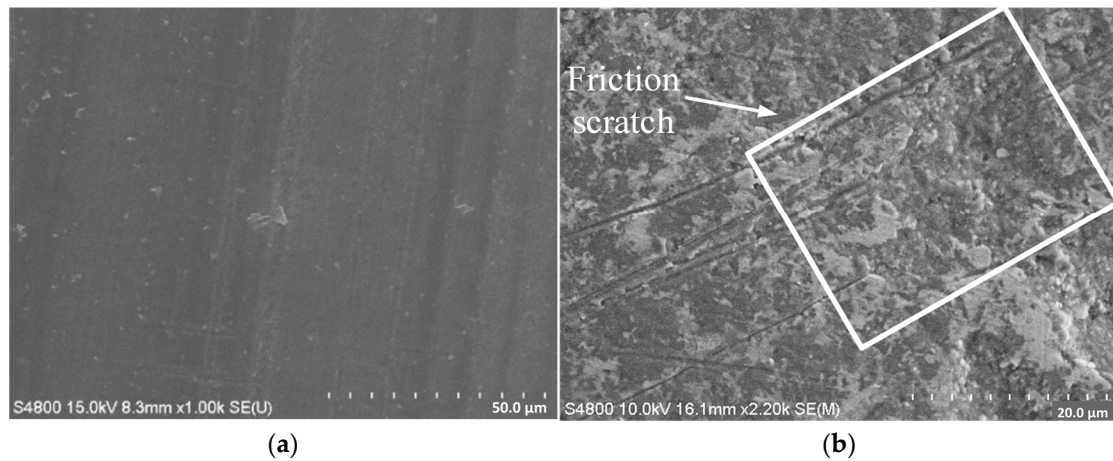


Figure 7. Surface morphology before and after the experiment. (a) G5 Ceramic ball surface before testing, (b) G5 Ceramic ball surface after testing.

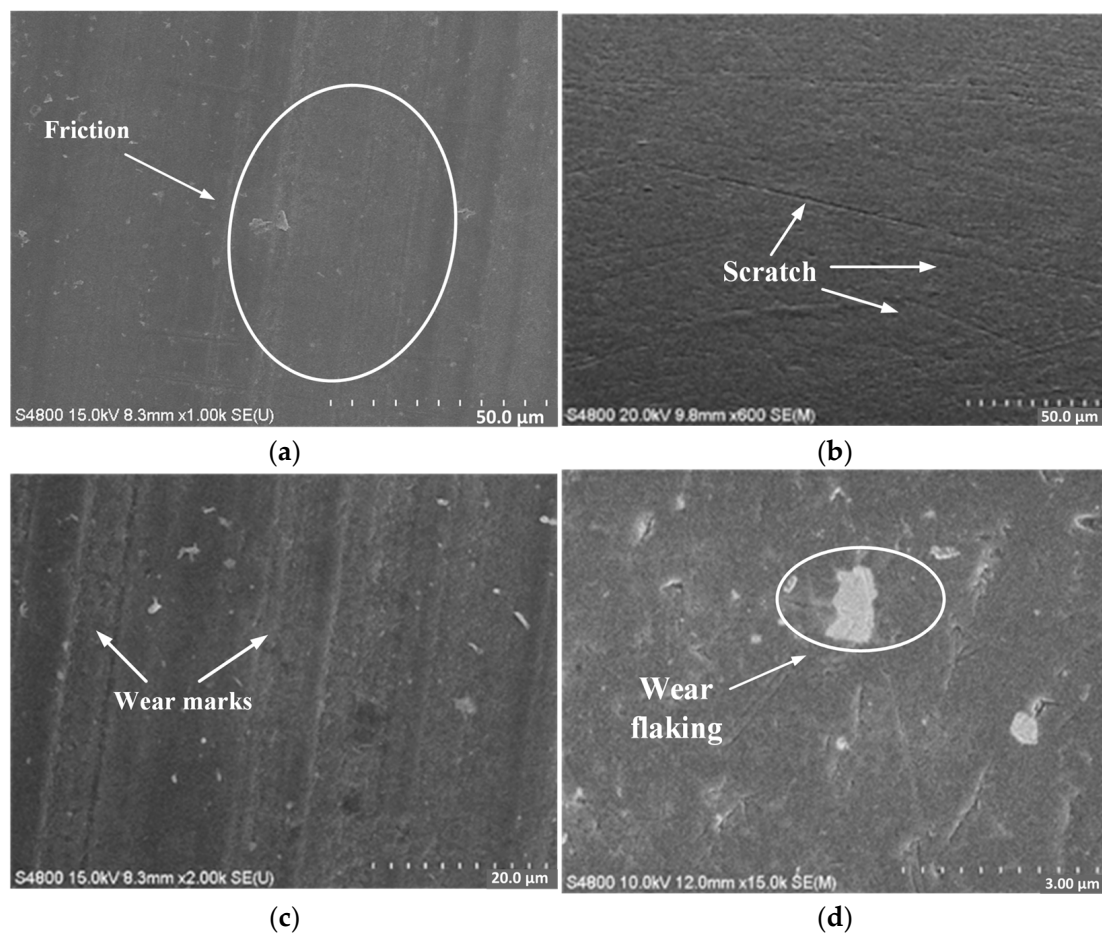


Figure 8. Cont.

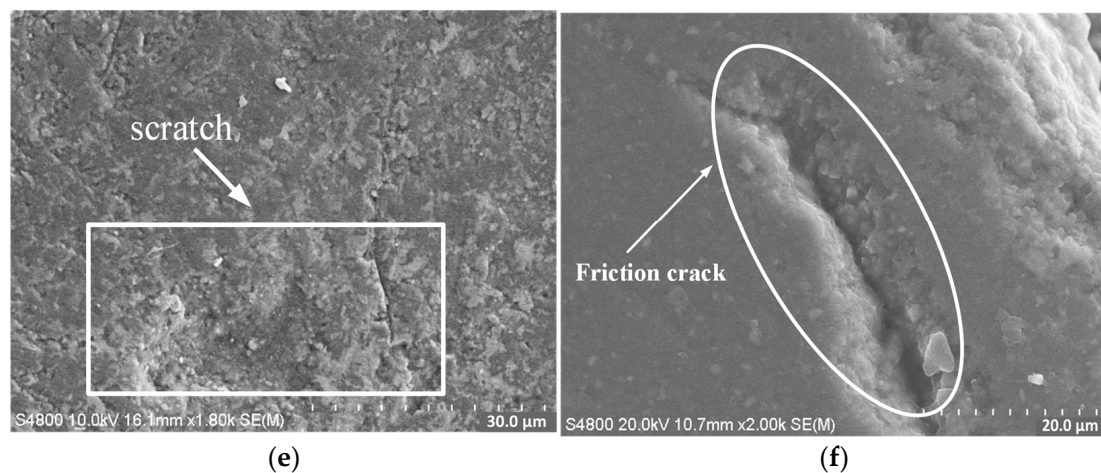


Figure 8. Surface morphology before and after the experiment. (a) G3 $V = 500$ r/min, $F = 35$ N, (b) $V = 500$ r/min, $F = 35$ N, (c) G10 $V = 500$ r/min, $F = 35$ N, (d) G10 $V = 100$ r/min, $F = 75$ N, (e) G10 $V = 500$ r/min, $F = 75$ N, (f) G10 $V = 1000$ r/min, $F = 75$ N.

3.2. Dynamic Model of Ceramic Bearing under Self-Lubrication

Bearings are components that can bear loads and rotate at the same time. During the rotation, the rolling elements will revolve around the central axis of the bearing; at the same time, they will also rotate around their axis [20]. To better analyze the heat generation state during the bearing's operation, it is assumed that there is no relative displacement between the shaft and the bearing's inner ring when establishing the model; and the slight influence of contact deformation and rotational speed on inertial force and contact friction force is not considered.

Figure 9 shows the running shape of the internal components of the ball bearing during the movement. The motion state of the rolling element of the bearing has a certain influence on the frictional heat. The rolling element in the bearing has a self-rotation around its axis and a revolution around the center of the inner ring.

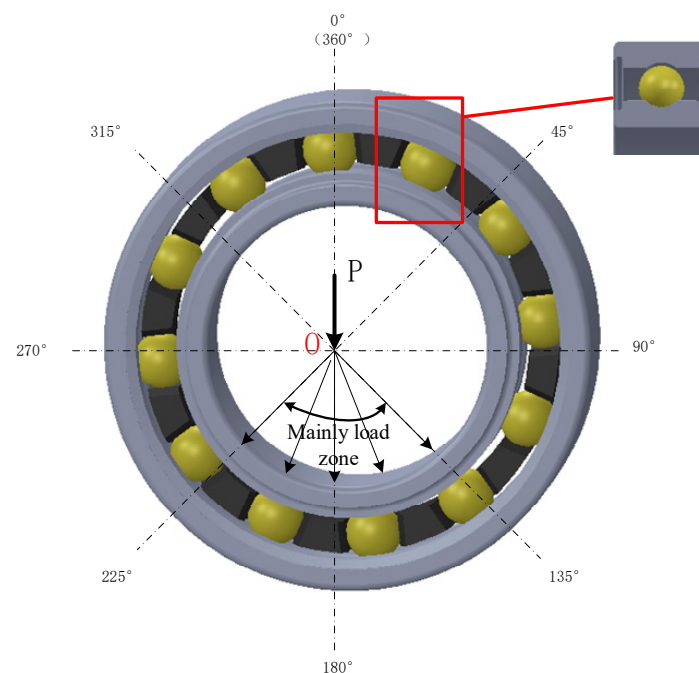


Figure 9. The structure of rolling bearing.

The orbital speed of the rolling is

$$V_m = \frac{1}{2} \cdot \frac{2\pi D_{pw} n_c}{60} \quad (1)$$

D_{pw} is the diameter of the bearing's pitch circle, and n_c is the revolution speed of the rolling body.

The revolution speed of the rolling body can be obtained from Formula (1)

$$n_c = \frac{1}{2} [n_i(1-r) + n_e(1+r)] \quad (2)$$

n_i is the speed of the inner ring of the bearing, n_e is the speed of the outer ring of the bearing, $r = D_m \cdot \cos \alpha / D_{pw}$ and α is the contact angle of the bearing.

Because the rotational speed of the rolling body is equal to the relative speed of the inner ring in the contact area, the rotational speed of the bearing's rolling body can be given as

$$n_m = \frac{D_{pw}}{2D_m} (n_e - n_i)(1+r)(1-r) \quad (3)$$

where D_m is the diameter of the rolling body.

Combined with Formula (3), it is obtained that the revolution angular velocity of the rolling body is

$$W_c = \frac{\pi}{60} [n_i(1-r) + n_e(1+r)] \quad (4)$$

The following expression can determine the centrifugal force and gyroscopic moment of the rolling body

$$\begin{cases} F_{ej} = 0.5 d_m m \omega_{cj}^2 \\ M_{gj} = J \omega_{bj} \omega_{cj} \sin \beta_j \end{cases} \quad (5)$$

K_e and K_i are the load deformation coefficients of the rolling body, and outer and inner ring.

$$Q_{ij} = K_{ij} \delta_{ij}^{3/2}; Q_{ej} = K_{ej} \delta_{ej}^{3/2} \quad (6)$$

With the force balance of the bearing's rolling body under the combined load, the following force balance equation can be obtained

$$F_a - \sum_{j=1}^z Q_{ij} \sin \alpha_{ij} = 0 \quad (7)$$

$$F_r - \sum_{j=1}^z Q_{ij} \cos \alpha_{ij} = 0 \quad (8)$$

$$M - \sum_{j=1}^z \frac{d_m}{2} Q_{ij} \cos \alpha_{ij} = 0 \quad (9)$$

F_a is the axial preload acting on the bearing; F_r is the radial preload; M is the overturning moment.

The bearing's rolling body is contacted with the inner and outer ring and the cage, and the contact situation is shown in Figure 10. Due to the role of bearing clearance, there is an eccentricity in the rotation center of the inner and outer ring as shown in Figure 9. The existence of the eccentricity of O_0O_1 in Figure 10 makes the force acting on the rolling body different in one rotation period [21]. It can be analyzed from Figure 8 that the rolling body is subjected to a relatively large load in the 180° area of the bearing. There is close contact between the inner and outer ring and the rolling body so that the temperature rise of the bearing here is maximum, as shown in Figure 9. On the other hand, when the bearing is located at 0° (360°), the contact between the rolling body and the groove is relatively small,

and the load is the smallest so that the temperature of the bearing in this area is relatively low as shown in Figure 9.

$$\begin{cases} Q_{ij}\sin a_{ij} - Q_{ej}\sin a_{ej} + F_{ij}\cos a_{ij} - F_{ej}\cos a_{ej} = 0 \\ Q_{ij}\cos a_{ij} - Q_{ej}\cos a_{ej} + F_{ij}\sin a_{ij} - F_{ej}\sin a_{ej} + F_{ej} = 0 \\ F_{ej} + F_{ij} - 2M_{gj}/D = 0 \end{cases} \quad (10)$$

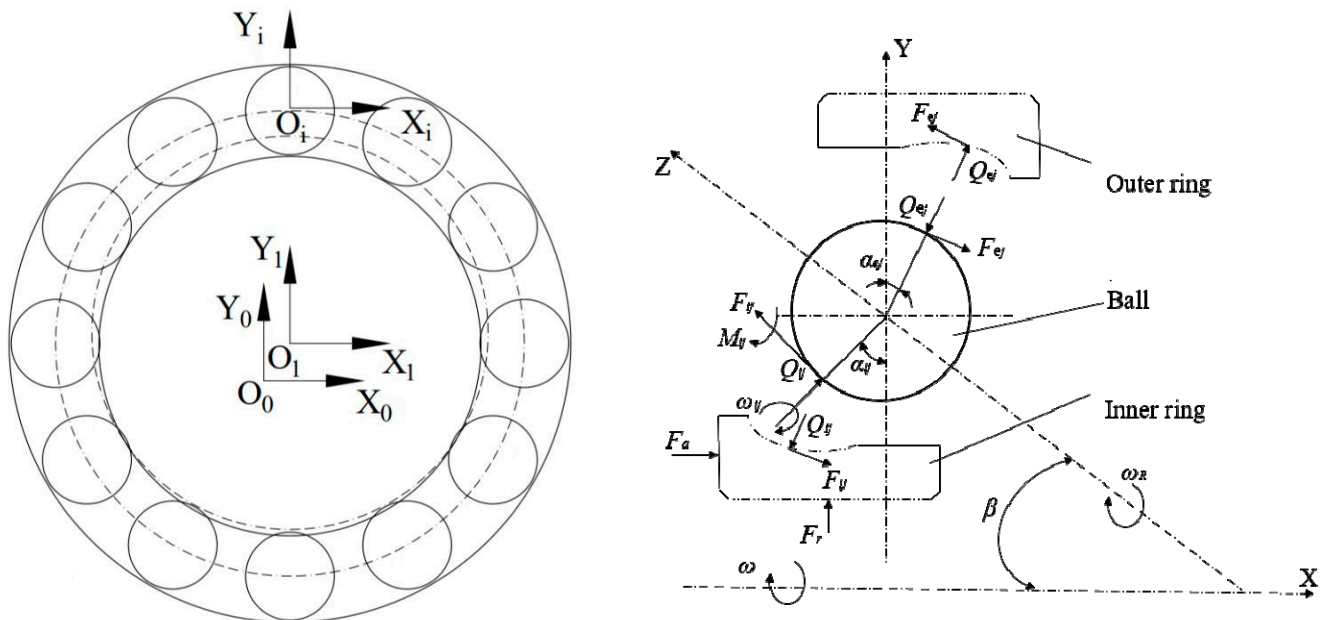


Figure 10. Bearing mechanics diagram.

Bearing heat generation is mainly the rolling body and bearing inside and outer ring friction heat generation. Palmgren summarized the calculation formula of the friction torque of the bearing under unload and load through many experiments [19].

The frictional moment generated by lubricant viscosity during the bearing's empty load is shown by:

$$n < 2000$$

$$M_0 = 160 \times 10^{-7} f_0 D_{pw}^3 \quad (11)$$

$$vn \geq 2000$$

$$M_0 = 10^{-7} f_0 (vn)^{2/3} D_{pw}^3 \quad (12)$$

f_0 is the coefficient related to bearing type and lubrication, ν is the lubricant's dynamic viscosity, and n is the bearing's speed.

For the load-dependent friction moment, M_1

$$M_1 = f_1 P_1 D_{pw} \quad (13)$$

f_1 is the coefficient related to the bearing's type and load, and P_1 is the bearing's equivalent dynamic load.

Therefore, the friction moment of the bearing formula is $M = M_0 + M_1$.

Because ceramic ball bearings are mostly used in high-speed rotation conditions, the spin sliding between the rolling body and the bearing's internal roller channel is also one of the main movements. The heat generated by spin friction is added on the basis of Formulas (11)–(13) so that the empirical formula is more accurate [22].

$$M_s = \frac{3\mu Q \alpha E(\eta)}{8} \quad (14)$$

M_s is the spin friction moment of the rolling body, α is the bearing's roller contact long half shaft, μ is the friction coefficient between the bearing's roller body and rolling body, Q is the normal contact load between the bearing's rolling body and rolling body, and $E(\eta)$ is the second type of elliptic integral of the roller contact zone.

Heat generated in the inner ring

$$H_i = 10^{-3} W_c \cdot M_i + 1.047 \times 10^{-4} M_{si} \cdot n_m \cdot z \quad (15)$$

Heat generated in the outer circle

$$H_e = 10^{-3} W_c \cdot M_e + 1.047 \times 10^{-4} M_{se} \cdot n_m \cdot z \quad (16)$$

z is the number of rolling bodies.

3.3. Heat Transfer Model

The bearing, rotating shaft and bearing seat are symmetrical rotation bodies. In the absence of radial torque load, the friction heat generated on the internal and outer circle remains unchanged along the circumference, and the friction heat generation and heat transfer model of the rolling body on any azimuth angle are similar [23]. Therefore, the approximate one-dimensional model is used to describe the heat transfer of the bearing.

Burton and Steph have found that the friction heat inside the bearing occurs only between the rolling body and the inner and outer ring of the bearing [24]. It is recommended that half of the heat generated go into the rolling body and half into the bearing ring. Figure 11 is the temperature node diagram of the key components of the internal bearing, and Figure 12 shows the model diagram of the bearing's heat transfer heat resistance network.

The heat transfer equations can be obtained, which include three unknown temperatures, T_{ce} , T_b and T_{ci}

$$\begin{cases} \frac{1}{2} H_i = \frac{T_{ci} - T_{\infty}}{R_i + R_s} + \frac{T_{ci} - T_{L\infty}}{R_{ci}} \\ \frac{1}{2} H_e = \frac{T_{ce} - T_{\infty}}{R_e + R_h} + \frac{T_{ce} - T_{L\infty}}{R_{ce}} \\ \frac{1}{2} H_i + \frac{1}{2} H_e = \frac{T_b - T_{L\infty}}{R_b} \end{cases} \quad (17)$$

T_{ci} and T_{ce} are the surface temperatures of the bearing's inner and outer channel, respectively. T_{∞} is the external ambient temperature of the bearing. $T_{L\infty}$ is the bearing's internal air temperature. T_b is the rolling body temperature. R_i is the bearing's inner ring heat resistance. R_e is the bearing's outer ring heat resistance. R_{ci} is the convective heat resistance of the bearing. R_{ce} is the convective heat resistance of the bearing's outer surface. R_b is the rolling body surface facing the flow heat resistance. R_s is the rotating shaft heat resistance. R_h is the heat resistance for the bearing seat.

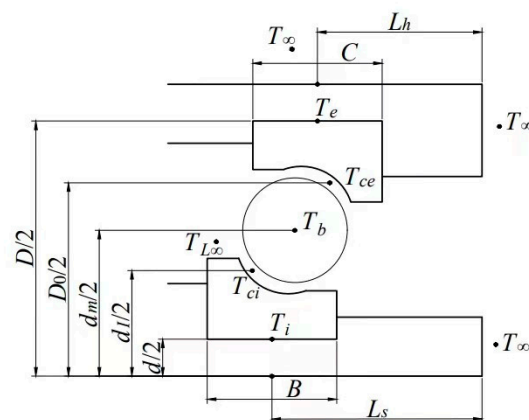


Figure 11. Temperature node diagram of key parts of bearing's internal components.

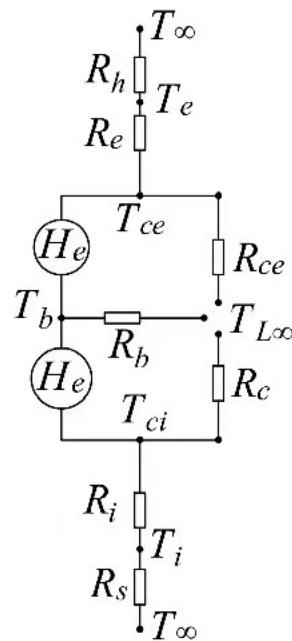


Figure 12. Thermal resistance network model of bearing's internal heat transfer.

3.4. Thermal Resistance of Full-Ceramic Bearing

For calculating the heat resistance of the bearing's inner and outer rings, the thickness of the bearing's inner ring and the outer bearing ring is much less than the overall width of the bearing, so the inner and outer bearing ring is regarded as a thin ring.

Under self-lubricating conditions, the air is the convection heat exchange medium around the bearing. The proposed average convection heat transfer coefficient between the internal bearing element and the heat exchange medium is

$$h = 0.0986 \left[\frac{n}{v} \left(1 \pm \frac{d \cos \alpha}{D_{pw}} \right) \right]^{1/2} \quad (18)$$

In formula (18), “+” indicates the outer bearing ring rotation; “−” means the inner bearing ring rotation. d is the inner bearing diameter. k is the material.

3.5. Thermal Analysis and Experimental Study of the Silicon Nitride Full-Ceramic Bearing

To better analyze the silicon nitride bearing under self-lubrication, the full-ceramic silicon nitride angular contact ball bearing was used in the test. Its specifications and parameters are shown in Table 4, and the test apparatus is shown in Figure 13. The level of ceramic balls used in the ceramic bearings was G5. The characteristics of the bearing cage affect the heating of the bearing, but due to the diversity of the cage, the heat generation is calculated without considering the influence of the cage [25]. The working conditions of the theoretical simulation of bearings are shown in Table 5.

Table 4. Bearing parameters.

Parameters	Values
Inner diameter d /mm	35
Outer diameter D /mm	62
Rolling body diameter D_{pw} /mm	48.5
Ball diameter D_m /mm	7.938
Contact angle $\alpha/^\circ$	15
Number of rolling bodies z /psc	14

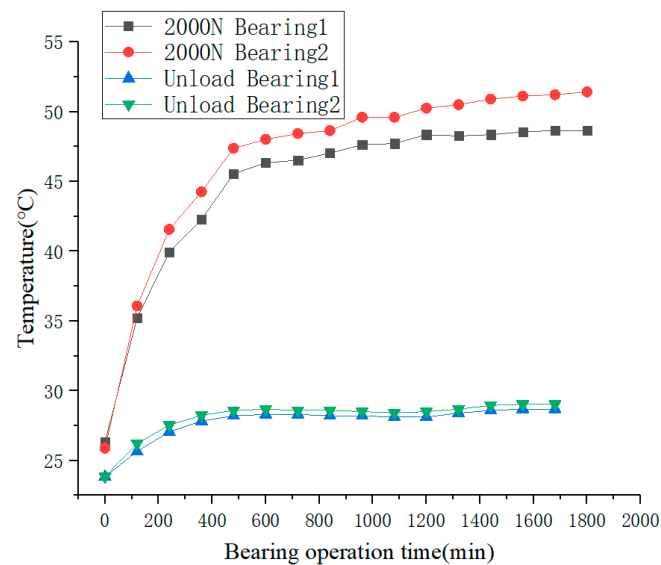


Figure 13. Relation between bearing's temperature rise and time.

Table 5. Working condition.

Working Condition	Values
Bearing's rotation speed/(r·min ^{−1})	8000~24,000
Axial load/N	0~2500
Air Prandtl number	0.699
Environment temperature/°C	24

Palmgren's empirical formula is modified based on silicon nitride ceramics' properties. Thermodynamic analysis of the ceramic bearing under self-lubricating conditions is based on modified f_0 (as Formula (12)). To verify the correctness of the thermal model, Figure 13 studies the time when the temperature rise characteristics of bearings tend to a stable state under fixed working parameters. The bearing's operation must consider the steady-state temperature field [26]. Through experimental analysis, it can be seen that for the bearing to reach its steady-state operating temperature, the time is about 400 min when it runs under unloading, and the time is about 500 min when the bearing is under load. Therefore, the temperature of the bearing's operation after 500 min is selected in the test. Under the rotating speed of 8000 r/min, the load test of the bearing is carried out using the life test machine. At the same time, the temperature change is calculated by using the model. At the speed of 8000 r/min, the test temperature, model calculation temperature of the bearing and the error are shown in Table 6.

Table 6. Comparison of temperature results.

Load/N	Simulation Result (°C)	Test Result (°C)	Error Percentage (%)
0	27.697	30.2	8.29
500	30.941	32.9	4.80
1000	36.472	37.9	3.77
1500	43.041	44.9	4.14
2000	50.387	52.8	4.57

Figure 14 shows the surface's working temperature outside the bearing's outer ring. The stable measured temperature of the bearing is consistent with the trend of temperature change in theoretical analysis when the bearing's speed is 8000 r/min. The temperature test temperature in the low load area is slightly different from the theoretical analysis. This is because with the lack of application of an external load leads to roller rotation torque that

cannot provide an accurate calculation; therefore, part of the thermal error is generated. With the increase in load, the error between the test and theoretical analysis temperature decreases.

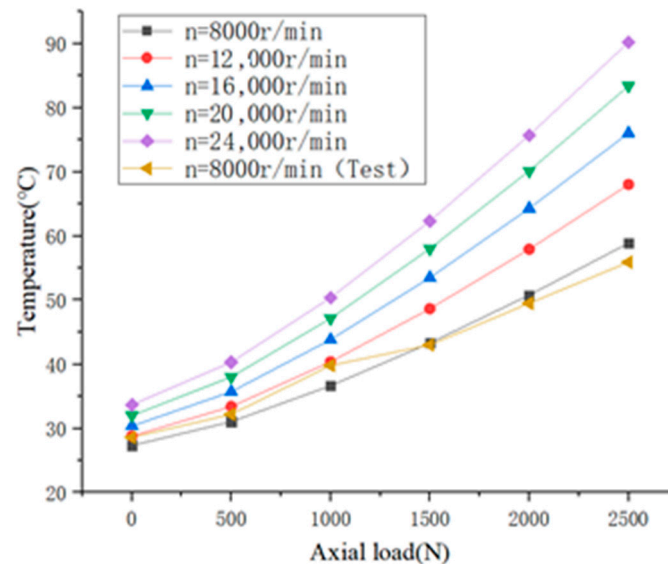


Figure 14. The surface temperature of the bearing's outer ring.

The simulation surface temperature of the bearing's outer ring increases with the load and the bearing's speed increase. When the speed is 24,000 r/min, The amplitude of the bearing's temperature rise is decreased. This is because under high-speed and heavy-load conditions, the friction coefficient and friction frequency between the bearing's rolling element and the inner and outer rings are increased. The increase in the friction coefficient and friction frequency leads to the increase in the bearing's temperature. When the load is 2500 N, the amplitude of the temperature increases is decreased with the increase in the rotation speed. This is because under a heavy load, the heat generated by the friction torque is the main heat, and the proportion of the heat generated by the rotation speed decreases. When the speed is 8000 r/min, the bearing's test and theoretical analysis tend to be consistent, but there is a slight fluctuation.

Figure 15 shows the curve of the operating simulation temperature of the bearing's inner raceway changing with speed and axial load. The variation law is the same as that of the operating temperature of the outer ring, but the temperature is higher than that of the outer ring [27]. This is because the diameter of the bearing's outer ring is larger than that of the bearing's inner ring, and the heat dissipation of the bearing's outer ring is better than that of the inner ring so that the friction heat between the rolling and the bearing's inner ring channels is easier to concentrate.

Figure 16 shows the working simulation temperature curve with the rotation speed and axial load changes. The rolling body temperature rises the highest because the rolling body is simultaneously in contact with the inner and outer channels. When the load is 2500 N and the speed is 24,000 r/min, the temperature of the bearing ball is higher than the inner ring and the higher temperature is above 40°. Under the condition of a high-speed bearing, the rolling body is heated in both directions, which is called the largest heat source in the bearing.

Through comparative analysis, it can be seen that under the same working conditions, the temperature of the bearing's rolling body is the highest, followed by the inner raceway, and the temperature of the outer ring is the lowest.

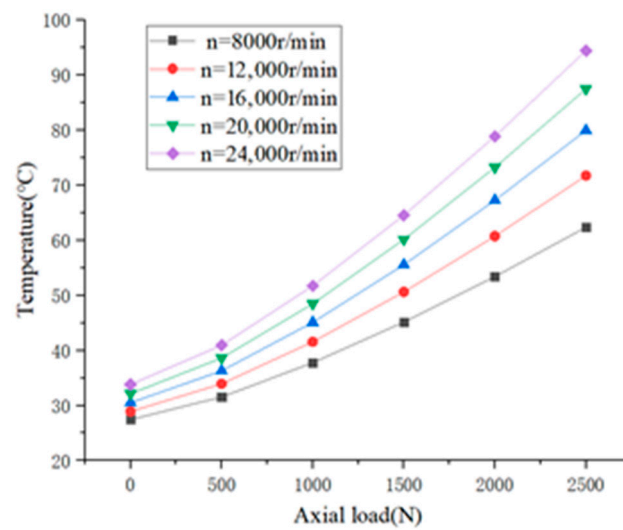


Figure 15. Raceway simulation temperature of bearing's inner ring.

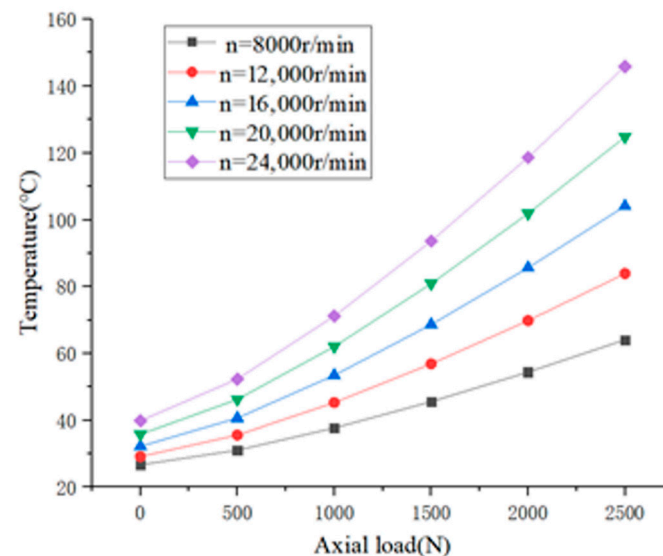


Figure 16. The temperature of rolling body simulation results.

4. Conclusions

Following are the conclusions that have been obtained after performing both the theoretical calculation and experimental comparison analysis of the self-lubricating heat generation of full-ceramic angular contact ball bearings:

(1) Through the analysis of the friction test, it can be seen that the high-grade rolling elements have a low friction coefficient and small friction torque in the process of operation, which leads to lower friction heat generation. During the friction process of G3 and G5 ceramic balls, the surface temperature fluctuation is small, between 5 °C and 10 °C. However, with G10, the fluctuation range reaches about 40 °C. Therefore, in the process of simulating bearing's heat generation, the bearing's rolling element's accuracy is considered.

(2) Based on the comparison between the calculated value of the heat generation model of the silicon nitride full-ceramic bearing and the test, when the axial load is 0 n, the error is the largest, reaching 8.29%. After loading the bearing, the minimum error is 3.77% when the axial load is 1000 N. Furthermore, the correctness of the heat generation model of full-ceramic silicon nitride bearings is explained.

(3) Under self-lubrication, the main heat source of full-ceramic silicon nitride ceramic ball bearings is the rolling element, followed by the inner ring, and finally, the outer

ring. Under heavy-load operation, the influence of speed on temperature rise tends to decrease. Under high-speed operation, the temperature rise increases with the increase in load. Therefore, the load borne by the bearing is the main factor affecting the bearing's temperature rise.

Author Contributions: Conceptualization, J.T. and Y.W.; methodology, J.S.; software, Z.X.; validation, K.R.; formal analysis, J.T.; investigation, H.W.; resources, Y.W.; data curation, J.T.; writing—original draft preparation, J.Y.; writing—review and editing, J.T.; visu-alization, Z.X.; supervision, S.L.; project administration, Y.W.; funding acquisition, Y.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (NSFC) (grant numbers 52105196); National Defense Science and Technology Innovation Special Zone Program (grant numbers 20-163-00-TS-006-002-11); Young and Middle-aged Innovation Team in Shenyang (grant number RC210343); PhD Fund of Liaoning Province of China (grant number 2020-BS-159).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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