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Study on the Effect of Thermal Characteristics of Grease-Lubricated High-Speed Silicon Nitride Full Ceramic Ball Bearings in Motorized Spindles

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Abstract: Grease lubrication is cost-effective and low-maintenance for motorized spindles, but standard steel bearings can fail at high speeds. This study focuses on high-speed full ceramic ball bearings lubricated with grease. The coefficient of friction torque in the empirical formula is corrected by establishing the heat generation model of full ceramic ball bearing and combining it with experiments. A simulation model of grease flow is established to study the influence of grease filling amount on grease distribution. The simulation model of the temperature field of a full ceramic ball bearing is established to analyze the influence of rotating speed on bearing heat generation, and experiments verify the calculation results of the theoretical model. The results show that an optimal grease filling amount of 15~25% ensures even distribution without accumulation. Additionally, when the amount of grease is constant, the outer ring temperature increases with higher rotating speeds. The test results show that when the grease filling is 0.9~1.2 g, it accounts for about 9~12% of the volume of the bearing cavity, and the temperature of the outer ring is the lowest. At a rotation speed of 24,000 rpm, the outer ring temperature of the grease-lubricated bearing is 50.1 °C, indicating a reasonable range for use in motorized spindles. It provides a theoretical basis for the optimization design of macro-structural parameters of full ceramic ball bearings in the future, which can minimize heat generation and maximize bearing capacity.

Keywords: high-speed motorized spindle; full ceramic ball bearing; grease lubrication; grease filling amount; temperature rise characteristics

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1. Introduction

With the advancement and development of science and technology, the quality standard of components in aerospace, national defense, and medical treatment has been promoted, and high-precision and high-speed machining technology has, thus, become important. As the core component of high-speed machine tools, the spindle's performance is directly related to the machining accuracy and efficiency of the machine tool, which is crucial to the development of precision machining technology [1]. Under high-speed working conditions, the motorized spindle needs to reach high speed (when the bearing D_mN value exceeds 1.0×10^6) to meet the demand for efficient machining. However, the high rotational speed is accompanied by high-temperature rise, which will directly or indirectly lead to thermal deformation of the spindle, demagnetization of permanent magnets, and reduced machining accuracy. Despite the significant advances in motorized spindle technology, there are still many challenges in controlling temperature rise [2,3]. Traditional lubrication

technology, such as oil mist lubrication, has a specific lubrication and cooling effect, but it is challenging to meet the demand for precise control of oil supply and a reduction in oil consumption under high-speed working conditions. The primary purpose of bearing lubrication technology is to control the rise in the temperature of bearings, which is the key to ensuring the operation precision and stability of the motorized spindle [4]. To solve the above problems, scholars at home and abroad have researched the influence of the thermal characteristics of high-speed motorized spindles. Among them, the grease lubrication technology has attracted much attention because of its advantages of a good lubrication effect, low pollution, and easy control; especially in the high-speed silicon nitride full ceramic ball bearing motorized spindle, the grease lubrication technology shows a unique advantage which is of great significance for the high speed of the motorized spindle.

At present, many scholars have extensively researched the influence of grease filling and rotational speed on the thermal characteristics of bearings. Within this context, bearing frictional torque stands as a pivotal factor in calculating bearing frictional heat generation. The complexity arises from the fact that various lubrication modes and working loads significantly impact the computation of this frictional torque, with each element intricately intertwined and mutually influencing the others [5]. When delving into the nuances of lubrication, the role of oil-based lubricants cannot be overlooked. The thermophysical and thermal properties of these lubricants play a crucial part in shaping their lubrication capabilities. Huang et al. [6] introduced the concepts of full space, moving, and static space, and their proportions for ball bearings with sealing rings. The study elaborated in detail on the optimal amount and proportion standard of grease filling under different working conditions. Xia et al. [7] emphasized the importance of collecting steady-state temperature data of bearings with high accuracy and speed to explore the limited speed of bearings. Wang et al. [8] systematically analyzed the temperature rise trend of asynchronous traction motor bearings under different grease filling amounts through experiments and determined the technological grease amount required to achieve the best lubrication effect, providing valuable data references for the lubrication optimization of other bearing structures. Sun [9] studied the influence of oil supply on the sound field distribution characteristics of full ceramic ball bearings under different working conditions. Bai [10] pointed out the ideal oil supply balance point, ensuring effective lubrication of the bearing and avoiding excessive friction torque. Even if the bearing temperature rises, the precipitated lubricating oil can maintain the bearing in the optimal working state. Wang Yameng [11] discussed the specific influence of grease filling amount on the friction torque of bearing components through comparative tests. Xue's [12] temperature rise test came up with the optimum range for the grease filling amount of angular contact ball bearings. Oh et al. [13] derived the calculation method of the standard grease filling amount based on the linear relationship between grease filling amount and bearing life. Cunningham [14] concluded that an increase in the filling amount of grease at room temperature directly leads to an increase in the average torque of bearings. Jain [15] focused on the specific influence of physical characteristics of grease on the friction torque and life of wheel bearings and discussed the relationship between grease and the friction coefficient. Gonçalves et al. [16] found that the thickening agent entered the contact surface at low speed, promoting oil film thickening and effectively reducing the friction coefficient. Townsend et al. [17] comprehensively discussed the influence of different lubrication conditions on bearing friction torque through theoretical analysis and experimental verification. Gentle and Pasdari [18] proposed a torque calculation model considering the friction between the bearing cage and internal and external channels. Unswroth and Hall [19] deeply analyzed the effects of lubricants and bearing materials on friction torque through numerous experiments and made a detailed theoretical analysis of the experimental results. Tong and Hong [20] put forward an improved model for calculating the friction torque of angular contact ball bearings, based on the analysis of the friction coefficient between the ball and the groove, and compared with industry standards (such as the SKF empirical formula). Shawki et al. [21] used the friction coefficient as the evaluation index and performed grease filling tests under different rotating speeds

and loads. It was found that the friction coefficient of bearings increased with the increase in grease filling at a low speed and a light load. The experiments of Ye et al. [22] covered various working conditions, such as vacuum/atmospheric pressure, horizontal/vertical installation, and different rotational speeds, comprehensively evaluating their effects on bearing friction torque. Wang et al. [23] built a dynamic prediction model of the friction torque of angular contact ball bearings using grey system theory and then verified its accuracy using online and offline methods. The study further analyzed the action mechanism of temperature rise, rotational speed, and lubricating oil drag coefficient on friction torque. Seyed Borhan Mousavi et al. [24–28] analyzed the effects of adding various nanoparticles to diesel oil. MoS_2 nanoparticles showed no significant impact on anti-wear performance, while ZnO or a combination of ZnO and MoS_2 nanoparticles notably improved tribological performance. Additionally, $Cu/TiO_2/MnO_2$-doped graphene oxide nanocomposites as additives demonstrated improved properties in various tribological experiments.

In summary, the research has provided valuable information on the impact of grease fill level on the temperature of bearings. Most previous studies focused on steel or hybrid bearings, and there is a lack of research on full ceramic bearings. Ceramic surfaces do not react with the lubricant, which can prevent lubricant oxidation or degradation [29]. Compared to steel bearings, silicon nitride full ceramic ball bearings have some self-lubricating properties. This means that they may require less grease, especially in high-speed conditions. Determining the optimal amount of grease to control temperature rise and improve the stability and lifespan of full ceramic ball bearings is an urgent problem that needs to be addressed.

This paper establishes a theoretical model of heat generation of full ceramic ball bearings, optimizes the friction torque coefficient in the empirical equation of heat generation according to the characteristics of ceramic materials, then simulates the flow and distribution of grease and air in the fluid domain of the bearings and analyzes the influence of grease filling amount on the distribution of grease as well as the influence of rotational speed on the distribution of the temperature field. At the same time, it reveals the influence of grease filling amount through the test of temperature rise of high-speed bearings. At the same time, the effects of grease filling amount and rotational speed on the thermal characteristics of silicon nitride full ceramic ball bearings are revealed through the high-speed bearing temperature rise test to clarify the appropriate grease filling amount further, and the test temperature is compared with the simulation temperature. The results of this study provide a theoretical basis and technical support for the use of grease lubrication of full ceramic ball bearings in high-speed motorized spindles, further promoting the application of full ceramic ball bearings in the field of high-speed precision machinery.

2. Analysis of Grease Filling Amount and Heat Generation in Full Ceramic Angular Contact Ball Bearings

It is essential to ensure the right amount of grease is filled in bearings for optimal performance. Excessive grease can increase friction and temperature, while insufficient grease can result in inadequate lubrication, leading to higher friction, wear, and a shorter service life for the bearing [30]. Therefore, finding the optimal grease amount involves considering various factors, like the friction between the ball and the groove, the ball's load, the lubricant's viscosity, and spin sliding. By adjusting the coefficient of the friction moment in the empirical formula, a theoretical basis can be established for simulating and analyzing the temperature field of grease-lubricated high-speed full ceramic ball bearings.

2.1. Calculation of Lubricating Grease Filling Amount

The geometric relationship of full ceramic ball bearings is shown in Figure 1.

The grease filling amount formula is noted in the literature and is as follows [7]:

$$V = f \times 10^{-5}\left(D^2 - d^2\right) \times B \quad (1)$$

where V is the grease filling amount ($10^3 \cdot cm^3$), D is the outer diameter of the bearing (mm), d is the inner diameter of the bearing (mm), B is the width of the bearing (mm), and the coefficient f takes the value of 3.6.

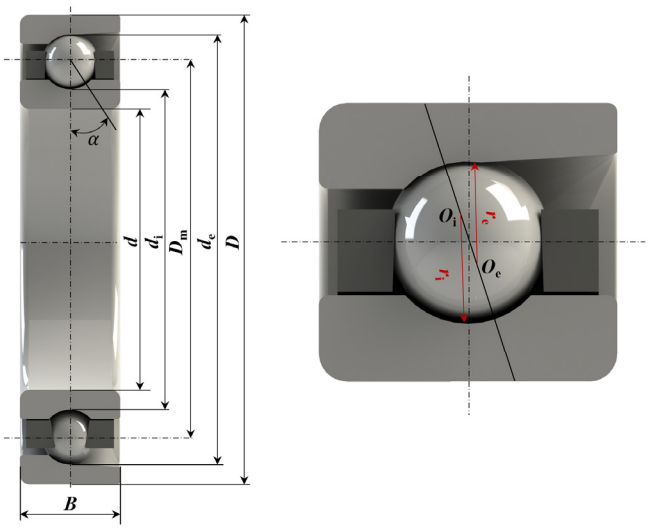


Figure 1. Structure of a full ceramic ball bearing.

The following grease filling amount formula is noted in the literature [31]:

$$Q = q_B \times D_m \times B \times 10^{-3} \quad (2)$$

where Q is the grease filling amount ($10^3 \cdot mm^3$), q_B is the bearing size factor, and D_m is the average bearing diameter (mm).

The recommended grease filling amount varies for each bearing company. Typically, high-speed steel bearings require a grease filling of 1/3 of the bearing space. Poon [32] and Wilson [33] found that after running for some time, the grease may be insufficient, with only a small amount actually participating in lubrication. For instance, for 7009C ball bearings, the grease filling amount calculated by Formula (1) is 20% of the bearing space, while Formula (2) yields 10%.

2.2. Frictional Torque Due to Combination of Load and Lubricant Viscosity

(1) Frictional torque related to the lubrication method is calculated as follows.

When $vn \geq 2000$:

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

When $vn \leq 2000$:

$$M_0 = 1.6 \times 10^{-5} f_0 D_m^3 \quad (4)$$

In this formula [34], M_0 is the friction torque independent of the load (N·mm), and f_0 is the coefficient related to the bearing type and lubrication method. Table 1 gives the value of f_0 for angular contact ball bearings under different lubrication conditions. Furthermore, n is the bearing rotation speed (rpm), v is the kinematic viscosity of the grease (mm^2/s), and D_m is the pitch circle diameter of the bearings (mm).

Table 1. Relationship between the coefficient f_0 value and ball bearing type and lubrication condition.

Ball Bearing Types	Grease	Oil Vapor Lubrication	Oil Bath Lubrication	Oil Spray Lubrication
Angular contact ball bearings	2	1.7	3.3	6.6
Deep groove ball bearings	0.7~2	1	2	4

(2) Frictional torque related to the magnitude of loads [34] is calculated as follows:

$$M_1 = f_1 P_1 D_{\mathrm{m}} \tag{5}$$

where M_1 is the frictional torque caused by the load; f_1 is the coefficient related to the applied load and structure; P_1 is the equivalent dynamic load of the bearing.

The coefficient f_1 related to the applied load and structure is calculated as follows [34]:

$$f_1 = 0.0013\left(\frac{P_0}{C_0}\right)^{0.33} \tag{6}$$

where P_0 is the bearing equivalent static load, $P_0 = X_0 + Y_0$, which can be found in the table, $X_0 = 0.52$, $Y_0 = 0.54$; C_0 is the bearing rated static load, $C_0 = \varphi_0 iZD^2 \cos\alpha$, the value of φ_0 is 12.3, i is the number of columns of the bearing balls, where the object of research in this paper is the single-row angular contact ball bearings, $i = 1$, Z is the number of balls, and α is the bearing initial contact angle.

The equivalent dynamic bearing load P_1 is calculated using the following formula [34]:

$$P_1 = F_a - 0.1F_r \tag{7}$$

where F_a is the axial load applied to the bearing; F_r is the radial load applied to the bearing; if $P_1 < F_r$, then $P_1 = F_r$.

2.3. Spin Sliding Friction Torque

The spin sliding in full ceramic ball bearings is affected by the contact angle being greater than zero. During bearing operation, the ball spin sliding is relative to the normal direction of the contact surface in the elliptical contact area of the groove. The friction resulting from spin sliding is referred to as spin sliding friction. According to the outer ring groove control theory, spin sliding does not occur in the ball in the outer ring groove. The analysis of spin sliding friction heat focuses only on the ball in the inner ring groove. The calculation of angular contact ball bearing spin sliding friction heat involves solving for the friction torque, starting with the calculation of the friction torque.

The spin friction torque of a single ball [35] can be expressed as follows:

$$M_2 = \frac{3}{8}\mu_s Q a L(e)\sin\alpha \tag{8}$$

where μ_s is the coefficient of friction between the ball and the inner and outer ring grooves, Q is the normal contact load from groove to groove, a is the half-length axis of the Hertz contact ellipse of the groove, and $L(e)$ is the type II full elliptic integral of the groove contact region.

2.4. Calculation of Heat Generation in Full Ceramic Angular Contact Ball Bearings

The total bearing frictional torque is calculated as follows [36]:

$$M = M_0 + M_1 + M_2 \tag{9}$$

According to the SKF bearing manual, it is possible to check that the bearing heat generation calculation formula is as follows [36]:

$$N_R = 1.05 \times 10^{-4} M n \tag{10}$$

where M is the total bearing frictional torque and n is the bearing speed.

2.5. Friction Due to Rolling Elastic Hysteresis

Among the sources of bearing frictional moments, the main ones determined by the material are the viscous torque and the hysteresis moment, whose main influencing factors are the modulus of elasticity, Poisson's ratio, and the elastic hysteresis moment. Due to the presence of elastic hysteresis, the strain in the material will gradually increase, resulting in an increase in the stress level of the material, which generates an additional elastic moment called the elastic hysteresis moment. The friction torque due to elastic hysteresis is shown schematically in Figure 2.

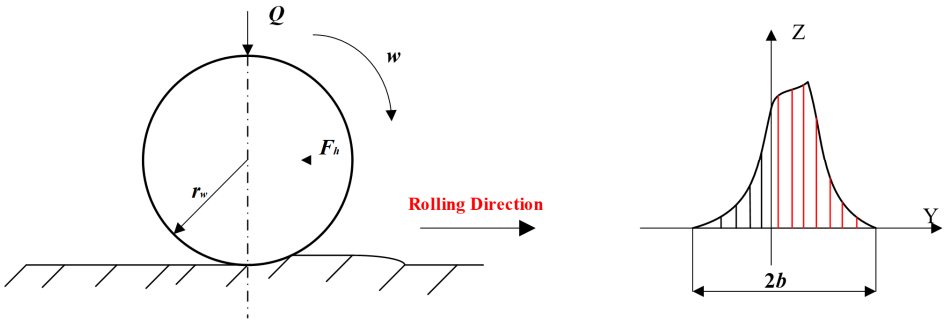


Figure 2. Frictional moment due to elastic hysteresis.

Silicon nitride ceramic's modulus of elasticity, Poisson's ratio, and thermal conductivity and other material properties are different from bearing steel, resulting in changes in the elastic hysteresis coefficient. Reference [37] takes 7007C silicon nitride full ceramic angular contact ball bearings as an example, and the coefficient optimization of Palmgren's empirical formula was carried out to establish a frictional heat generation model for bearings without lubrication. It was calculated that the elastic hysteresis coefficient of silicon nitride was about 90% of that of bearing steel, which was used to correct f_0 in the viscous friction torque formula of the empirical formula.

2.6. Viscous Friction of Lubricants

The viscous frictional resistance of the lubricant consists of the fluid flow resistance to which the balls are subjected as they rotate in a bearing filled with an oil–air mixture; and the fluid stirring frictional resistance to which the balls are subjected as they are subjected to self-transferring motion. The flow resistance of each ball is calculated as follows [38]:

$$F_{dj} = \frac{\pi}{32} C_D \rho (D D_{\mathrm{m}} \omega_{\mathrm{m}}) \tag{11}$$

where F_{dj} is the flow resistance (N); C_D is the drag coefficient around the flow; and ρ is the mass density of the oil–gas mixture (kg/m^3);

The above equation is the conventional calculation of the viscous friction of lubricants, although it suffers from the following three defects. First, the stirring frictional resistance is ignored because of the complicated calculation; second, C_D is a crucial parameter, but the traditional drag coefficient around the flow C_D cannot be completely obtained by theoretical calculations so far, and mainly relies on the experimental determination; third, the bearing cavity contains a mixture of lubricant and air, and the mass density of the mixture is not easy to calculate and measure [39].

It is evident that the viscous friction of the lubricant is associated with the amount of lubricant. Equations (3) and (4) provide an empirical formula for the friction torque related to steel bearings and their lubrication mode. For steel bearings, the recommended grease filling amount for the cavity is approximately one-third of the empirical formula, which establishes the basis for determining the coefficient f_0. This study examines the thermal characteristics of high-speed conditions for grease lubrication of silicon nitride all-ceramic ball bearings. According to Formulas (1) and (2), the range of the grease filling amount is

between 10% and 20%. Less grease filling corresponds to less participation of the lubricating oil, leading to a smaller mass density of the oil–air mixture. Grease lubrication represents a stable thin oil lubrication. The friction coefficient of grease-lubricated silicon nitride full ceramic ball bearings is lower than that of steel bearings. However, when the friction torque is calculated using the empirical formula f_0, the temperature exceeds the experimental value when the heat generated from the friction torque calculation is substituted into the simulation. This study corrects the coefficient f_0 with low-speed grease lubrication silicon nitride full ceramic ball bearing temperature rise tests, verifies the reasonableness of the empirical formula coefficient correction with high-speed tests, and ultimately determines that f_0 should be 83.3% of its original value.

3. Simulation Analysis of the Temperature Field of Grease-Lubricated Full Ceramic Ball Bearings

The research focuses on the 7009C silicon nitride full ceramic ball bearing, and its structural and material parameters are detailed in Tables 2 and 3. A solid model of the full ceramic ball bearing, encompassing the rolling body, inner and outer rings, and cage, along with the fluid domain as a whole, was created using three-dimensional modeling software, as shown in Figure 3. Due to the challenging nature of studying the influence of grease filling amount through experimental methods, fluid simulation technology was employed to simulate the flow and distribution of grease and air within the bearing's fluid domain. The study also involves analyzing the influence of the grease filling amount on grease distribution, as well as rotational speed on temperature field distribution, by combining it with the theory of heat generation of full ceramic ball bearings.

Table 2. 7009C angular contact bearing parameters.

Form	Sizes	Units
Inner diameter	75	Mm
Outer diameter	45	Mm
Pitch circle diameter	60	Mm
Bearing width	16	Mm
Contact angle	15	Degree (°)
Number of balls	17	Pieces
Ball diameter	8.731	mm

Table 3. Material parameters of the 7009C bearing.

Bearings Commponent	Materials	Elasticity Modulus (GPa)	Poisson's Ratio	Density (g/cm^3)	Coefficient of Thermal Expansion (10^{-6}/K)
Outer/inner ring/balls	Si3N4	300~320	0.26	3.2~3.3	3.1~3.3
Cage	Peek	3.6~3.8	0.35	1.32~1.35	22~60

Under high-speed conditions, the grease should have a certain degree of shear stability, and it should show better stability under a high shear rate. Thickener shear thinning release of the base oil plays a lubricating role, but when shear stability is poor, this will lead to base oil loss, resulting in a thin oil state with a poor lubrication effect. Therefore, the thickener is selected as polyurea base with better shear stability, and the base oil is selected as synthetic grease with better anti-wear and wear reduction performance and high temperature stability, while L252 grease is selected based on the above considerations. L252 grease reaches 40 °C when the base oil viscosity is 25 mm^2/s, and its physical properties are shown in Table 4.

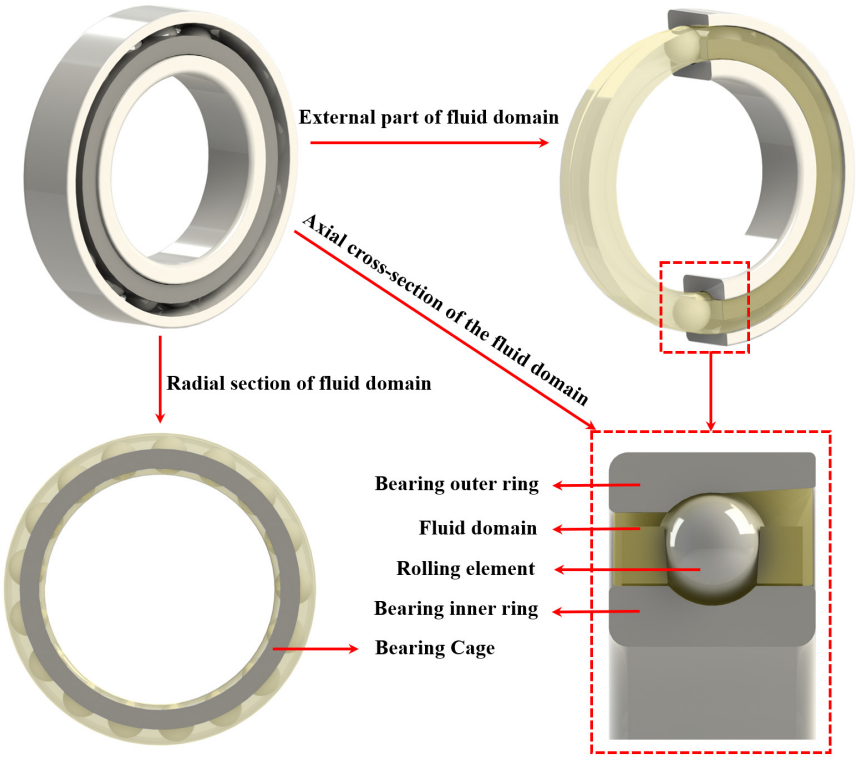


Figure 3. Solid model and whole fluid domain of full ceramic ball bearing.

Table 4. Physical performance parameters of lubricating grease.

Grease	L252
Thickener	Polyurea
Base oil	Synthetic grease
Consistency	3
Working temperature	80

3.1. Effect of Grease Filling Amount on Grease Distribution

When the rotational speed is 18,000 rpm, Figure 4 shows how grease is spread in the bearing cavity with different amounts of grease. The grease filling ranges from 5% to 45%. The simulation results, presented in Figure 4a–e, reveal distinct patterns in terms of the grease distribution.

At lower grease filling levels, centrifugal forces associated with bearing movement propel the grease towards the outer ring, limiting lubrication in the inner regions. When the grease filling reaches 15%, an increase in grease concentration is observed in the outer ring, enhancing lubrication performance. However, the inner ring remains grease-deficient, and the combined effects of high-speed motion and ball collisions facilitate grease shear-thinning and escape from the inner ring groove. With 25% grease filling, the inner ring continues to exhibit limited grease distribution, whereas the outer ring exhibits ample lubrication. As the grease filling percentage increases to 35% and 45%, excessive grease accumulates on the outer ring surface, potentially exacerbating friction and impeding heat convection. Furthermore, excessive grease filling incurs higher costs and may not contribute significantly to improved lubrication performance.

Based on the analysis of the simulation results, a suitable grease filling amount range is identified as 15% to 25% of the bearing cavity volume. Beyond 35% filling, the accumulation of excess grease is detrimental to bearing lubrication, suggesting an optimal balance between grease quantity and lubrication efficiency.

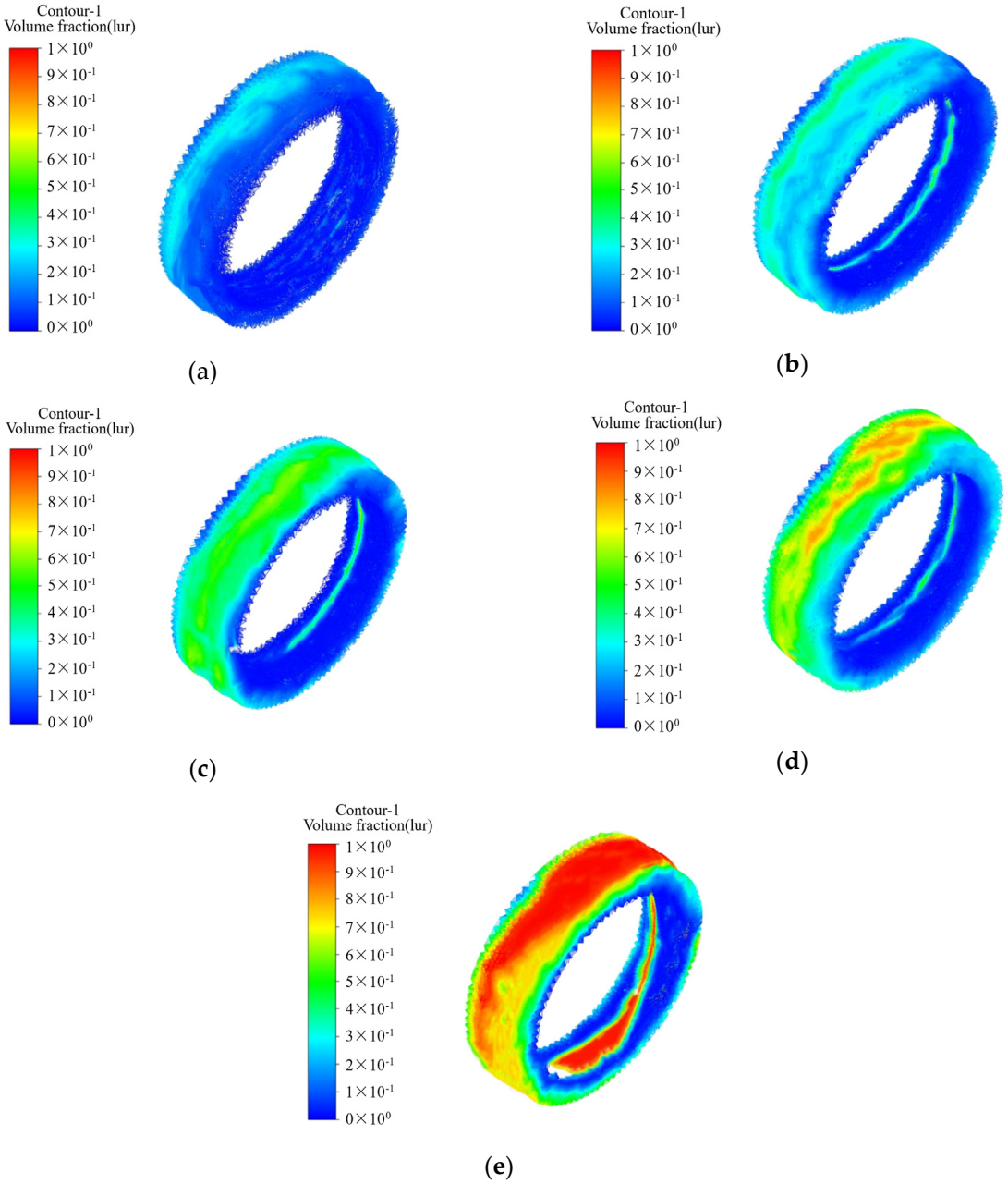
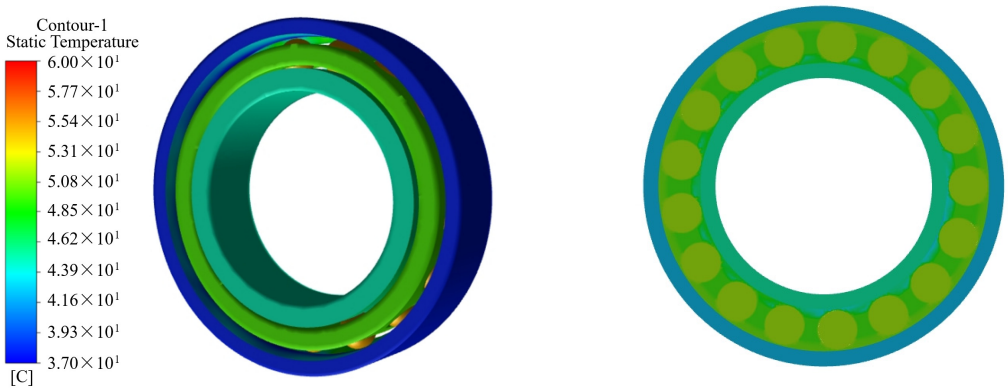


Figure 4. Bearing cavity grease distribution with different filling amounts: (**a**) 5%; (**b**) 15%; (**c**) 25%; (**d**) 35%; (**e**) 45%.

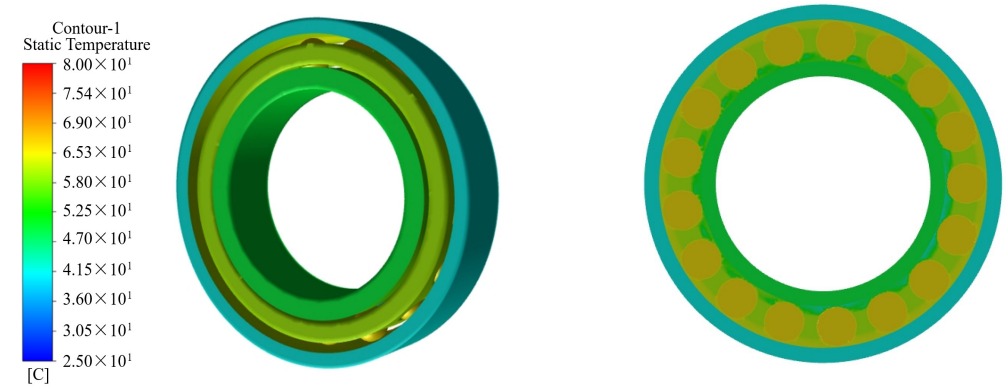
3.2. Effect of Speed on Thermal Characteristics of Silicon Nitride Full Ceramic Ball Bearings

According to the results in Section 3.1, the lubricating effect is best when the grease filling amount is 15%~25%, and the full ceramic bearing has a specific self-lubricating performance. Here, the simulation test grease filling amount is 15%, the rotational speed is set to 6000~24,000 rpm, the gradient of change is 3000 rpm, and the focus is on the analysis of the temperature field distribution when the rotational speed is 12,000~24,000 rpm. The grease-lubricated silicon nitride full ceramic ball bearing is shown in Figure 5. From the simulation results, it can be seen from Figure 5a–e that the overall temperature of the bearing increases when the rotational speed changes from 12,000 rpm to 24,000 rpm. The peak temperature reaches 41.5 °C at 15,000 rpm and up to 46.3 °C at 18,000 rpm. At a speed of 24,000 rpm, the temperature peaks up to 54.764 °C. There is a more obvious temperature difference between the ball and the inner and outer rings, with the highest temperature of the ball followed by a higher temperature of the inner ring and the lowest temperature of

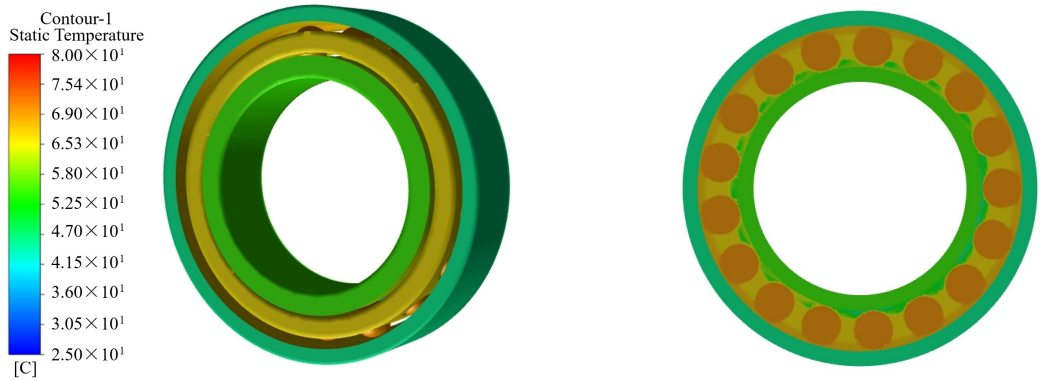
the outer ring. Due to the centrifugal force, there is less distribution of grease around the balls. The balls are constantly undergoing rolling friction and sliding friction. Inside the motorized spindle, it is not easy to dissipate the heat, so the temperature around the balls is the highest. Moreover, the temperature is lower under the action of cooling water, the outer ring, and cooling water convection heat exchange. The increase in rotational speed affects the viscosity and distribution of grease, which in turn affects the distribution of bearing temperature.



(**a**)



(**b**)



(**c**)

Figure 5. *Cont.*

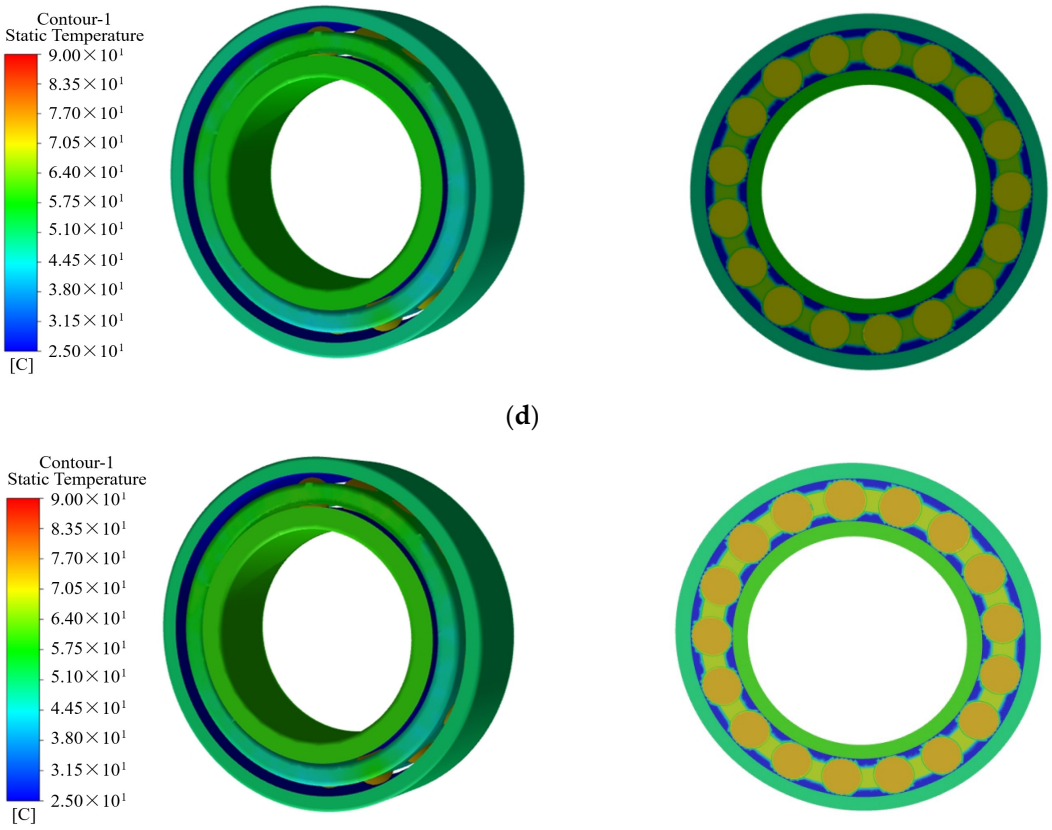


Figure 5. Temperature field distribution with different rotating speeds: (**a**) 12,000 rpm; (**b**) 15,000 rpm; (**c**) 18,000 rpm; (**d**) 21,000 rpm; (**e**) 24,000 rpm.

4. Experimental Verification

4.1. Design of High-Speed Motorized Spindle-Bearing Test Bench

In order to verify the accuracy of the simulation results, an experimental study of silicon nitride full ceramic ball bearings under grease lubrication conditions was carried out by using a high-speed motorized spindle-bearing test bench, and the performance parameters of the high-speed motorized spindle are shown in Table 5. The experimental test bearings are shown in Figure 6, and their material and structural parameters are consistent with Tables 2 and 3.

The schematic diagram of the test equipment and its composition is shown in Figure 7. The high-speed motorized spindle-bearing test bench consists of the control system, water cooling system, and temperature rise data acquisition system. The experimental bench is driven by a Delta VFD-VE inverter, which supplies power to the motorized spindle prototype and realizes spindle start/stop and speed adjustment through the RS485 module of PLC. The water-cooling system cools the spindle by convecting heat away from the bearings, and the equipment used was the MCW-15C-01 precision water cooler, which uses distilled water at 20 °C as cooling water and circulates it to ensure that the temperature of the cooling water is within a specific range. PT100 temperature sensors were placed in the front and rear bearing shells of the high-speed spindle to collect data on the critical temperature measurement points of the spindle. PLC obtains the address and port number through TCP/IP to establish a connection with the upper computer system, converts the collected operation parameters between analog and digital quantities, and saves them to the temperature rise data acquisition system in real time.

Table 5. Performance parameters of the spindle.

Parameters	Values
Rated speed (rpm)	30,000
Rated voltage (V)	350
Rated frequency (Hz)	500
Rated current (A)	19
Rated power (kW)	15
Pole logarithm	4

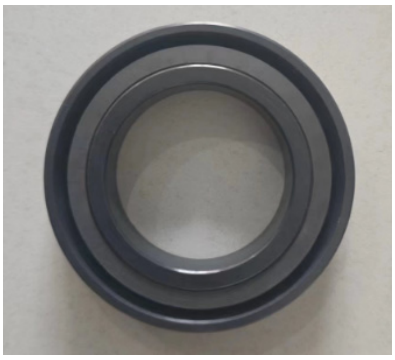
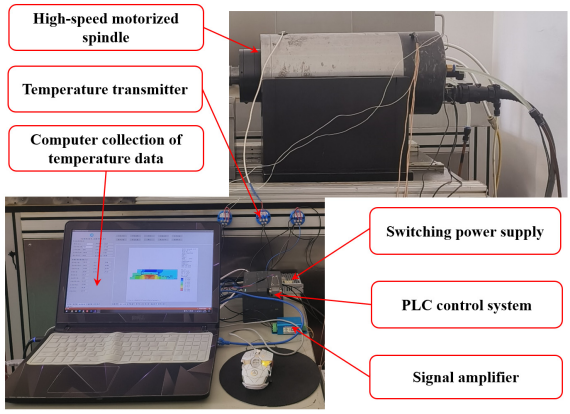
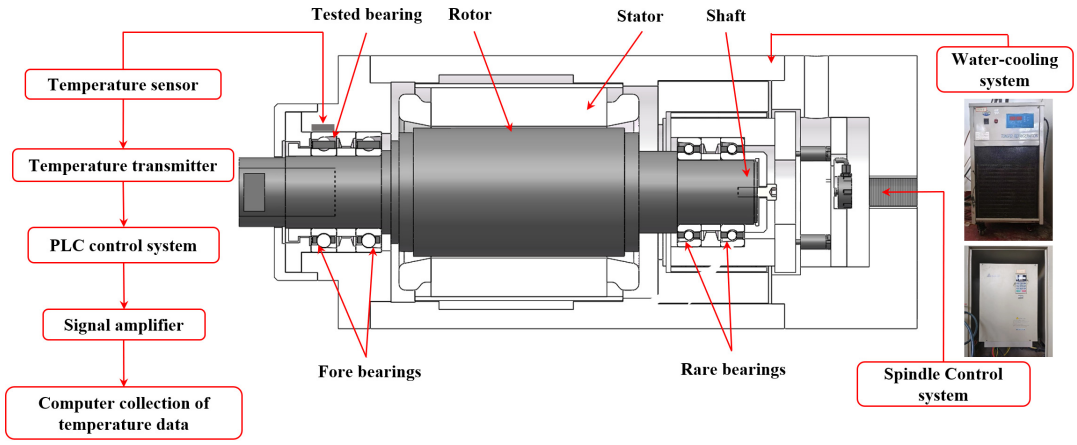


Figure 6. Test bearings—silicon nitride full ceramic bearings.



(**a**)



(**b**)

Figure 7. Experimental equipment and schematic diagram: (**a**) high-speed motorized spindle-bearing temperature rise test platform; (**b**) experimental schematic diagram.

4.2. Experimental Program and Process

The ambient temperature in the laboratory was 20 °C, and we kept the cooling water flow at 10 L/min. For grease-lubricated bearings, it is necessary to avoid particles and dust contaminants on the grease. To ensure that the bearings were clean, we used bearing cleaning agent in the beaker to submerge the bearings and used an ultrasonic cleaning machine to clean the bearings, before wiping them with a dust-free cloth and then air drying them. The test using the composite lithium grease L252 grease filling was completed after the break-in. The break-in was completed for the grease lubrication bearing temperature rise test in order to ensure that the amount of grease filling was accurate, and was carried out each time that grease was re-added for the test. First of all, we controlled a single variable, namely grease filling amount for the test. The test speed was 18,000 rpm, and we collected information on the bearing outer ring temperature. A 7009C ball bearing has a cavity volume of 10 cm^3, and according to Section 2.1, the calculation of the grease filling amount range and Section 3.1's simulation were used to determine the range for the grease filling amount. The test grease filling amount ranged from 5% to 25%, and grease L252 had a specific gravity of 0.94 g/cm^3. High-speed conditions require a small amount of grease for effective lubrication. To determine the amount of grease filling from Table 6, a high-precision load cell was used to weigh the amount of grease filling, and special equipment was used to fill the grease. After the completion of the grease filling amount test, to determine the appropriate grease filling amount of the silicon nitride full ceramic ball bearings, the single-variable speed test set the speed of 6000~24,000 rpm for the test. Because of the number of groups, we tested the groups at increments of 3000 rpm, so there were seven groups for testing the speed conditions for the thermal characteristics analysis. Figure 8 shows the overall grease lubrication bearing temperature rise test flow chart.

Table 6. Lubricating grease filling weight.

Grease	Filling Weight (g/%)
L252	0.6/6% 0.9/9% 1.2/12% 1.5/15% 1.8/18% 2.1/21%

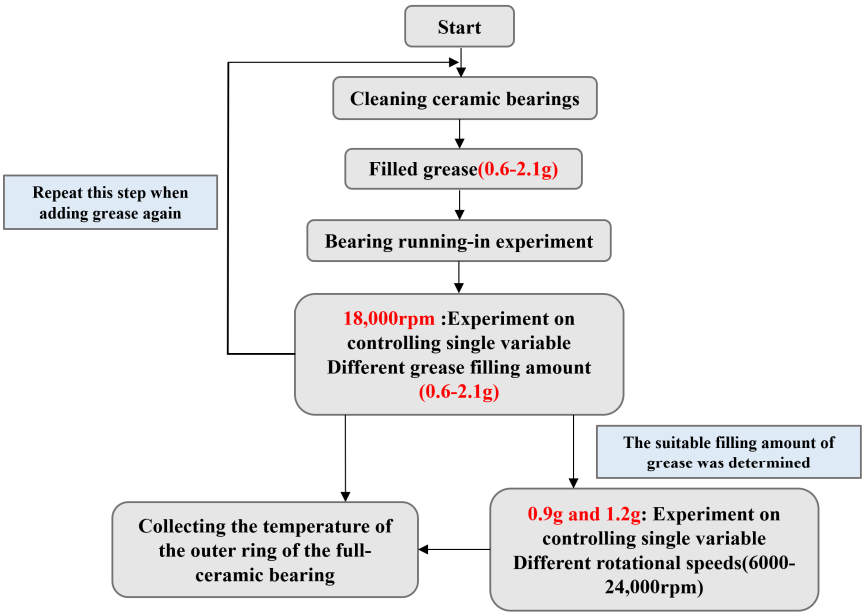


Figure 8. Flow chart of the grease lubrication test.

4.3. Analysis and Discussion

4.3.1. Effect of Grease Filling Amount on the Thermal Characteristics of Full Ceramic Ball Bearings

When the test speed is 18,000 rpm, it can be seen from Figure 9 that the temperature rise of the outer ring of the bearing decreases and then increases with the increase in the grease filling amount, and there exists a minimum inflection point value of the temperature within the range of 0.6~2.1 g. The lowest and smoothest working temperature is found at the time of 0.9~1.2 g, with the temperature stabilized at about 46.1 °C; the bearing temperature is the highest at the time of adding 2.1 g of grease, and it can be up to 50.3 °C. The difference between the highest and lowest bearing temperature can reach 4~5 °C with different grease filling amounts. When the filling amount is less than 0.9 g, the grease cannot completely cover the ball and the inner and outer ring grooves, and the bearing lacks oil lubrication, meaning that the surfaces of the micro-convex peaks are in direct contact, so the friction heat increases. As such, the grease filling amount is increased from 0.9 g to 1.2 g, although this increases the friction torque. The grease churning heat increases, but the lubricating oil film between the balls and the grooves will be thicker, which will reduce the heat of the friction between the balls and the inner and outer rings. As such, the friction heat generation between the ball and the inner and outer rings is reduced. When the filling amount exceeds 1.2 g, due to the large amount of grease, the excess grease hinders the bearing operation and generates a large stirring moment, causing the temperature to rise. When the grease filling amount continues to increase, the temperature rises significantly, because the thicker layer of grease, though initially intended to enhance lubrication and reduce friction between contact surfaces, paradoxically leads to decreased heat dissipation efficiency. The thicker grease film acts as an insulator, impeding the effective heat transfer generated by friction to the surrounding environment. Consequently, the heat accumulates within the bearing, causing a notable rise in temperature. Furthermore, the excess grease can also contribute to increased viscosity drag, further elevating the operational resistance and frictional heating. As the grease filling amount increases beyond the optimal level, the viscosity of the grease becomes a more significant factor affecting the bearing's performance. The higher viscosity leads to more excellent energy dissipation in the form of heat, further exacerbating the rise in temperature. The rise of temperature observed in Figure 9 for higher grease filling amounts is a result of the combined effects of increased churning heat, reduced heat dissipation due to insulation by the thicker grease film, and increased viscosity drag. These factors underscore the importance of maintaining the grease filling amount within the optimal range to ensure optimal bearing performance and temperature stability.

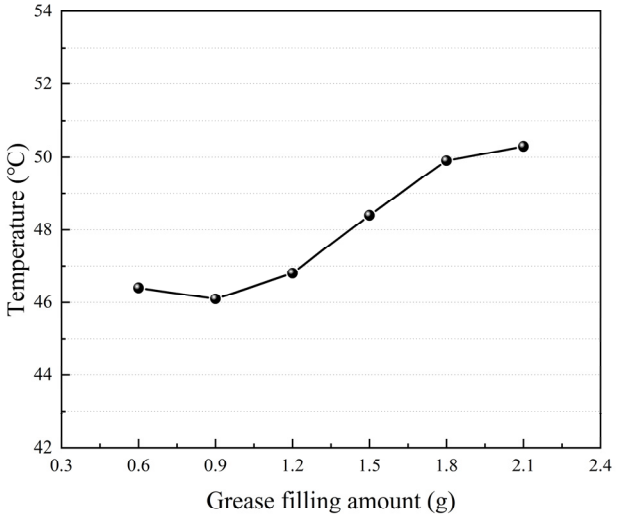


Figure 9. Temperature change in the bearing with the grease filling amount.

4.3.2. Effect of Speed on the Thermal Characteristics of Full Ceramic Ball Bearings

Full ceramic bearing temperature changes with rotational speed. As shown in Figure 10, the bearing outer ring temperature increases with the increase in rotational speed. When the rotating speed is 24,000 rpm, the highest temperature is 50.1 °C. As the speed of the ball centrifugal force increases, affecting the bearing contact load inside the bearing, the contact load increases so that the friction between the ball and the groove of the friction heat increase, meaning that the temperature of the outer ring of the bearing increases. At the same time as the speed increases, the ball spin angular velocity and differential speed change, so that the friction heat increases. The slight saturation of the temperature rise between 21,000 rpm and 24,000 rpm is because the full ceramic ball bearings relies on lubrication for friction reduction and heat dissipation. The lubrication system's effectiveness may also reach its limits at these higher speeds. Changes in lubricant viscosity, film thickness, and distribution could contribute to the observed temperature saturation.

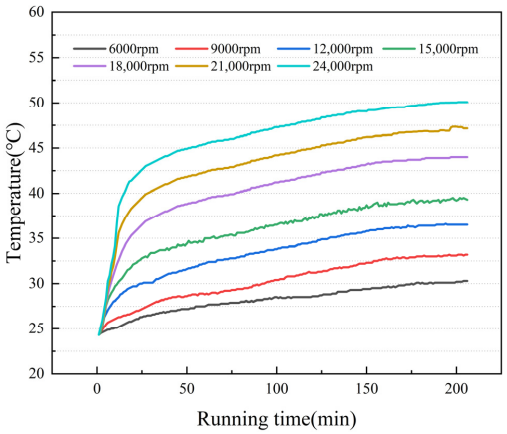


Figure 10. Temperature variation of bearings at different speeds.

After the temperature of the grease-lubricated bearing reaches the steady state, the comparison between the experimental and simulated temperatures of the bearing outer ring position at different speeds is shown in Figure 11. When the spindle speed is 9000 rpm (a low speed), the relative error is about 6.2%; when the speed is 15,000 rpm (a medium speed), the relative error is about 7.3%; when the speed is 24,000 rpm (a high speed), the relative error is about 9.3%. In summary, the temperature rise trend of the full ceramic ball bearing is approximately the same with the simulation, and the average relative error is less than 10%, which indicates that the simulation model and the experimental data have good consistency. This verifies that the modification of the empirical formula coefficients and fat lubrication of the full ceramic ball bearing temperature field analysis is reasonable.

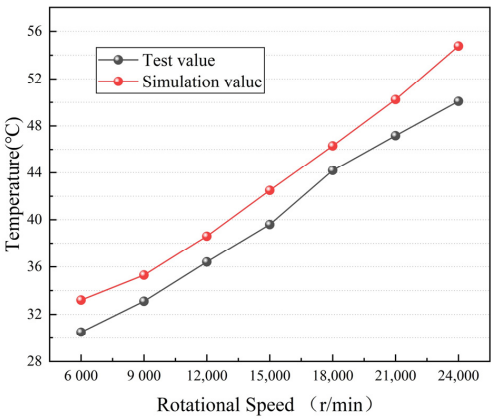


Figure 11. Comparison of simulation and test temperatures.

5. Conclusions

In this study, the theoretical analysis, model establishment, and experimental verification of the thermal characteristics of grease-lubricated bearings were carried out, and the effects of grease filling amount and rotational speed on the thermal characteristics of silicon nitride full ceramic ball bearings were investigated, respectively, so as to provide a theoretical basis for the grease lubrication of full ceramic ball bearings in high-speed motorized spindles. The main conclusions are as follows:

(1) We analyzed the heat generation between the balls and the grooves caused by the spin-sliding of the balls and the load and the viscosity of the lubricant. For a small number of grease-lubricated full ceramic ball bearings, the coefficient of friction moment in the empirical formula was corrected by the test, and the foundation was laid for the simulation and analysis of the temperature field of the grease-lubricated full ceramic angular contact ball bearings.

(2) The simulation model of the grease flow and temperature field of full ceramic ball bearings was established, and the influence of grease filling amount on grease distribution and rotational speed on temperature field distribution were analyzed. The simulation results show that 15~25% is a suitable range for the grease filling amount, and the grease is uniformly distributed in the bearing. The phenomenon of insufficient grease or the accumulation of grease does not occur. The temperature of the bearing increases with the increase in rotational speed, and the temperature of the outer ring of the bearing is 54.764 °C when the rotational speed is 24,000 rpm.

(3) The simulation results were verified through the temperature rise test of the grease filling amount, and the suitable grease filling amount for grease-lubricated full ceramic ball bearing was further determined. For 7009C ball bearings, when the grease filling amount increases from 0.6 g to 2.1 g, the temperature decreases first and then increases. When the grease filling amount is 2.1 g, the temperature of the outer ring of the bearing is 50.3 °C at its highest. When the filling amount is 0.9~1.2 g, the temperature of the outer ring of the bearing is the lowest, and the temperature stabilizes at about 46.1 °C. The reasonableness of modifying the coefficient of the empirical formula and the temperature field analysis of fat and fat-lubricated full ceramic ball bearings is verified.

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