Design and Experimental Investigation of Innovative Fully Ceramic Spindle-bearing System for NC Machine Tools

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Abstract

High-speed machining (HSM) is a forward-looking areas for drastically reducing production time and improving production efficiency. The implementation of HSM strategically depended on development of spindle technology. However, Traditional spindles are not suitable for high speed condition because of their low damping ratio and high rotational inertia. In addition, centrifugal force and heat generation caused by high speed rotation of conventional steel spindles have been obstacles for improving the limit speed. The application of new materials is an fascinating alternative to increase life-time and the boundary speed of bearings. The high performance hybrid steel/ceramic bearing or ful-ceramic and other ceramic structure components has emerged because of advanced structure ceramics as an extraordinary potential material. For this research study, an innovative speed fully ceramic system of spindle-bearing provided with superior performance characteristics of structural ceramics shaft but also ful-ceramic bearing without inner rings were effective developed and optimization designed. Internal structure parameters factor of full ceramic ball bearing were optimized and designed based on its failure mechanism analysis. The preload and lubrication condition of high-speed spindle-bearing system were optimized. It implements a high-precision, high-speed assembled with ceramic electric spindles,which maximum speed achieves 30000r/min, and maximum power achieves 15kW. Performance test and analysis of the developed ceramic motorized spindle were completed. Experimental results showing that the radial run out of shaft is less than 1μm, in the condition of best lubrication and appropriate preload, radial rigidity of the ceramic spindle achieves 322N/μm, no-load vibration is less than 0.8mm/s, no-load temperature rise is less than 10 ºC. Motorized spindle of ceramic can reduce the high-speed rotational moment of inertia, increase the rigidity and greatly improve totating precision of the system of spindle-bearing, on account of physical characteristics of engineering ceramics such as light weight, resistance abrasion and good thermal, so as to accommodate the high precision and high speed demand of spindle system for NC machine tools.

Keywords: CERAMIC BEARING, CERAMIC MOTORIZED SPINDLE, PRELOAD, STIFFNESS

1. Introduction

Spindle bearing system can be used as an important requirement for modern NC machine tools, the development direction is to improve processing efficiency and achieve a higher speed[1]. In addition, for a more robust within a given speed range, spindle bearing systems require desensitization of improper operating conditions [2].The load carrying capacities and the rotational speed limits of their spindle-bearing system determined the productivity of modern NC machine tools.

To fulfill high speed machining requirements, the characteristic of speed constant $D_m \cdot n$ has to be measure up to more than 3.5×10^6 mm/min, assuring a sufficient stiffness of the spindle body [3, 4].

Compared with the traditional spindle, there was a built-in electric motor and a better balance of power transmission configurated in the motorized spindles, achieved high speed operation under condition of power transmission. Until now, the field of high precision and high strength processing becoming more popularization [5]. However, the thermal deformation of the spindle system caused by a large motor.Achieve the stabilized operation of spindle, high damping than the low moment of inertia and the spindle axis and small deflection and thermal distortion is indispensable [6-9]. However, the conventional ball bearing spindle and the ingot axis and the high moment of inertia, a large elastic modulus and a large deflection is not suitable for high speed operation. Therefore, The problems mentioned above will be solved by carbon fiber material or engineering ceramics [10].

In 1963, Taylor and others manufactured bearing balls by thermocompression of Al_2O_3 and SiC, taking experiment under environment of temperatures above 811K, the experimental results the material of ceramic can able to guarantee better rigidity as well as the temperature range of corrosion resistance much wider than that of steel bearing[11].

In 1988, Aramaki, who proposed the hybrid bearings and steel were compared. Experimental results show that the higher critical speed of the hybrid ceramic bearings [12]. In 1989, R. Wada and Y. Namba et al developed an surface grinder owning a ceramic motorized spindle of low coefficient of thermal expansion to accomplish electronic and optical materials [13]. In 1995, Chiu and other take fatigue tests about hybrid ceramic bearings respectively under condition of heavy loading and high rotational speed. The results show that high speed hybrid bearings under condition of poor lubrication, its temperature rise is still below the steel bearing temperature increase [14]. In 2002, K.G Bang and D.G Lee designed high speed air spindles composited by carbon fiber. The safety of the designed carbon composite shaft was evaluted by considering residual thermal stresses, bending load and centrifugal force [15]. In 2003, Weck and Brecher et al proposed the ceramic spindle bearings multi-point angular contact (3P, 4P), and sprayed ceramic coating that is wear on the bearing channel. Machine tool spindle speed had been further improved, the value of $D_m \cdot n$ has reached more than 3.5×10^6 mm/min [16].

As now known, product of hot isostatically pressing of silicon nitride (HIPSN) ceramics are considered as an increased application, in case of their physical properties, such as light weight, low expansion hot thermal, high temperature rises and high speed and others, good chemical stability and wear resistance and stability [17-19]. There has been used for structural engineering materials because of the high strength, fracture toughness and wear resistance of Yttria partially stabilized zirconia (Y-PSZ). Increasingly widely used in the chemical, aviation, mechanical and other industries mainly due to the excellent properties of material. The goal of the applications of engineering ceramics in the spindle-bearing system are to improve the precision and strength of the spindles, to reduce the centrifugal force of the spindles during high speed rotation, and precision to meet the requirements of quick raising speed and high rigidity of the very high speed motorized spindles [20]. Upon this study, built under the conditions of oil or air lubrication, it comes to ful-ceramic bearings without inner rings and Y-PSZ ceramic spindle speed HIPSN equipped with ful-ceramic bearings, carried out research and experimental developement. Aside from the description on the temperature rise and the thermal deformation effect of an oil or air lubricated, there also emerged the effects of bearing preload on the static rigidity in this paper. The ceramic spindle consequents show that it has a good behavior under the woring conditions of light load and high speed circumstance. These final consequents provide a high speed motorized spindle designing its higher precision, longer lifetime, lower temperature rises and enough static stiffness to provide a useful reference.

2. Parameter Optimization of Fully Ceramic Ball Bearing

2.1. Selection of Ceramic Material for Bearing

Properties of ceramic materials for the parts, the manufacture of bearings as follows: a low thermal expansion, moderate elastic modulus, low density, high toughness, high strength, resistance ability to contact fatigue. Furthermore, high heat resistance , stability and corrosion resistance in the particular area is necessary.Table 1 showed the performance of bearing steel and ceramic materials. The Si_3N_4 and ZrO_2 are most appropriate for construction of ceramic bearings and shaft as a result of their superiority through experimental investigations and applications.

Table 1. Different performance of the bearing material

Material	Poisson's ratio	Density/ (g/cm3)	Coefficient of thermal expansion/ (10-6/℃)	Fracture toughness / (Mpa·m1/2)	Elastic modulus/GPa	Hardness/HV
Steel	0.3	7.85	10.0	25	208	700
Si3N4	0.26	3.24	3.2	7.0	320	1400
ZrO2	0.30	6.00	10.5	9.0	210	1100

2.2. The Failure Mechanisms of Ceramic Ball Bearing

The mainly failure form of fully ceramic ball bearing are fatigue spalling, wear, fragmentation and others. As shown in Figure 1, the suddenly breaking of the Si_3N_4 ceramic balls causes ZrO_2 ceramic outer ring raceway scratch marks. Figure 2 shows the contact fatigue spalling pits of ZrO_2 ceramic outer ring raceway surface.

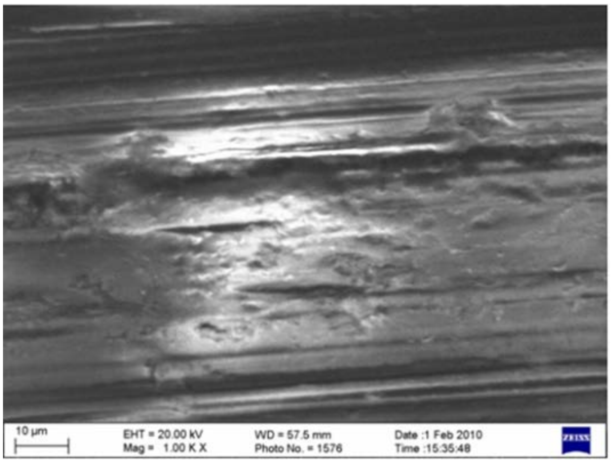

Figure 1. Scratch of ceramic bearing race

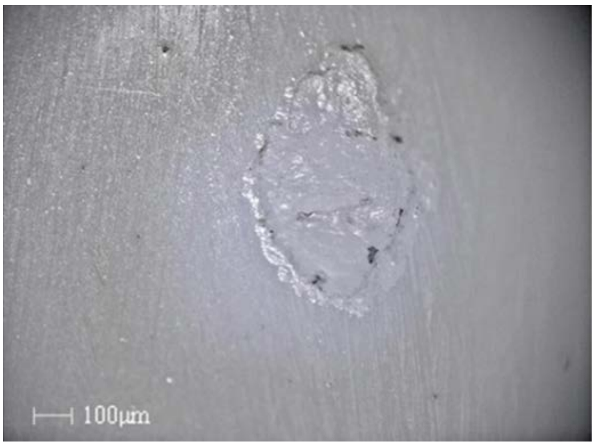

Figure 2. Fatigue spalling of ceramic race

Although the failure forms of the ceramic balls fragmentation and ceramic outer ring fracture, which are mainly caused by ceramic parts defects, are devastating, but they are belong to a very small probability phenomenon, they can be avoided by rigorous quality testing. There is no inner light load slip failure in the high speed operation of ceramic ball bearing for high-speed spindle system, the fatigue spalling of ceramic raceway surface is caused by the micro cracks and impurities of ceramic raceway surface. Thus, the fatigue failure of the outer ring raceway is the main destruction form of ceramic ball bearing, this is particularly obvious when the bearing outer ring material is ZrO_2 ceramic. Compare with the outer ring of ZrO_2 ceramic, the possibility of the Si_3N_4 ceramic balls fatigue spalling is very small, and there is almost no sign of wear.

2.3. The Optimization Design of Ceramic Bearing

The mechanism model of Fatigue failure and ceramic ball bearings are not entirely confirmed theoretically, and so, optimum design of ceramic bearings established on the calculation model about fatigue life of of hybrid ceramic bearings [21]. The penalty function point method can solve inequality constrained problem more quickly and accurately, combined with the actual characteristics of the rolling bearing, is a good method of strict, time-saving, better economic.The main structure parameters of bearing as following: the diameter of ball D_b, the center circular diameter of ball D_m, the balls number Z , inner and outer groove curvature radius factor are f_i and f_e , the angle of contact is α. The decisived formula as follows.

The range of experience limits the size of the diameter of rolling elements ,namely,

$$K_{D\min} \cdot (D-d) \le D_b \le K_{D\min} \cdot (D-d) \tag{1}$$

Among them, K_{Dmax} and K_{Dmin} are related empirical constant diameter, maximum and minimum values respectively. The series of ceramic bearings 7000C, typically ranging: $K_{\text{Dmin}} = 0.24$, $K_{\text{Dmax}} = 0.30$.

Better assembly, the number of rolling elements should be some restrictions, namely,

$$Z \le \frac{\pi D_m}{K_z D_b} \tag{2}$$

The K_Z is related to the holder of the type of experience constants.

Ensuring the adaptation of ceramic balls group and cage and keeping good rotation, the distinction of the average diameter $(D+d)/2$ and the center circle diameter of rolling element,it should satisfy certain requests, namely,

$$0.5(D+d) \le D_{\mathrm{m}} \le 0.515(D+d) \quad (3)$$

Inner and outer bearing raceway groove curvature radius factor have a significant impact on the frictional heat and bearing stress. For ceramic bearings,the elasticity modulus is large, on the race and the ball contact area is reduced, resulting in the increase of Hertz stress. Accordingly, compared with steel material bearing, f_{i} and f_{e} of ceramic bearing should be reduced suitably, The contact area among ceramic race and ball are big enough to ensure that contact stress is not too high that influence the life of the bearing. After calculation, reducing the amount of desirable from 0 to 0.3, and because at high speed ope- rating conditions, the centrifugal force of a large rol- ling elements, taking into account the internal and external stress such as raceways and equal strength,the value of f_{e} may be bigger than f_{i}. And so f_{i} and f_{e} should satisfy the following one constraint condition,

$$f_{\mathrm{e}} \ge f_{\mathrm{i}} \ge 0.505 \quad (4)$$

Through the above analysis,we can draw a mathematical model to optimize the design of ceramic bearing,the formula is expressed as follows:

$$\min f(x) = \min(-C(D_{\mathrm{b}}, Z, D_{\mathrm{m}}, f_{\mathrm{i}}, f_{\mathrm{e}})) \quad (5)$$

$$\begin{cases} g_1(x) = D_{\mathrm{b}} - K_{\mathrm{Dmin}}(D-d) \ge 0 \\ g_2(x) = K_{\mathrm{Dmax}}(D-d) - D_{\mathrm{b}} \ge 0 \\ g_3(x) = \dfrac{\pi D_{\mathrm{m}}}{K_Z D_{\mathrm{b}}} - Z \ge 0 \\ g_4(x) = D_{\mathrm{m}} - 0.5(D+d) \ge 0 \\ g_5(x) = 0.515(D+d) - D_{\mathrm{m}} \ge 0 \\ g_6(x) = f_{\mathrm{i}} - 0.505 \ge 0 \\ g_7(x) = f_{\mathrm{e}} - 0.505 \ge 0 \end{cases}$$

According to the above optimization model, the software of ceramic bearing optimal design was developed. The program block diagram of optimization design for ceramic ball bearing is shown in Figure 3.

In this paper, the ceramic bearing design is based on the 7008C series bearing, the mainly internal structure parameters of the final design ceramic ball bearing refers to the optimized design results that shown in Table 2.

Table 2. The optimization results of ceramic ball bearings

Bearing Model	Structure size(mm)	Contact angle	Db(mm)	Z	Dm(mm)	fi	fe
7008C	40×68×15	15°	7.144	18	54.005	0.505	0.510

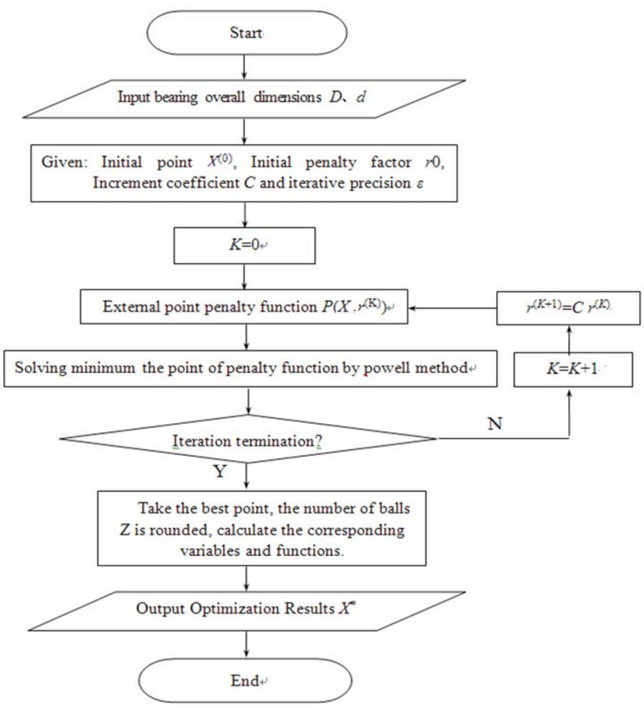

Figure 3. Block diagram of optimization design for ceramic ball bearing

Compared with the traditional steel ball bearings, the biggest change of the ceramic ball bearings optimized design results is the curvature radius coefficient of bearing race (f_{i} and f_{e}) becoming smaller, while f_{i} and f_{e} of steel bearing are generally between 0.515 to 0.54. The mainly reason is the ball material and outer circle of the fully ceramic ball bearing that is the ceramic material that has the performance of the high hardness and big elastic modulus, ceramic balls and ceramic race are difficult to plastically deform. If using the race curvature coefficient of steel ball, the contact area between ceramic ball and ceramic circle race will be reduce, the contact stress will be increasing, it is not conductive to extend the fatigue life of bearing. Thus, compared with the steel ball bearings and hybrid ceramic ball bearings, the inner and outer race curvature coefficient of fully ceramic bearing should be reduced, the contact ellipse area of ceramic balls and race is big enough, the ceramic bearing life is not influenced by the excessively high Hertz stress. Because of the lack of systematic research and analysis about contact fatigue spalling failure mechanisms and life estimation model of fully ceramic ball bearing, the optimization results is only partially relevant material parameter modification based the ball bearing life estimation model. In the current conditions, it only will used to the ceramic bearing design reference. Figure 4 is the picture of ceramic bearing without inner ring.

3. Structure Design and Processing and Manufacturing

3.1. Structure Design of Spindle

In order to solve precision assembly problem between the ceramic inner ring and ceramic shaft, this paper innovative design the fully ceramic ball bearing without inner ring. By comparing the property of different structural ceramic materials simultaneously considering the reliability and economy, in this paper the Y-PSZ is selected as the material of ceramic shaft and outer ring of ceramic bearing, the processing of the bearing inner ring achieved on the installation of PSZ spindle shaft directly. The mate- rial of ceramic ball is HIPSN. The material of retainer selects Polyether Ethyl Ketone (PEEK), the friction coefficient between the Si3N4 ceramic balls and PEEK is very small. Figure 5 demonstrated the overall structure design program of ceramic spindle.

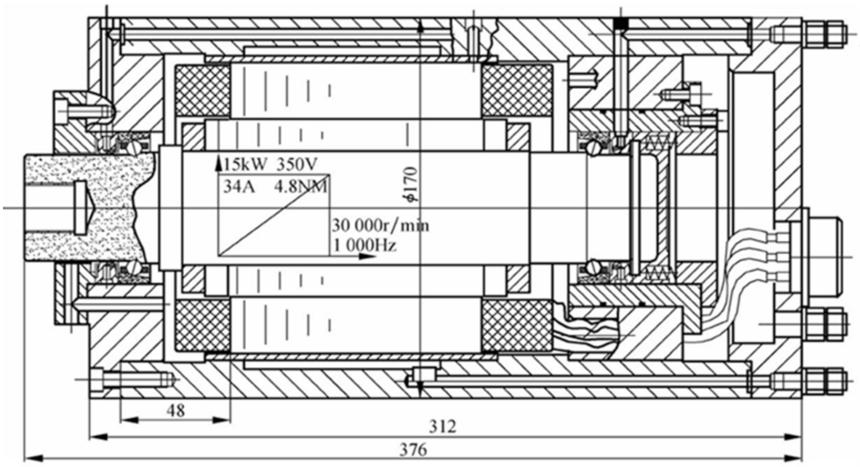

Figure 5. Structure design of ceramic spindle

3.2. The Fabrication of Ceramic Shaft

About ceramic shaft in volume manufacturing of ceramic parts, there are two technical difficulties. (1) Difference between the process and the complexity of the process, resulting in manufacturing costs of raw materials increased. (2) The metal materials was Compared, ceramic materials province unique mechanical discreteness becoming larger. Therefore, the optimization process must be deployed in the ceramic member. For this research, the blank portion of the ceramic dry-pressed by cold after isostatic pressing. figure 6 illustrates the completed ceramic shaft.

Figure 4. The picture of ceramic ball bearing without inner ring

3.3. Ultra-precision Congregation of the Ceramic Motorized Spindle

Motorized spindle should have excellent transmission capability and running accuracy, its components keep surface quality and precision maching, also requires a assembly precision. Assembly methods of Two Points can really guarantee accuracy of the static dynamic equilibrium of spindle stiffness. Compare the properties of the traditional materials with ceramic materials, the properties of the steel is very different, high thermal expansion, low co-efficiency. It also vary a lot in other characteristics. Therefore, the amount of interference between the architectural invention of it is not fully applicable to traditional electric spindle shaft and rotor, it must be recalculated. Interference amount ceramic rotor spindle and elongation were analyzed by dynamic and static calculation, and the interference amount reaches Study from 0.08 to 0.10mm. For the purpose of accurate balance of the rotor assembly, apart from the proportion of the layout, the diameter of the rotor to be achieved after the press-fit and precision grinding, to meet accuracy of the design. Figure 7 shows the congregation of ceramic spindle.

Figure 6. Ful-ceramic motorized spindle of ful-ceramic shaft

Figure 7. The congregation of ceramic motorized spindle

4. Analysis of Ceramic Spindle

4.1. Critical Speed Analysis

For facilitate of calculation, simplify the ceramic spindle. Elastic supports, each bearing evenly synthesized by four unity of spring. Although the formerly modeling, the consequents of six natural frequencies are shown in Table 3 below.

The relationship between the frequency and the critical velocity for n = 60×f. The critical speed is the natural frequency conversion of the spindle,Table 3 shows the manipulating speed designed of the spindle is 30000r / min.

Table 3. The critical rotation speed of ceramic motorized spindle

Ordinance	2	3	4	5	6
Natural frequencies (Hz)	2145.8	2147.1	3141.4	3180.8	4284.3
Critical speed (rpm)	128748	128826	188484	190848	257058

4.2. Harmonic Response Analysis

Figure 8 shows Frequency and response displacement of the former spindle radial direction, the figure can be seen from:

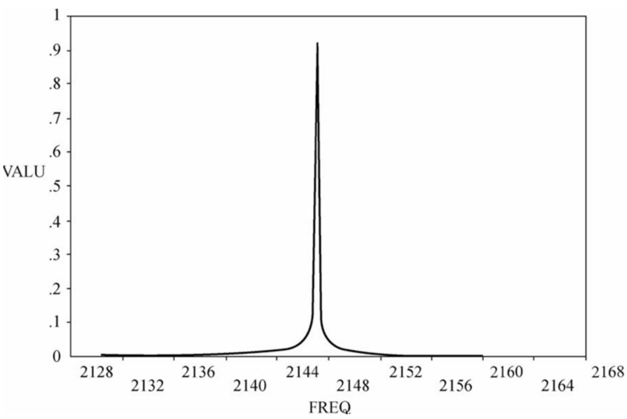

Figure 8. The radial direction responses of front and rear ceramic shaft (2130~2160Hz)

The range from 2130 Hz to 2145 Hz represent the frequency increment, radial displacement direction of former spindle was increased greatly. When the frequency of spindle increased to 2150 Hz, there is a sharp decline in the front of the radial runout of the spindle, frequency is less than 2145 Hz.

The results showed that motorized spindle has a relatively stiffness of dynamic. Which can be determined the occurrence of a spindle 2145 Hz resonance region, which is close to the first frequency. The maximum working frequency of the spindle up to 1000 Hz, the maximum working speed up to 30,000 rev / min, so that prevent promptly the resonance hazards.

Figure 9 shows radial displacement of motorized spindle on the front end of the response, the dynamic of the displacement of the front end of the responses. The operating frequency of spindle, front end of the spindle maximum displacement is from 0.48μm to 0.49μm, related design meet the requirements.

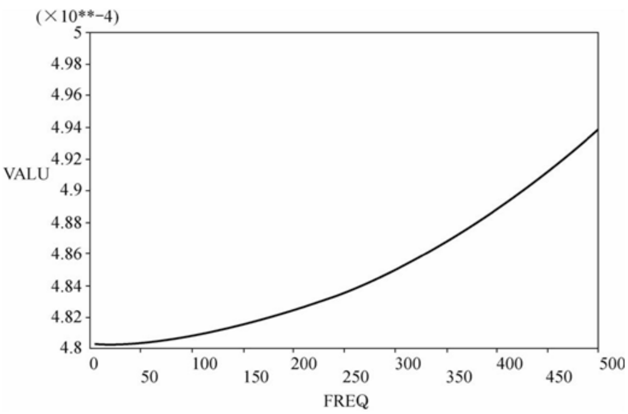

Figure 9. The radial deracination response of front and rear ceramic shaft

5. Experimental Research of Ceramic Motorized Spindle

5.1. The Experiment Conditions

The test object is the prototype SJD170SD30 of ceramic motorized spindle without inner ring developed in this paper. Its main technical parameters are shown in Table 4. The test environment is a constant temperature and humidity laboratory, the room temperature is 20ºC, the ambient noise is not higher than 35dB.

Table 4. Specifications of the ceramic motorized spindle

Rated power [kW]	Rated torque [Nm]	Maximum speed [r/min]	Rated current [A]	Rated voltage [V]	Rated frequency [Hz]
15	4.8	30000	34	350	1000

The comprehensive performance testing platform for Figure 10 shows the ceramic motorized spindle, the load characteristics, temperature, vibration, noise, stiffness and accuracy test for the ceramic motorized spindle can be tested on the platform. The entire test system consists of a high-speed spindle dynamometer, Kistler torque speed sensor and display device, the DASP INV3018 data collection instrument and the vibration and noise sensor, Keyence high-precision laser sensor and acquisition instrument, WT230 three-phase electrical parameter measuring instrument, high-speed precision couplings, the TC series multi-channel temperature tester and temperature sensors, asynchronous dynamometers machine frequency conversion control power supply, load resistance boxes, industrial machines, oil lubrication system, cooling system.

Figure 10. Integrated performance test platform of ceramic spindle

5.2. The Temperature Increase Test of Ceramic Spindle

The temperature rise is an important performance indicator of motorized spindle. it comprehensive reflects the design and manufacturing level of motorized spindle. As shown in Figure 11, it analyses three cases that the ceramic bearing preload is 400N, 600N and 800N respectively, it also analyses the changes between the temperature increase of the front and rear bearing of ceramic spindle and the spindle speed in the best lubrication conditions. The experimental results show that the temperature change of the front and rear ceramic bearing is steady when the cera- mic bearing preload below the 600N. The maximum no-load temperature increase of the ceramic motorized spindle front bearing is only 8.6 ºC in the best lubrication conditions. When the preload force of ceramic bearing is 800N, the temperature of front and rear bearing rises sharply. When the spindle speed is 20000r/min, the temperature of front bearing has exceeded the 35 ºC that is the maximum setting temperature. Therefore, in the study, the pre-load of ceramic bearings is set from 400N to 600N, it can ensure the stable operation of ceramic motorized spindle in high speed.

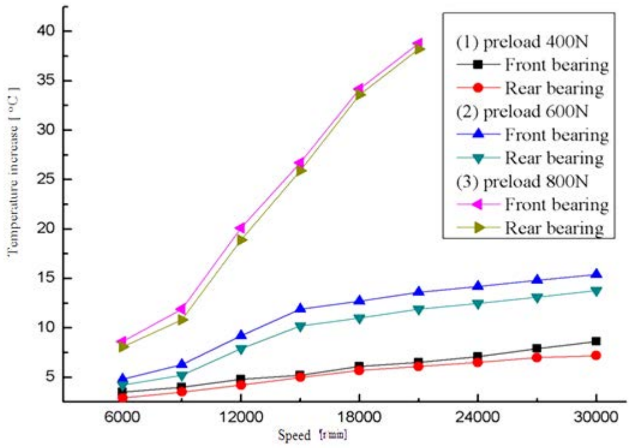

Figure 11. Temperature increase of ceramic motorized spindle

5.3. The Vibration and Noise Test of Motorized Spindle

Vibration is one of the key indicators of spindle dynamic performance. it directly affects the machine life, the dimensional accuracy of the workpiece machined and surface roughness [22, 23]. The vibration and noise of motorized spindle mainly come from the spindle bearings of high-speed operation. The vibration of motorized spindle should be controlled below 1.5 mm/s at the highest speed. As is shown in the Figure 12, in the velocity range of motorized spindles, the vibration of ceramic motorized spindle front and rear will be gradually increase with the spindle speed increasing, but the vibrations are not more than 0.8mm/s, they meet the design requirements.

The noise of ceramic motorized spindle should be controlled below 75 dB at the highest speed. Just as evident seen from the Figure 13, the noise of motorized spindles reaches 95dB at the highest speed 30000r/min, it goes far exceeded the horizontal of traditional motorized spindles noise control. It is related to the material properties of full ceramic ball bearings and the groove-shaped error and surface quality of ceramic bearing raceway. The method of lower the ceramic motorized spindle noise requires further study.

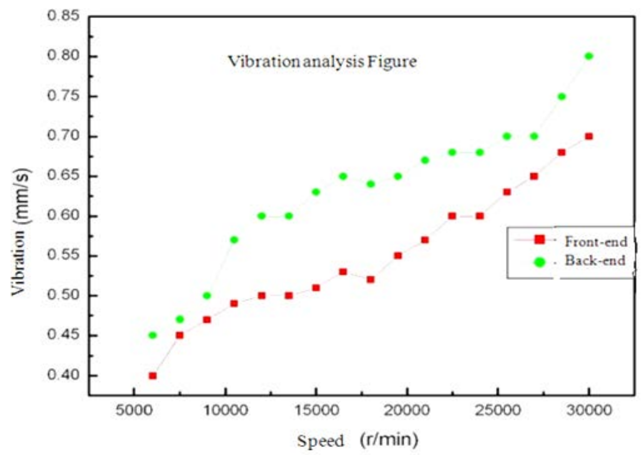

Figure 12. Vibration performance of ceramic motorized spindle

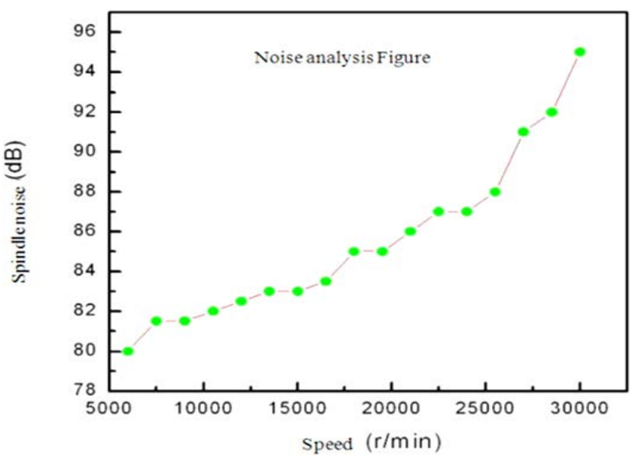

Figure 13. Noise of the ceramic motorized spindle

5.4. The Stiffness and Accuracy Test of Ceramic Spindles

Nowadays, there is no uniform international standard about the stiffness and precision value of motorized spindle. Table 5 shows the static rigidity test value of the front spindle of ceramic spindle in the different preload, the model of ceramic motorized spindle is SJD170SD30. The preload increased from 600N to 800N has not obvious influence to the spindle rigidity, instead, there is a dramatic effect on the temperature rise situation of ceramic bearings, it can be seen from the Figure 9. Therefore, in the study, the highest rigidity with radial direction can achieve 322N/μm with the preferably preload 400 ~ 600N, far exceeded the level of same spindle rigidity of 150N/μm.

The static accuracy test value of SJD170SD30 ceramic spindle listed in Table 6. As is shown in the table, in this study, Ceramic motorized spindles meet the design requirements.

Table 5. Static rigidity of the ceramic motor spindle with different preloads

Prelod [N]	Radial rigidity [N/μm]	Axial rigidity [N/μm]
400	258	164
600	322	190
800	328	195

Table 6. Static accuracy of ceramic spindle

Radial runout of inner hole	Radial runout of extension rod	Circular runout of end face	Radial runout of shaft end
<1μm	<5μm	<1μm	<1μm

6. Conclusion

High performance spindle-bearing system is one of the key function units of NC machine tools. In case of physical performances characteristics of engineering ceramics, such as low thermal expansion, high hardness, abrasion resistant, light weight, thermal stability and good chemical, so as to accommodate and precision of spindle system. In addition, it can reduce friction and decrease the temperature response, accordingly effectively reduce the energy consumption and save resources. Development of ceramic spindle can improve the performances and quality of the spindle system and NC machine-tools significantly. Upon this research, an innovative ceramic high speed spindle within bearing without inner rings is designed and manufactured. The bearings are a kind of (HIPSN) ful-ceramic bearings, whose rotor shaft is made from yttria partially stabilized zirconia (Y-PSZ), on which the outer race is designed. Ceramic ball bearings' dynamics and failure mechanism are researched. Internal structure parameters of ceramic bearings and the overall structure of ceramic motorized spindle are designed and optimized. It achieves an assembly of a ceramic spindle with high speed and high precision.

Performance test and analysis of developed motorized spindle were accomplished. Experimental result show that the maximum speed achieves 30000r/min, the maximum power achieves 15kW, radial run out of shaft is less than 1μm, in the condition of best lubrication and appropriate preload, radial rigidity of the ceramic spindle system achieves 322N/μm, no-load vibration is less than 0.8mm/s, no-load temperature rise is less than 10 ºC. Ceramic motorized spindle has been applied in NC machine tools successfully. This study can provide the theoretical basis and technical support for design and development of ceramic motorized spindle without inner rings on high speed NC machine tools, promote application and development of high speed ceramic motorized spindle in NC machine tools.

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