Ceramic motorized spindle for NC machine tool

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Abstract. In order to reduce the inertia force and centrifugal force generated when the spindle bearing unit rotates at a high speed and to increase its limit rotation speed, precision, rigidity, service life and reliability, it can meet the high speed and high precision requirements of the spindle system. The innovative design of the ceramic motorized spindle unit, testing and analysis of the comprehensive performance of ceramic motorized spindle and the related research on the intelligentization of the ceramic motorized spindle were carried out. Finally, the current limitations and challenges are discussed, and the future development trend of the numerically-controlled machine tool ceramic motorized spindle is forecasted.

1. Introduction

With the requirement of high-speed precision manufacturing technology and the development of machine tool technology, motorized spindle technology develops toward high speed, high power, high precision, high stiffness, high reliability and long lifetime. The ordinary motorized spindle has limited rotational speed, stiffness, precision, and relatively short lifetime, which are due to the limitations in bearing, lubrication and cooling technologies. This has also seriously affected the development and application of high-performance NC machine tool. Prof. M Weck in the Laboratory of Machine Tools and Production Engineering (RWTH Aachen University), who plays an international leading role in the research on motorized spindle of high-speed NC machine tool, pointed out: “The static and dynamic properties of spindle system are mainly affected by the spindle's bending strength and the moment of inertia. The flexural deformation of spindle is the main factor influencing the static and dynamic deflection of its front end. The moment of inertia of spindle directly influences the acceleration time of spindle. High-speed high-precision spindle system must meet the requirements of high stiffness and fast acceleration. The application of new structural materials such as engineering ceramics can help solve above problems” [1, 2].

Therefore, high-performance engineering ceramics such as hot isostatically pressed silicon nitride and zirconia toughened ceramic are considered most suitable for manufacturing high-speed high-precision parts like ceramic bearings, spindle and so on since they have excellent properties including low density, high strength, high stiffness, high temperature resistance, wear resistance, being non-magnetic and being insulated [3, 4]. When fabricating motorized spindle of NC machine tool, the use of high-performance structural ceramics aims to reduce the inertia force and centrifugal force generated by spindle-bearing unit during high-speed rotation and improve its extreme speed, precision,
stiffness, lifetime and reliability, thus meeting the high speed and high precision requirements of the spindle system.

2. Innovative design of ceramic motorized spindle unit

2.1. Structural design of ceramic motorized spindle without inner ring

Engineering ceramics have properties of high stiffness and high brittleness, which are completely different from those of steel materials. This causes a series of technical problems for the structural design, manufacturing and control of engineering ceramics. For example, the problems of installation and positioning of full ceramic bearings on the axis of a ceramic rotor have to be solved if the traditional design method for motorized spindle is adopted. However, since ceramic materials have high stiffness, extremely small thermal expansion coefficient, extremely high compressive strength and relatively low tensile strength, it is impossible to ensure the precision assembly of ceramic inner ring and ceramic rotor. In addition, thread needs to be drilled into the rotor axis in order to achieve the axial positioning of ceramic bearings. However, because of the high stiffness and brittleness of ceramic materials, it is hard to ensure the precise machining of threads into the axis of ceramic motor. Moreover, there may exist unpredictable machining cracks, which will affect the strength of the rotor axis. Therefore, in order to solve these problems, an inner ring-free all-ceramic ball bearing was creatively designed as shown in Figure 1 [5, 6].

After many considerations, it was decided to use a Y$_2$O$_3$-partially stabilized ZrO$_2$ (Y-PSZ) ceramic as the main spindle, a hot isostatic pressing silicon nitride (HIPSN) ceramic for the ball, and Y-PSZ and HIPSN for the bearing outer ring, respectively. In order to adapt to the high-speed rotation of the ceramic motorized spindle, an outer race guided cage was adopted which can help improve the lubrication of the outer ring raceway of ceramic bearing. Polyetheretherkerone (PEEK) was used for the ceramic bearing cage. The coefficient of the friction between Si$_3$N$_4$ ceramic and PEEK is only 0.028. Clearly, PEEK is very suitable for the high-speed ceramic ball bearing.

![Figure 1. Optimization design of ceramic motorized spindle.](image)

2.2. Ceramic ball bearing design

The high speed, high-precision bearing technology is one of the key technologies of the high-speed spindle system. For the first time, the design and development of all-ceramic ball bearings without inner rings have been proposed. Because ceramic materials have different properties from metal materials, the structural parameters of the ceramic ball bearing have to be designed and optimized according to the properties of ceramic materials. Moreover, the mechanical analysis, failure mechanism and life prediction of the inner ring-free all-ceramic ball bearings are discussed.

(1) Mechanical analysis of ceramic ball bearings. In general, angular contact ball bearings for high-speed spindles only work properly with axial preload. Preloading not only eliminates the axial clearance of the bearing, but also improves the stiffness of the bearing and the accuracy of the rotation
of the spindle while suppressing the vibration and slippage of the ceramic ball during rotation. By mechanically analyzing the bearing, we can obtain the minimum preload of the bearing that prevents the gyro from slippage by the following formula:

$$ F_a \geq \frac{M_s Z \sin \alpha}{\mu D_b} + 1.9 F_r \tan \alpha, \tag{1} $$

where $J$ is the moment of inertia of ceramic ball, $J = \frac{1}{60} \rho \pi D_b^4$ (kg·m²); $\omega$ is the absolute angular speed of ring (rad/s); $\omega_m$ is the angular speed of revolution (rad/s).

(2) The failure mechanism and life prediction theory of the inner ring type full ceramic ball bearings. The failure modes of the fully ceramic ball bearing are fatigue spalling, wear and fragmentation. And under light-load working condition the fatigue spalling of ceramic materials should be the main failure mode. Micro-pores or impurities on the surface of ceramic raceway are the main reason causing fatigue spalling. Figure 2 shows the scratch marks on the raceway of ZrO₂ ceramic outer ring caused by the sudden fracture of Si₃N₄ ceramic balls. Figure 3 shows a pit caused by contact fatigue spalling on the raceway of ZrO₂ ceramic outer ring.

![Figure 2. Scratches on the raceway of ceramic bearing ring.](image1)

![Figure 3. Fatigue spalling of the inner raceway of ceramic bearing.](image2)

In addition, the failure mode of ceramic ball bearings is mainly manifested as the fatigue failure of the ceramic bearing rings (mainly the bearing outer ring). However, the contact fatigue spalling failure mechanism and life estimation model of all-ceramic ball bearings lacks systematic theoretical basis. In this paper, the life prediction model of ceramic bearings is established by modifying the life prediction model of steel bearings as shown in equation 2:

$$ L_{hn} = \left( \frac{10^6}{60 n} \right)^{\frac{1}{6}} \left( \frac{C}{f_p P} \right)^{\frac{1}{6}} f_R f_m f_T f_u f_E, \tag{2} $$

where: $L_{hn}$ is the life of the ceramic ball bearing when the reliability is (1-h)%; $f_p$ is the load factor; $f_R$, $f_m$, $f_T$, $f_u$, $f_E$ are the lifetime corrections for reliability, material, temperature, clearance, axial deflection, respectively.

(3) Optimization design of the structural parameters of ceramic ball bearing. We considered the failure mechanism and lifespan prediction of ceramic ball bearings to optimize the design parameters of ceramic ball bearings. The failure mode of ceramic ball bearing is mainly shown as the fatigue failure of ceramic bearing rings (mainly the outer ring of bearing). Therefore, this study designed and optimized the internal structural parameters of ceramic ball bearing with the aim to prolong fatigue life.

The ceramic motorized spindle was designed on the basis of 7008C bearing. The main internal structural parameters of the final ceramic ball bearing were determined according to the optimization
design results shown in table 1. The curvature radius coefficients of the inner and outer raceways of the full ceramic ball bearing ($f_i$ and $f_e$) should be smaller than those of steel bearing or even hybrid ceramic ball bearing. This can avoid the case where the contact (Hertz) stress is too high and affects the lifetime of the ceramic bearing.

Table 1. The optimization design results of ceramic ball bearings.

| Bearing type | Size (mm) | Contact angle | $D_b$ (mm) | $Z$ | $D_m$ (mm) | $f_i$ | $f_e$ |
|--------------|-----------|---------------|------------|-----|------------|------|------|
| 7008C        | 40×68×15  | $15^\circ$    | 7.144      | 18  | 54.005     | 0.505| 0.510|

2.3. Tool interface design of ceramic motorized spindle

We have optimized the overall structure of the ceramic spindle, developed a variety of ceramic shaft tip tool interface technology and successfully developed the front threaded hole ceramic shaft and external cone ceramic shaft.

For ceramic motorized spindle with built-in connecting rod, the internal thread in the front end of the shaft requires high precision. However, it is difficult to ensure the precision of the internal thread during the sintering process and precision machining of ceramic motorized spindle. Moreover, the rate of end product is very low. Thus, we proposed an alternative design plan such as in figure 4. Internal thread would not be directly sintered in the front end of shaft. Instead, a steel threaded insert was bonded to corresponding site by using high-strength adhesive. In this way, the manufacturing cost is reduced and the precision of the assembly of connecting rods is ensured. At the same time, the use of a steel threaded insert has a "buffering effect". Specifically, it can avoid the load’s direct action on the ceramic motorized spindle and ceramic bearing under overloading and causes destruction of the whole structure.

![Figure 4. Design of the ceramic motorized spindle with built-in steel thread insert.](image)

2.4. Precision assembly of the ceramic motorized spindle

In order to meet the design requirements including high rotational speed, high rotation precision, high stiffness and little vibration for the ceramic motorized spindle, high-speed dynamic balancing of spindle-bearing rotor system must be performed. In addition, the precision assembly of the main parts of the ceramic motorized spindle system should be also ensured. The spindle torque output is achieved through the interference fit between the ceramic motorized spindle and the motor rotor. Ceramic materials have different characteristics from traditional steel materials, and different ceramic materials have different thermal expansion coefficients.

$$\Delta = \frac{k_c(1-\nu^2)M_t}{\pi \mu E B a} \left( \frac{1+c_e^2}{1-c_e^2} + \frac{1+c_i^2}{1-c_i^2} \right) + \frac{\rho \omega^2 (1+\nu)(3-2\nu)(1-c_e^2, c_i^2) \beta^3}{2 E c_e^2} \quad (3)$$

where $k_c$ is safety factor; $M_t$ is the transmission torque of shaft (N·m); $\omega$ is the angular velocity of motor rotor (rad/s); $\rho$ is the average material density of motor rotor (kg/m$^3$); $B$ is effective contact length of matching surface (m); $\mu$ is the coefficient of friction between matching surfaces.
After calculation, the amount of interference fit between ceramic shaft and motor rotor in the spindle system designed in this research reaches 0.08–0.10 mm. The rotor is loaded into the spindle after the rotor is heated to about 200°C for 6-8 hours. The motor rotor is then subjected to precision turning and grinding so that its outer diameter can meet the design requirement. Subsequently, the weight balance method is used to achieve the dynamic balance of the motor rotor. The precision of dynamic balance can reach G0.4 level. Figure 5 shows the main components of the ceramic motorized spindle and the assembled ceramic motorized spindle prototype.

![Figure 5. Ceramic motorized spindle prototype.](image1)

3. Testing and analysis of the comprehensive performance of the ceramic motorized spindle

Testing and evaluating the comprehensive performance of the ceramic motorized spindle is one of the most important steps in the design and manufacture of high-quality motorized spindles. Because of the high hardness and high brittleness of ceramic materials, evaluating and analyzing the comprehensive performance of the ceramic motorized spindle is particularly important. In this study, a prototype of the ceramic motorized spindle for NC machine tool was successfully fabricated and a platform for testing and evaluating its comprehensive performance was also built. In order to further improve the quality and performance of the ceramic motorized spindle for product upgrading, the ceramic motorized spindle was tested for its load characteristics, temperature rise, vibration, noise, precision, stiffness under different working conditions [7-15].

3.1. Test conditions
The testing object was SJD170SD30 ceramic motorized spindle without an inner ring designed and fabricated in this research. The main specifications of the ceramic motorized spindle tested are listed in table 2. It was tested in laboratory with constant temperature and humidity. The temperature in the laboratory was 20 °C, and the environmental noise was not higher than 35 dB. The platform for testing the comprehensive performance of the ceramic motorized spindle is shown in figure 6.

![Figure 6. Platform for testing the comprehensive performance of the ceramic motorized spindle.](image2)
Table 2. Specifications of the ceramic motorized spindle.

| Rated power (kW) | Rated torque (N·m) | Maximum rotational speed (r/min) | Rated current (A) | Rated voltage (V) | Rated frequency (Hz) |
|------------------|---------------------|----------------------------------|-------------------|-------------------|----------------------|
| 15               | 4.8                 | 30000                            | 34                | 350               | 1000                 |

3.2. Load characteristics test of the ceramic motorized spindle
Figure 7 and figure 8 show the changes of the input power, output power and efficiency of the ceramic motorized spindle as the load increases from 0 to 4.8 N·m at 6000 r/min and 8000 r/min, respectively. It can be seen that the efficiency of the ceramic motorized spindle under full load operation can reach 85.64%, which is quite close to the designed efficiency of ceramic shaft motor.

![Figure 7](image7.png) ![Figure 8](image8.png)

Figure 7. The output power of ceramic motorized spindle at 6000 r/min in loading process.  
Figure 8. The output power of ceramic motorized spindle at 8000 r/min in loading process.

3.3. Temperature rise test of the ceramic motorized spindle
(1) The influence of the lubrication system on the temperature rise of the ceramic motorized spindle.
In this research, an orthogonal experiment was performed to investigate the influence of the main design parameters of the oil/air lubrication system on the temperature rise of spindle bearings. We designed an orthogonal experiment with four factors and three levels as shown in table 3.

Table 3. Factors and levels for temperature rise experiments of ceramic motorized spindle.

| Factors                  | Amount of oil supplied each time A (mL) | Oil supply interval B (min) | Pressure of oil supplied C (MPa) | Viscosity of lubricating oil D (cSt) |
|--------------------------|----------------------------------------|------------------------------|----------------------------------|--------------------------------------|
| Level 1                  | 0.02                                   | 2                            | 0.3                              | 15                                   |
| Level 2                  | 0.04                                   | 5                            | 0.4                              | 32                                   |
| Level 3                  | 0.08                                   | 10                           | 0.5                              | 68                                   |

The results of the temperature rise experiment for the ceramic motorized spindle under different parameter settings of lubrication system are shown in figure 9.
The influences of the four factors of the lubrication system on the temperature rise of the ceramic motorized spindle are shown in figure 10. In order to achieve the minimum temperature rise, experimental results demonstrate that the amount of oil supplied each time by the oil/air lubrication system should be set at 0.02 mL. The oil supply interval of the oil/air lubrication system should be set at 10 min. The pressure of the oil supplied should be set at 0.5 Mpa. The viscosity of the lubricating oil should be 68 cSt for the full ceramic spindle-bearing system.

(2) The influence of the preloading force on the temperature rise of ceramic motorized spindle. As shown in figure 11, we analyzed the temperature rise of the front and rear bearing of the ceramic motorized spindle under optimum lubricating conditions and under preloading forces of 400 N, 600 N and 800 N. Experimental results suggest that the temperatures of the front and rear ceramic bearings increase slowly when the preloading force is 400 N. When the preloading force of ceramic bearings reaches 800 N, the temperatures of the front and rear ceramic bearings increase rapidly. When the rotational speed of spindle reaches 20,000 r/min, the temperature rise of the front bearing exceeds the set highest temperature rise 35 °C. Thus, the preloading force of ceramic bearings should be within 400–600 N so as to ensure the high-speed rotation of the ceramic motorized spindle.
3.4 Vibration and Noise test of the ceramic motorized spindle
The experimental results show that the noise of the ceramic motorized spindle reaches 95 dB at a speed of 30,000rpm, which exceeds the traditional motor spindle noise control. This high-frequency noise generated by a ceramic electric spindle is considered to be related to the material properties. In addition, many factors affect the noise generated by the ceramic spindle. So far, the theories of vibration and noise of spindles and bearings are still not mature. Through high-speed rotation experiments, we discovered and proposed the vibration and noise problems of the ceramic electric spindles. However, we only proposed a simple discussion and analysis. The in-depth analysis and control of high-frequency noise of the ceramic motorized spindle should become the key research topic in the future [17].

4. Intelligence of the ceramic motorized spindle
Intelligent prediction of the temperature rise of the motorized spindle and the intelligent control technology of the spindle bearing preload are studied.

4.1. Intelligent prediction of the temperature rise of the ceramic motorized spindle
The prediction of the temperature field in the interior of the motorized spindle is of great significance to the construction and optimization design of early warning systems for motorized spindles. The combination of the measured temperature of the spindle surface and the finite element model is conducive to the improvement of the prediction accuracy of the whole temperature field in motorized spindles. In other words, the heat transfer coefficient can be optimized based on the measurement data of the surface temperature and then this coefficient can be taken as the boundary condition for the finite element model. Subsequently, the temperature field can be calculated. In order to reduce calculation amount and time, as well as to quickly obtain the heat transfer coefficient, a model for the
intelligent and accurate prediction of the temperature field in motorized spindles can be constructed on
the basis of the optimization of the heat transfer coefficient by a genetic algorithm[16].

Let $f_i$ be the objective function of the optimization problem and $fit$ be the fitness function.

$$f_i = \frac{1}{m} \sum_{i=1}^{m} \sqrt{(T_{ei} - T_{si})}$$  \hspace{1cm} (4)

$$fit = \frac{1}{1 + f_i}$$  \hspace{1cm} (5)

In equations (4) and (5), $m$ is the number of the temperature measuring points, $T_{ei}$ is the steady-state
temperature of motorized spindle monitored in the experiment, and $T_{si}$ is the steady-state temperature
of motorized spindle obtained by finite element simulation. The fitness value was set as $f_{i} \leq 0.67$. When
$f_{i} \leq 0.5$, iteration ended. Then, the optimal heat transfer coefficient and the optimal temperature field of
motorized spindle were output.

As shown in table 4, the initial value of the heat transfer coefficient is input into the finite element
model of the motorized spindle. Then the initial temperature field before the optimization of the heat
transfer coefficient is calculated by simulation. The initial steady-state temperature field obtained by
simulation was extracted. Combined with the steady-state temperature monitored by experiments, a
genetic algorithm was used to optimize the 100-generation iteration to obtain the best heat transfer
coefficient and an accurate temperature field prediction model.

**Table 4.** The initial values of heat transfer coefficients.

| Parameter name | Heat transfer coefficient between motorized spindle and external air $h_1$ (W/m²·°C) | Heat transfer coefficient between rotor and stator $h_2$ (W/m²·°C) | Heat transfer coefficient of shaft end $h_3$ (W/m²·°C) | Heat transfer coefficient between bearing and compressed air $h_4$ (W/m²·°C) | Heat transfer coefficient between stator and cooling water $h_5$ (W/m²·°C) |
|----------------|----------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|
| Initial values | 9.7                                    | 146.81                                 | 121.35                                 | 71.42                                  | 190.12                                 |
| Optimization values | 19.99                                 | 188.42                                 | 188.20                                 | 127.71                                 | 500.29                                 |

The experimentally monitored temperatures at certain points of shell, front bearing, stator, rear
bearing were compared with the simulated steady-state temperatures before and after optimization as
in figure 14. Before optimization, the average error reached 8 °C. After optimization, the average error
decreased to 0.81 °C.

**Figure 14.** The comparison between the experimentally monitored temperatures of various parts of the
motorized spindle and the simulated steady-state temperatures before and after optimization.
4.2. Research on the intelligent control method of preload of the ceramic motorized spindle

A variable preload control platform for a ceramic motorized spindle based on a piezoelectric actuator was designed. The aim is to determine the required preload of the machine tool spindle under different working conditions, and apply pre-tightening force to the bearing through the piezoelectric actuator to meet the full-speed performance requirements of the high-speed machine tool spindle, thereby realizing a highly efficient spindle system. In order to realize the control platform, some related technologies need to be studied. The output force characteristics of the piezoelectric actuator is studied in this article.

(1) As the inner ring-free all-ceramic motorized spindle shown in figure 1 is modified. Eight piezoelectric ceramic actuators are uniformly arranged at the rear end of the motorized spindle to preload the bearings to ensure that each piezoelectric ceramic actuator is evenly applied. Tightening and maintaining of good contact with the bearing outer ring determine its axial position with bolts.

The front and rear bearings are respectively provided with a temperature sensor on the outer ring and a vibration sensor is arranged above the corresponding housing of the bearing to monitor the working state of the main shaft. By adjusting the driving voltage of the piezoelectric ceramic driving power source, the magnitude of the output force is changed and the control of the bearing preload during the working process of the motorized spindle. This device scheme provides the corresponding bearing preload under the premise of different working conditions of the motorized spindle, and can also compensate for the thermal expansion of the spindle. The final design of the preload control device based on piezoelectric ceramics is shown in figure 15.

![Variable preload control platform structure of the ceramic motorized spindle.](image1.jpg)

(2) Research on the force output characteristics of piezoelectric ceramic driver. A device for testing the output characteristics of piezoelectric actuators based on 9257B plane dynamometer and HVA-150.A1 piezoelectric actuator driving power was designed. The force output characteristics of PSt 150/4/7 VS9 piezoelectric actuators at different initial loads and voltage frequencies were analyzed by test. The test device is shown in figure 16.

![Test device of piezoelectric actuators.](image2.jpg)

The piezoelectric actuator was tested at different initial voltages of 150 N and the driving voltage of 0-150 V. The test result is shown in figure 17. We can see that the maximum output force of the piezoelectric actuator is maximum at 150N initial preload.
(3) Modeling and prediction of hysteresis main ring of piezoelectric actuator. In this paper, we model and analyze the hysteresis at 150N initial pressure and 1Hz driving frequency. The first 4 working cycles are used as a training set to predict the output power of the 5th duty cycle. The input layer voltage is determined using the principle of the Preisach model, and the BP neural network is used to complete the identification of the density function [18].

As can be seen from figure 18, the prediction results of the model based on the time-series input voltage are linear, and the prediction result based on the input voltage of the Preisach model is close to the expected value. This kind of hysteresis prediction model can better predict the output force of the piezoelectric actuator in different working cycles. The maximum prediction error is 2.9252N, the minimum prediction error is -3.3327N, and the average prediction error is 1.54%. The prediction effect of this model is good and the accuracy of the prediction model can basically meet the control requirements.

5. Conclusion and Outlook

5.1 Conclusion
The innovative design of the ceramic motorized spindle unit including the structural design of the ceramic motorized spindle without inner ring, ceramic ball bearing design, tool interface design of ceramic motorized spindle and the precision assembly of the ceramic motorized spindle have been studied. What is more, testing and analysis of the comprehensive performance of the ceramic
motorized spindle including load characteristics test of temperature rise test and vibration and noise test have been done. In addition, intelligence of the ceramic motorized spindle including the intelligent prediction of the temperature rise and intelligent control method of preload of ceramic motorized spindle have been studied. A variable preload control platform for a ceramic motorized spindle based on a piezoelectric actuator has been designed and a model for predicting the hysteresis main ring of piezoelectric actuator has been built.

5.2. Outlook
(1) In the innovative design of ceramic electric spindle unit, the failure mechanism and life of all ceramic ball bearings are worthy of further study and discussion. (2) In testing and analysis of the comprehensive performance of the ceramic motorized spindle, due to the large number of factors affecting the noise of ceramic motorized spindles, the theories regarding spindle and bearing vibration and noise are recognized as immature. The in-depth analysis and control of the high-frequency noise of ceramic motorized spindles will be worth focusing on in the future. (3) In intelligence of the ceramic motorized spindle, one of the future trends is likely to move toward prognostics-centered control and maintenance [19]: Techniques that support condition-based control and maintenance can be divided into two main categories: diagnostics and prognostics [20]. Diagnostics, as a posterior event analysis, deals with fault detection, isolation and identification when an abnormality occurs. Prognostics, as a prior event analysis, deals with fault and degradation prediction before they occur. Prognostics-centered control and maintenance is much more efficient than the diagnostics-based strategy in achieving zero-downtime performance of intelligent spindles.

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