Ceramic Motorized Spindle

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Preface

High accuracy and high efficiency are two eternal themes of manufacturing technology. With the rapid development of high-tech manufacturing industry, especially the growing requirements of defense industry and cutting-edge technology, modern machinery industry is making efforts in improving the accuracy and efficiency of cutting and grinding machining. High-efficiency, high-accuracy cutting and grinding technology can solve many problems in the manufacture of mechanical products. It enables to obtain the required machining accuracy and surface quality. This technology has been more and more widely applied in various equipment manufacturing industries, and it also makes the manufacture of high-speed precision machine tool become a strategic industry among the equipment manufacturing industries. High-speed precision spindle unit is one of the main carriers of high-speed cutting and grinding technology. It is used to achieve the precise movement of tool/workpiece and the transfer of energy required for cutting and grinding. Therefore, it has become the core functional part of high-grade machine tools used in sophisticated manufacturing industries including national defense, aviation, aerospace, automobile, shipping, precision machinery, *etc*. The performance of spindle unit determines the precision, stability and application fields of machining system.

Compared with mechanical spindle, motorized spindle has many advantages such as compact structure, light weight, small inertia, and good dynamic characteristics. Besides, it can improve the dynamic balance of machine tool and reduce vibration and noise. Therefore, it has become the main form of spindle system for high-speed precision machine tool. High-performance structural ceramics such as hot isostatically pressed silicon nitride and zirconia toughened ceramic have good properties such as light weight, high abrasion resistance, high-temperature resistance, high elastic modulus, being non-magnetic, being insulated, *etc*. High-performance structural ceramics can be used to fabricate high-speed spindle units and bearings so as to fully utilize their good properties including low density, high-temperature resistance, high abrasion resistance and high strength. Also, the centrifugal force and inertia force of spindle parts during high-speed rotation can be greatly reduced, and the stiffness and rotational accuracy of spindle unit can be improved, thus meeting the high speed and high precision requirements of spindle unit.

Motorized spindle is a key functional part of highly mechatronic CNC machine tool. It directly depends on (a) key technologies such as high-performance engineering ceramics and precision machining, high-speed precision bearing technology, high-speed motor and servo drive technology, oil/air lubrication and cooling technology, precision manufacturing and assembly technology, as well as (b) relevant supporting technologies. Its performance determines, to a large extent, the machining accuracy and production efficiency of the whole machine tool. With the development of high-speed machining technology and the advancement of NC machine tool technology, motorized spindle technology developed toward high speed/ultra-high speed, high power, high torque, high precision, high stiffness, high reliability, long lifetime and precise positioning control.

The goal of this book is to improve the performance of ceramic motorized spindle and apply it in NC machine tool. We systematically analyzed and studied the key technical problems in the design and manufacture of ceramic motorized spindle units. This book summarizes part of the research results of related projects led by the author. These projects were supported by The National Natural Science Foundation of China, National Science and Technology Department, Science and Technology Department of Liaoning Province, *etc*. These projects provide important theoretical basis and technical support for the design and development of ceramic motorized spindle for NC machine tool. In addition, original results are obtained regarding the basic theories and key technologies of motorized spindle, such as the structural design and optimization of ceramic motorized spindle, the design and machining of ceramic parts, the design of spindle motor and drive control. These achievements promote the development and application of ceramic motorized spindle units in NC machine tool.

More than ten researchers participated in the above research projects, and they are from Shenyang Jianzhu University (China), Shanhai Institute of Ceramics, Chinese Academy of Sciences (China), Shanghai Research Institute of Materials (China), Northeastern University (China), Dalian University of Technology (China), Shenyang Machine Tool Group (China), Luoyang Bearing Science & Technology Co., Ltd (China), University of Michigan (USA), *etc*. During the progression of the projects, the author of this book, as senior visiting scholar, conducted collaborative research with researchers in Japan and USA. They include Prof. Katsuo Shoji from Tohoku University (Japan), Prof. S. Malkin and Dr. Changsheng Guo from University of Massachusetts (USA), and Prof. S. Jack Hu from University of Michigan (USA). Herein, the author thanks a lot for the support from these researchers.

About Authors

Wu Yuhou, male, Ph.D., Professor, Doctor Supervisor, Director of the Key Discipline in Liaoning Province, and Director of National-Local Joint Engineering Laboratory of NC Machining Equipment and Technology of High-Grade Stone, Shenyang Jianzhu University, China. His major research interests: Ceramic parts precision machining manufacturing technology, key technology of high-speed spindle system of CNC machine tools, high-grade stone processing equipment and technology. He was granted the special government allowances of the State Council, the first batch of leading talents in Liaoning Province, the "Climate Scholars" in Liaoning Province, the "Liaoning BaiQianWan Talents Project" in Liaoning Province, and a hundred experts from Liaoning Province. He is the deputy chairman of the Machinery Steering Committee of the Ministry of Education, and the executive director of the Production Engineering Branch of the Chinese Mechanical Engineering Society, and a national outstanding scientific and technical worker. He won the second prize of national technology invention, the second prize of national science and technology progress, the Chinese patent gold medal, and the Chinese patent excellence award. He has won more than ten national invention patents, published eight academic works, published more than 100 papers, and was indexed by Web of Science and Ei Compendex for over 80 papers.

Li Songhua, male, Ph.D., Professor, Doctor Supervisor, is currently the director of the Engineering Training Center of Shenyang Jianzhu University. His major research interests: engineering ceramic precision machining technology, high-precision ceramic bearing technology, CNC machine tool spindle system technology. In 2016, he was granted the special government allowances of the State Council. In 2014, he was selected as a national talent project and awarded the honorary title of "Young and Middle-aged Experts with Outstanding Contributions". He was awarded the title of "Top Ten Talents" of the 8th Liaoning Youth Science and Technology Award and was selected in the Liaoning Province Talent Support Program. In 2012, he was a visiting scholar to visit the University of Michigan, in Wu Xianming Advanced Manufacturing Research Center (WuMRC) for one year. He has participated in more than 30 national, provincial, and ministerial-level projects, including the National Science and Technology Support Program, the National Natural Science Foundation of China, the National 863 Plan, the International Science and Technology Cooperation Program, the National Key New Product Plan, and the National Torch Plan. Many research results have won ten national, provincial and ministerial-level scientific and technological awards, of which the "high-speed CNC machine tool ceramic electric spindle unit" won the second prize of National Technological Invention in 2010, and "high-precision hot-pressed silicon nitride ceramic ball bearings" won the 2005 national Second prize for scientific and technological progress. He won 3 national invention patents, four utility model patents and two industry standards. He has published one high-level academic book funded by the National Science and Technology Academic Publications Fund (NFAPST) and more than 60 high-level academic papers.

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Chapter 1 Introduction

High-speed machining technology is a high and new technology, which indicates a revolutionary leap in manufacturing technology. Its successful application has resulted in great social and economic benefits. In fact, it has become a hot research topic globally. High performance numerically controlled (NC) machine tool is a prerequisite for the development and application of high-speed machining technology. NC machine tool, as a modern high-tech “Mother Machine of Working” [1], is an important fundamental equipment for achieving the modernization of advanced manufacturing technology and equipment manufacturing industry. The performance, quality and quantity of NC machine tools owned by a country is an important indicator of the industrial modernization level and the comprehensive strength of this country. NC machine tool mainly involves three high and new technologies: high-speed motorized spindle, numerical control system and feed drive system. Motorized spindle is a key functional part of highly mechatronic NC machine tool. It directly depends on (a) key technologies such as high-speed precision bearing technology, high speed motor and drive technology, oil/air lubrication and cooling technology, precision manufacturing and assembly technology, as well as (b) relevant supporting technologies. Its quality and performance directly influence and determine the technical level and performance of NC machine tool [2–5].

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. 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), which 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” [6,7]. 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 [8–10]. 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.

1.1 The development of motorized spindle technology for NC machine tool

Most materials need to be machined to obtain the required geometric structure and shape. During machining, machine tool spindle plays an important role. Machine tool spindle enables the relative motion of tool and workpiece, thus materials are removed from workpiece and product is obtained. Each type of machining process (such as drilling, turning, milling, grinding, boring, *etc.*) requires a specific feed speed and cutting speed. During basic turning process, the spindle enables the workpiece to rotate and thus provide a cutting speed. Also, the drive system drives the tool and gives it a feed speed so that it can remove materials from workpiece. During drilling and milling process, the spindle provides a cutting speed by rotation of tool. During drilling process, the direction of feed motion is that of the axis of spindle. During milling process, the direction of feed motion is perpendicular to that of the axis of spindle. During grinding process, spindle gives grinding wheel a cutting speed.

1.1.1 Overview of the spindle system of NC machine tool

Machine tool spindle refers to the spindle in machine tool that can drive the rotation of workpiece or tool. It consists of shaft, bearings, transmission parts (gears or pulleys), *etc.* Except for planer and broaching machine which mainly involves linear motion, most machines tools have spindle systems. The stiffness and precision of spindle system are important factors determining the machining efficiency and quality.

The typical components of NC machine tool spindle system include tool interface, rod, shaft, bearings, motor and drive system, cooling system, box, *etc.* Figure 1.1 shows the main components of a spindle with built-in motor.

Generally, according to drive type, spindle can be classified into four types: belt drive, gear drive, direct drive and built-in motor drive [11].

(1) Belt-driven spindle

V-type belt is used for power transmission between external motor and spindle. Because of the low cost and high performance of this spindle type, it has been widely applied in conventional machining process. Belt drive allows a medium rotational speed (15,000 r/min) and produces a high torque under low rotational speed. Since motor and spindle are independent, more space is needed, but the installation and maintenance of belt-driven spindle is relatively easy. The efficiency of belt-driven spindle reaches 95%, which is lower than that of motorized spindle (direct drive, about 100%) [12–14].

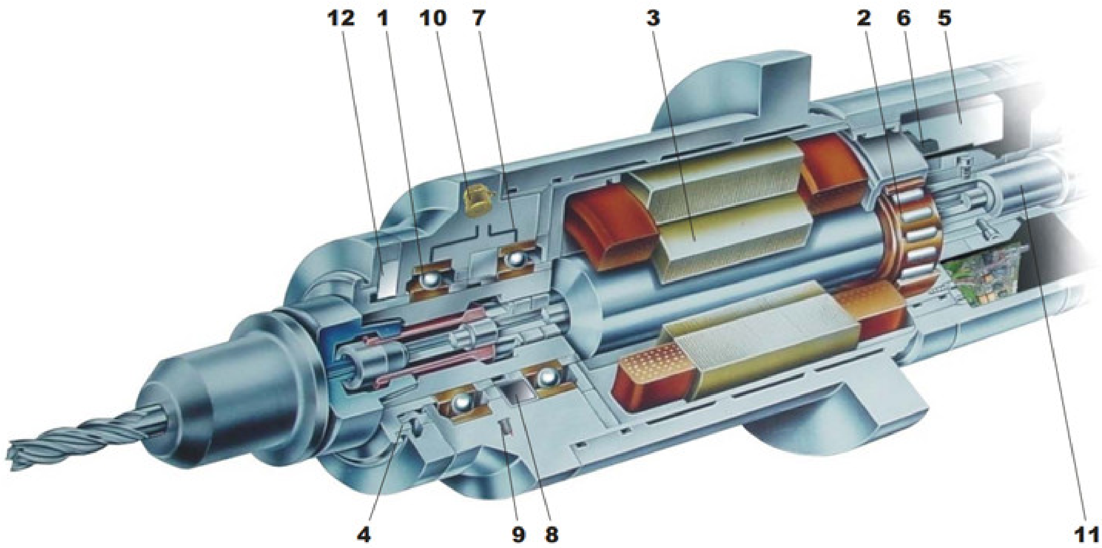

Figure 1.1 NC machine tool spindle system (from Step-Tec GmbH). 1-Ceramics Bearing; 2-Cylindrial Roller Bearing; 3-Stator; 4-Air Seal Ring; 5-Analog Sensor System; 6-Encoder; 7-Oil Mist Lubrication; 8-Bearing Pre-tightening System; 9-Tempearature Monitoring System; 10-Acceleration Sensor; 11-Cooling Unit System; 12-Axial Movement Sensor.

(2) Gear-driven spindle

Gear drive enables high torque under low rotational speed and a wide speed range. However, gear drive can result in vibration, which has bad influence on the surface of products. Moreover, the efficiency of gear-driven spindle is not high because of its structural features and part of energy is transformed into heat [15]. The production of heat is unfavorable. For example, thermal expansion can reduce the machining accuracy. Although gear drive can be used in heavy machining, it is not suitable for high-speed machining [16]. Figure 1.2 shows Haas EC-630 gear-driven spindle with two-speed gearbox (from Haas Automation).

(3) Direct drive spindle

The efficiency of direct drive spindle can reach almost 100%. In addition, direct drive spindle can achieve high-speed rotation under low torque. Since there exist no intermediate drive chains such as belt or gears, the torque of direct drive spindle will not decrease with the decrease of the rotational speed of motor. This drive system enables little vibration, meaning high rotational speed can be reached and at the same time high-quality machining surface can be obtained.

(4) Built-in motor spindle

With the rapid development of motor frequency control, gear drive and belt drive are basically not used any more as the drive system for high-speed NC machine tool. As shown in Figure 1.1, machine tool spindle is driven directly by a built-in motor, which reduces the length of main drive chain and theoretically leads to zero drive power loss. This transmission structure integrating motor into machine tool spindle is called motorized spindle [17–19]. It also has many other names, such as motor spindle, electric spindle, high frequency spindle, *etc*. [20]. This kind of drive system can effectively reduce vibration and noise, as well as enables a rotational speed of 15,000 r/min or even higher. In addition, the whole structure is very compact. These explain why motorized spindle has been widely applied in high-speed machine tools. However, there exist heat generation problem, so cooling system is needed to reduce the heat produced by stator and rotor in the spindle [21]. In order to meet the high speed requirement of motorized spindle, independent lubrication system is also needed for lubricating and cooling the high-speed bearings. In order to achieve high speed and position control, spindle drive control system should be designed. In addition, to ensure the safety, precision and intelligence of high-speed spindle system, supporting technologies and functions such as high-speed automatic balancing, fast automatic tool change, accurate position compensation, motor overload and overheat protection, spindle vibration monitoring, fault diagnosis, *etc*. are integrated into the motorized spindle system.

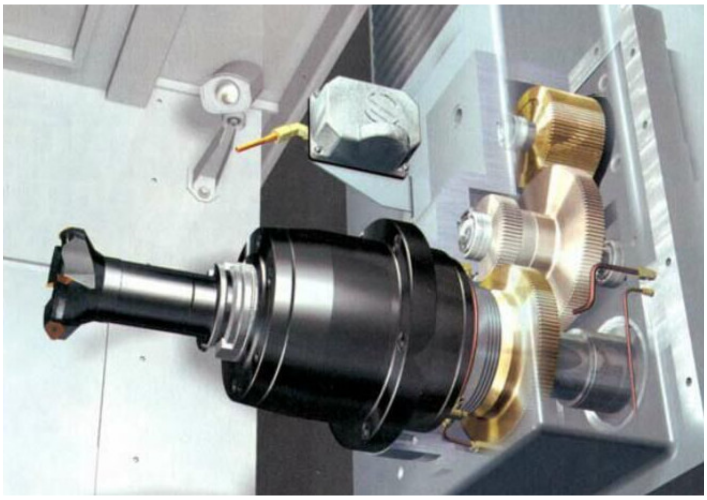

Figure 1.2 Haas EC-630 gear-driven spindle with two-speed gearbox (from Haas Automation).

Therefore, motorized spindle of NC machine tool is an intelligent, highly mechatronic functional part, employing (a) key technologies such as high-speed high-precision ceramic bearings, high-speed motor and drive technology, oil/air lubrication and cooling technology, precision manufacturing and assembly technology, as well as (b) supporting technologies such as built-in pulse coder, automatic tool change, online automatic dynamic balancing, axial positioning and accurate compensation, temperature rise and vibration monitoring, gas sealing of spindle ends, cone purge flow systems, fault monitoring and diagnosis and other security technologies. Motorized spindle is an independent subsystem monitored by the numerical control system of high-speed machine tool [22].

Currently, motorized spindle is mainly used in eight fields: grinding machine, milling machine, turning machine, drilling machine, centrifuge, woodworking machinery, rotating machinery and testing machine [23,24]. According to their application, motorized spindles for NC machine tools can be classified into four types: grinding spindle, milling spindle, turning spindle and drilling spindle. Figure 1.3 shows the classification of motorized spindle for NC machine tool [25].

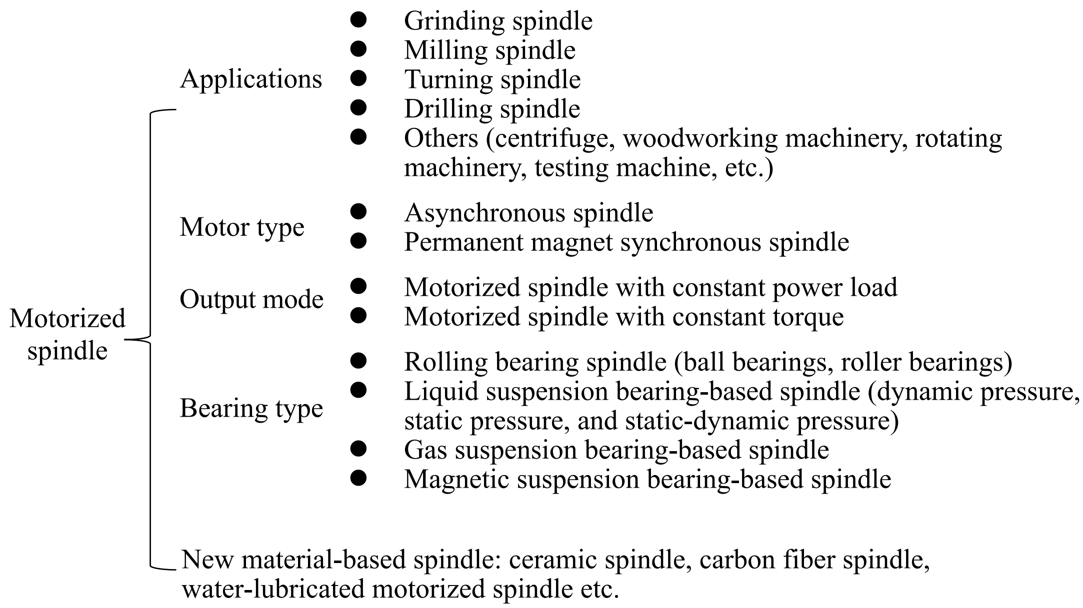

Figure 1.3 Classification of motorized spindle for NC machine tool.

In recent years, due to the advances in materials science and technology, more and more new materials have been used in spindle-bearing system for machine tool. Especially, ceramic motorized spindle is a kind of motorized spindle whose supporting bearings, rotating shaft and other main parts are made of high-performance structural ceramic materials. currently, ceramic motorized spindles that have been extensively studied and applied include hybrid ceramic bearing-based spindle, full-ceramic bearing-based spindle, full-ceramic bearing-based spindle without inner rings, carbon fiber composite spindle, water-based dynamic/static pressure ceramic bearing-based spindle, air dynamic/static pressure ceramic bearing-based spindle, spindle with ceramic sprayed onto bearing raceway, *etc*.

1.1.2 Status and development trend of motorized spindle technology

The research on motorized spindle can date back to the 1950s. Motorized spindle was initially used in internal grinder. In 1976, Vought company (USA) fabricated the first motorized spindle for milling machine, the maximum rotational speed of which reached 20,000 r/min. This spindle adopted built-in motor system (Bryant) and its power could reach 15 KW. In the 1990s, motorized spindle developed toward "40-40"; *i.e.*, rotational speed should reach 40,000 r/min and power should reach 40 kw [26]. Since the 21st century, motorized spindle has been more and more widely used in NC machine tools, and it has currently become an indispensable functional part of modern NC machine tool. Globally, there are more and more leading companies manufacturing motorized spindle: for example, IBAG, STEP-TEC and FISCHER in Switzerland, GMN, SIEMENS, HOFER, CYTEC and KESSLER in Germany, FAEMAT, GAMFIOR and FAMUP in Italy, INGERSOOL and PRECESE in America, FANUC and OKUMA in Japan, and S2M in France [27]. Some companies have experienced fast development of technology and fast growth of business, and their technical level can even represent the most advanced level in the world. In addition, some manufacturers manufacturing host computers for NC machine tool and some large companies manufacturing bearings set up their own spindle production sectors.

Currently, machine tools produced by most of the manufacturers have corresponding motorized spindle system. For example, the maximum rotational speed and power of the motorized spindle for SuperMach high-speed machining center (Cincinnati Company, USA) reach 60,000 r/min and 80 KW, respectively [28]. Table 1.1 shows the application and performance indicators of some motorized spindles for NC machine tools manufactured in some countries. The machining accuracy of these motorized spindles all reach ±1 μm.

Table 1.1 Application and performance indicators of some motorized spindles.

Country	Machine tool type	Bearing type	Rotational speed of motorized spindle (r/min)	Power of motorized spindle (kW)
Germany	SPECHT600 machining center	Ceramic ball bearing	16,000	22
Switzerland	HSM700 machining center	Ceramic ball bearing	42,000	12
Italy	Precision machine tool	Ceramic ball bearing	30,000	17
USA	HTM high-speed machine tool	Ceramic ball bearing	20,000	25

In addition, several professional manufacturers of motorized spindle develop some technologies and launch related products, whose technical level can indicate the most advanced level in the world. For example, FISCHER (Switzerland) produces a type of high-speed motorized spindle with online automatic balancing system. Machining center using this type of motorized spindle can change tools and automatically balance itself within 1 s. Also, it can reduce more than 80% of the vibration caused by the imbalance of spindle after tool change. IBAG (Switzerland) simultaneously launches magnetic suspension bearing-based motorized spindle and static pressure bearing-based motorized spindle. The motorized spindle is equipped with a sensor that can detect size change in the axial direction of spindle, so the axial size of machine tool spindle can be compensated through numerical control system [29]. Motorized spindle with permanent-magnet synchronous motor has been successfully developed, and this can solve the problem of poor heat dissipation of built-in motor.

In China, the research on motorized spindle can date back to the 1950s, but the development process was slow and research was mainly focused on internal grinder. In the late 1990s, researchers in China began to study motorized spindles that can be used in other fields and the research progress tent to be faster [30]. Especially in recent ten years, investment in motorized spindle research has been increased in China. Currently, the rotational speeds of motorized spindles for machining centers and NC milling machines, over which China has intellectual property rights, can reach 40,000 r/min and the maximum power is higher than 40 kW. The comprehensive precision gradually reaches the international level. In recent years, the achievements made by China in machine tool spindle includes the following aspects:

(1) Established the dynamic design theory of rolling bearing spindle system and developed a quasi-dynamic model-based software for the design and analysis of the dynamic characteristics of motorized spindle. In conventional methods, the stiffness of angular contact ball bearings is considered as a static parameter, on which basis the critical rotational speed of motorized spindle is calculated. In fact, because of the effects of Coriolis acceleration and Gyro moment, the stiffness of bearings changes during high-speed rotation of spindle. Luoyang Bearing Research Institute (Luoyang, China) systematically studied angular contact ball bearing and developed a software for analyzing the dynamic characteristics of spindle-bearing system. According to the dynamic and static characteristics, bearings can then be designed, manufactured and selected for use. In fact, this software has been successfully applied in engineering design practice. Hunan University (Changsha, China) developed quasi-dynamic model for angular contact ball bearing and spindle shaft model based on Timoshenko beam model. These models can be used to analyze heat transfer among spindle, motor, bearing and cooling system under different loads [31–33]. Southeast University (Nanjing, China) developed a coupled dynamic model for double-rotor motorized spindle with rod and a coupled dynamic model for whole machine with shell and rod. The loading theory and method was investigated. The thermal characteristics of motorized spindle were studied and a model analyzing the stiffness and thermal resistance of the combination region of spindle-bearing was proposed [34].

(2) Established the electromechanical coupling dynamics of motorized spindle system and revealed the influence of design parameters and coupling factors on the performance indicators of motorized spindle. Based on the conventional mechanical model of rigid rotor, Hunan University (Changsha, China) studied the influence of inverter operating

parameters, established the electromechanical coupling dynamics of "spindle-inverter-grinding wheel-load" system, and proposed to inhibit electromechanical coupling vibration by optimizing inverter operating parameters [31]. Chongqing University, Beijing Institute of Technology and other institutes tested and evaluated the comprehensive performance of high-speed motorized spindle, explored the electromechanical coupling modeling and dynamic analysis methods, built a simulation and virtual experiment system for motorized spindle, and revealed the electromechanical coupling mechanism of motorized spindle [35].

(3) Developed new high-tech motorized spindle products such as water-lubricated motorized spindle, full-ceramic ball bearing-based motorized spindle, high-speed liquid dynamic/static pressure bearing-based spindle, ultra-high-speed air dynamic/static pressure bearing-based spindle and so on, which have also been applied in engineering practice. Tianjin University (Tianjin, China) developed a kind of low-viscosity "green" lubricating fluid based on high-purity water, which can be used for lubricating high-speed sliding bearing spindle and whose viscosity can be adjusted. On this basis, Tianjin University studied the friction performance of the friction pair of engineering ceramic sliding bearing under lubrication of new lubricating fluids, water lubrication and dry friction, respectively [36]. Yuhou Wu *et al.* in Shenyang Jianzhu University (Shenyang, China) patented "Inner ring less heating isostatic pressure silicon nitride full-ceramic ball bearing and its manufacturing method" and "Hot-isostatic pressure silicon nitride all-ceramic electric main shaft and its manufacturing method" [25]. In addition, they successfully developed a series of high-speed high-power ceramic ball bearing-based spindle products and related technologies, with rotational speed of 30,000 r/min and power of 20 kW [37–39]. Shanghai Creator Precision Machine Tool Spindle Company (Shanghai, China) developed a liquid dynamic/static pressure bearing-based motorized spindle, whose maximum rotational speed reaches 5000 r/min and radial runout is 1 μm. Hunan University (Changsha, China) developed a type of permanent-magnet synchronous liquid dynamic/static pressure bearing-based spindle with built-in motor, whose rotational speed and power reach 10,000 r/min and 30 kW, respectively [31]. Beijing Dongfangjingyi Mechanical Equipment Company (Beijing, China) successfully developed the technologies of self-feedback throttling on oil chamber surface and automatic axial positioning, which have already been widely applied in all kinds of high-speed precision grinding machines. Wuxi Machine Tool Plant (Wuxi, China) developed SDQ180 air bearing spindle that can be used in nozzle manufacturing industry. Its rotational speed and power are 180,000 r/min and 90 W, respectively [40]. Guangzhou Institute of Mechanical Science (Guangzhou, China) developed a kind of pneumatic grinding head. It is driven by air turbine. The diameter of rotor is 18 mm, bearing capacity is 178 N, stiffness is 13.8 N/μm, rotational speed is 100,000 r/min, and rotational accuracy is 0.5 μm. Its technical level is close to that in Western developed countries [41]. Luoyang Bearing Research Institute (Luoyang, China) and Beijing University of Aeronautics and Astronautics

worked together to successfully develop a type of ultrahigh-speed high-precision air spindle, whose rotational speed reaches 300,000 r/min. Guangzhou Julian High-speed Spindle Company (Guangzhou, China) developed a high-power high-stiffness air static pressure spindle with multi-support rear-layout structure, the performance of which is close to that of its counterparts in international community.

From the application of motorized spindle in NC machine tools, motorized spindle is supposed to develop towards the following directions [42–51]:

(1) Ultrahigh speed. Because of the requirements of high-speed cutting and practical application, NC machine tool spindle need to develop toward high speed. For example, the maximum rotational speed of the milling spindle produced by CAMFIOR (Italy) reaches 75,000 r/min. The maximum rotational speed of the drilling spindle produced by IBAG (Switzerland) reaches 140,000 r/min. The maximum rotational speed of the carving and milling spindle produced by SEIKO SEIKI (Japan) reaches 260,000 r/min.

(2) Low speed and high torque, as well as high speed and high power. In practical application, NC machine tool should meet the requirements of heavy cutting (low-speed rough machining) and fine cutting (high-speed fine machining). Consequently, motorized spindle for NC machine tool should have low-speed, high-torque performance or high-speed, high-power performance. For example, the output torques of the machining center spindles produced by STEP-TEC (Switzerland) and GMN (Germany) are all above 200 N·m at low speed. The maximum torque of the turning machine spindle produced by CYTEC (Germany) even reaches 800 N·m. In addition, the power of motorized spindle can generally reach 20–50 kW. The rotational speed and power of motorized spindle produced by STEP-TEC (Switzerland) are 42,000 r/min and 65 kW, respectively. The power of motorized spindle produced by IBAG (Switzerland) is as high as 80 kW.

(3) High stiffness and high accuracy. For example, spindle radial runout lower than 1 μm and axial positioning precision lower than 0.5 μm can be achieved by using high-precision bearings (ceramic bearings, dynamic/static pressure bearings, magnetic suspension bearings, *etc*.), advanced lubrication methods (oil/air lubrication), and special preloading method (adjustable, intelligent preloading). The stiffness of motorized spindle system is higher than 300 N/μm, which meets the requirements of high-speed, high-efficiency and high-precision machining.

(4) Long lifetime and high reliability. For example, an acceleration sensor is integrated into the motorized spindle produced by STEP-TEC (Switzerland). It can achieve real-time detection of spindle vibration. The reliability and lifetime of motorized spindle are thus improved. Using ceramic rolling bearings or spraying wear-resistant materials onto bearings can help prolong the lifetime of spindle. In addition, tool interface (IBAG, Switzerland; CYTEC, Germany.) is close to HSK tool interface. Dynamic/static rigid connection, repeated positioning precision and reliability of motorized spindle are improved.

(5) Fast start, fast stop and accurate positioning (accurate stop). For example, the performance of spindle motor is continuously improved. Compared with asynchronous

motor, permanent magnet synchronous motor (FISCHER, Switzerland) with the same power has smaller size but higher power density. The start and stop accelerations of motorized spindle are all above 1 g, and the motorized spindle can start or stop within 1 s, thus auxiliary time is greatly reduced and machining efficiency is greatly improved. In addition, motorized spindle is required to have accurate angular positioning function (accurate stop) in order to meet the requirements of C-axis function, automatic tool change, thread processing and non-cylindrical part machining.

(6) Multifunction and intelligence. For example, motorized spindle produced by GMN (Germany) have functions such as fast automatic tool change, hollow air blowing and automatic balancing during tool change. FANUC (Japan) developed motorized a type of spindle with accurate angular positioning function, which can compensate axial positioning errors and achieve accurate positioning. Motorized spindle also becomes more intelligent, which is reflected by spindle vibration monitoring, fault diagnosis and various security measures. For example, STEP-TEC developed a type of motorized spindle with diagnosis module. All kinds of operation data of this motorized spindle can be read from an infrared interface, so the lifetime of the motorized spindle can be statistically analyzed and faults can be identified.

In addition, new materials such as engineering ceramics and carbon fibers begin to be used for manufacturing the supporting or rotary parts of motorized spindle in order to improve its performance.

1.2 Key technologies of ceramic motorized spindle for NC machine tool and current research status

Ceramic motorized spindle is a highly mechatronic, key functional part of NC machine tool. It directly relies on (a) key technologies such as preparation and precision machining of high-performance structural ceramics, high-speed high-precision ceramic bearings, high-speed motor and drive technology, oil/air lubrication and cooling technology, precision manufacturing and assembly technology, as well as (b) related supporting technologies. In China, the speed, stiffness, accuracy, lifetime and reliability of motorized spindle unit for NC machine tool should be further improved. This is done to meet the high speed, high accuracy requirements of spindle system and the "high speed, high accuracy, high stiffness, high reliability and less vibration" requirements of high-speed machining. In sum, machinery equipment manufacturing industries in China should work hard to catch up with the international leaders in motorized spindle, which is also an urgent task.

1.2.1 High-speed precision ceramic spindle-bearing system

The speed of spindle is often evaluated using $D_{\mathrm{m}} \cdot n$, where D_{m} is the middle diameter of bearing (mm) and n is the rotational speed of spindle (r/min). High-speed spindle refers to spindle with the value of $D_{\mathrm{m}} \cdot n$ higher than 1.0×10^6 [52]. Since the

1980s, the value of $D_m \cdot n$ of spindle system has been increased from 0.5×10^6 to 2.5×10^6 with the development of high speed bearing technology and new lubrication technology. NSK (Japan) developed a type of angular contact ball bearing for high-speed spindle [53]. It uses under-ring lubrication technology and the value of $D_m \cdot n$ even reaches 3.5×10^6.

Currently, high-speed angular contact ball bearing is the main type of rolling bearing used for high-speed spindle. Because high centrifugal force and large gyro moment can be produced by bearing steel balls when spindle is in high-speed rotation, the lifetime and bearing capacity of bearing are greatly reduced. In order to reduce the centrifugal force and gyro moment, hybrid ceramic ball bearing using ceramic balls instead of steel balls has become more widely used for high-speed spindle [54,55]. Hot isostatically pressed silicon nitride (HIPSN) is the most frequently used ceramic material. HIPSN has some excellent properties such as low density, high hardness, high strength, small thermal expansion coefficient, large elastic modulus, *etc*. Using HIPSN for the rolling parts of high-speed spindle bearings can greatly reduce the centrifugal force and gyro moment of rolling parts. As a result, the spindle can have performances such as high rotational speed, small temperature rise and long lifetime.

In the middle 1970s, FAG company (Germany) began to develop ceramic bearing spindle [56]. In 1980s, there was more in-depth research on ceramic bearings, and the research field was also wider. During this period, researchers in USA, Japan, Germany, *etc*. conducted a lot research in this field. Morrison *et al* in USA investigated the lifetime prediction theory for ceramic ball bearings. They pointed out that the lifetime of ceramic ball bearing is an exponential function of load. In 95 percent confidence interval, lifetime index in the lifetime equation ranges from 3.16 to 5.42 and the maximum likelihood estimate of lifetime index is 4.29 [57]. In 1986, Takashi Fujiwara in Japan studied the rated load of ceramic ball bearing. He believed that the rated dynamic/static loads of ceramic ball bearing are higher than those of steel ball bearing, respectively. In addition, he proved by experiments that the service life of ceramic ball bearing is longer than that of steel ball bearing. Ceramic ball bearing failed by fatigue spalling, and before destruction, silicon nitride ceramic ball would not experience plastic deformation. In 1988, Hirotoshi, Aramaki, *et al*. compared the performances of steel and ceramic bearings [58]. They found that the heat produced by ceramic ball bearing is less (by 20%) than that produced by steel ball bearing. In addition, the centrifugal force and gyro moment produced by hot pressed silicon nitride ceramic balls during high-speed rotation are lower and smaller than those produced by steel balls, respectively. Ceramic balls have self-lubrication function, so they can adapt to no-lubrication operation. Since 1990, researchers have begun to study the performance of hot pressed silicon ceramics and the performance of hybrid ceramic bearings, which laid a solid foundation for the analysis and design of ceramic ball bearings [59]. In 1993, Weck *et al* studied the application of ceramic bearing-spindle system in high-speed machine tool [60]. Oil/air lubrication system was used and the value of $D_m \cdot n$ can even reach 1.8×10^6. In 1995, Chiu *et al* conducted fatigue test of hybrid ceramic bearing under high speed and heavy load conditions [61]. The results indicate that the $D_m \cdot n$ value of ceramic bearing reaches 2.5×10^6 and its stress reaches 2.6 MPa. The ceramic bearing is in good condition after operated for 2000 h. Its temperature rise is also smaller than that of steel bearing. In recent decade, hybrid ceramic bearing has been widely used for high-speed machine tool and machining center spindles. The research focus has changed into the integrated design of ceramic bearing-spindle system, high-efficiency, high-precision and low-cost machining and manufacturing of ceramic parts, and other fields.

In addition to hybrid ceramic bearing, some countries begin to use all ceramic ball bearing for high-speed precision spindle and even use all ceramic rotor spindle. In 1989, Namba *et al* in Japan developed a kind of glass-ceramic spindle used for ultra-precision surface finishing [62]. This spindle has zero thermal expansion characteristics, so it can be used for submicron-scale and nano-scale surface finishing of optical and electronic materials. Eguro Machinery (Japan) developed a turning machine made of a new type of ceramics (called Ceracom) [63,64]. It is mainly used for machining electronic industrial products (maximum machining diameter is 80 mm). The spindle and bearing of the turning machine are made of silicon nitride ceramics. In 1995, Jin Yu *et al* analyzed the characteristics of ceramic spindle for the first time [65]. They proposed a dynamic model and optimization method for high-speed precision spindle, with the aim to minimize its weight. In 1999, Baojie Xu *et al* studied the thermodynamic and dynamic characteristics of ceramic spindle [66]. They found that ceramic spindle has properties such as high dynamic/static stiffness, large damping, light weight, small inertia and small thermal expansion coefficient, and its application in machining center would indicate a significant advance in technology. For a wide application of ceramic spindle in machine tool, it is necessary to conduct in-depth theoretical analysis and calculation on the basis of experimental studies. In 2002, Kyung Geun Bang and Dai Gil Lee designed a composite air spindle made of carbon fibers [67]. Compared with conventional steel spindle, this spindle has smaller rotational inertia and higher natural frequency. This helps reduce the bending and thermal deformation of spindle system caused by centrifugal force and temperature rise under limiting rotational speed conditions. In 2003, Weck, Brecher, *et al.* in RWTH Aachen University (Germany) developed creatively multipoint (3P and 4P) angular-contact ceramic bearings for spindle and then sprayed wear-resistant ceramics onto the bearing raceway, which led to further increase in the speed of spindle ($D_m \cdot n$ even reaches 3.5×10^6) [68].

Since 2006, the author of this book and his research team have proposed to use engineering ceramics to manufacture spindle bearing and spindle, *i.e.*, the design of full-ceramic motorized spindle. A kind of full-ceramic spindle without inner ring has been successfully developed for the first time by the author and his research team [69–73]. This means that the performance (precision, stiffness and service life) of high-speed motorized spindle is greatly improved. However, due to the high hardness and brittleness of ceramic materials, high-efficiency and high-precision machining of ceramic spindle parts (shaft, balls, bearing rings, *etc*.) has limited the wide application of ceramic materials in high-speed machine tool spindle and other fields. In addition, since ceramic materials have different properties from metal materials, the structural parameters of full-ceramic ball bearing should be designed and optimized according to the properties of ceramic materials. On this basis, in-depth research should be conducted on full-ceramic ball bearings in terms of fundamental theories such as design theory, failure mechanism and lifetime prediction.

1.2.2 High-efficiency precision machining of ceramic materials

High-performance structural ceramic materials have many advantages such as low density, relatively large elastic modulus, high-temperature resistance, corrosion resistance and high stiffness, so they have become key materials for cutting-edge technology. Currently, ceramic materials have been more and more widely used in mechanics, electronics, national defense, chemical engineering, aerospace, biological engineering and other fields. Especially, some high-performance structural ceramics such as silicon nitride, zirconium oxide and silicon carbide have excellent properties including low density, light weight, high strength at high temperature, wear resistance and corrosion resistance. These structural ceramics have been actively applied in traditional industrial fields such as machine tool, engine, petrochemical industry, and especially in machinery manufacturing industry. Predictably, there is an irreversible trend of using ceramics instead of metals for key parts of mechanical equipment.

However, ceramic materials are typical hard and brittle materials. Meanwhile, ceramic materials are sensitive to defects, and even extremely tiny surface scars (scratches or crevices) or inner defects (gas hole, microcracks or inclusions) can lead to sudden destruction. This is the greatest weakness of ceramic materials. Although the advanced ceramic molding and sintering technologies enable to improve the precision of ceramic products, ceramic materials need to be machined when they are used as structural materials for mechanical structure so that the size and shape accuracy of sintered products and the completeness of machining surface can be improved. Since ceramic materials and metal materials have significantly different physical and mechanical properties (especially tenacity and strength), their removal mechanisms are also different. In fact, the machinability of ceramic materials is poor. Therefore, they can be hardly machined using the ordinary machining method and technology. The machining of ceramic products with complicated shape and high precision is especially difficult. “Poor machinability, great machining difficulty, low machining efficiency and high machining cost” has limited the wide application of ceramic materials in China. In fields such as high-precision ceramic bearings, ceramic engine parts, silicon wafers, semiconductor, flat panel display substrate, *etc*., China is largely dependent on imported products. Consequently, the theory and technology of precision machining of ceramic materials remains a hot research topic in international community.

In the early 1980s, Lawn *et al*. studied the removal mechanism of ceramic materials using blunt indenter, sharp indenter and contact sliding [74]. Their results indicate that the ceramic materials are removed by crack propagation and brittle fracture behavior. In 1987, Inasaki *et al*. pointed out that the removal of ceramic materials is largely dependent on their density and defects existing in them [75]. In 1988, Bifano *et al* proposed a new technology for ductile-regime grinding of brittle materials [76]. They described the relationship between feed rate and the properties of materials during ductile-regime grinding of brittle materials and provide a method for calculating critical grinding depth. In 1991, Dow *et al* systematically studied the technology of ductile-regime grinding of ceramic materials [77]. They pointed out that all brittle materials are removed by plastic removal instead of brittle fracture mode when the grinding depth is small enough. This kind of removal mechanism enables high-quality machining surface, but its efficiency is low and the cost is high. In 1996, Malkin *et al* studied the mechanism of high-speed and ultrahigh-speed grinding of ceramics [78]. They found that the machining surface of ceramic materials exhibits less brittle fracture but more plastic flow behaviors during high-speed and ultrahigh-speed grinding. After further analysis, they thought that this should be related to the glassy phase formed at relatively high grinding temperature. In 1997, Subramanian *et al* verified the brittle removal mechanism of ceramic materials [79]. In 1999, Warnecke *et al* believed that the removal mechanism of hard and brittle materials such as ceramics is determined by the interaction among the material properties, abrasive, the speed of grinding wheel and the speed of workpiece [80]. Since 2000, there have been more and more new results on machining theory. For example, the focus of research on the grinding mechanism of ceramics has changed from indentation fracture mechanics to continuous damage mechanics and quantitative evaluation of machinability [81–85]. Also, the research focus has changed from simple crack propagation to brittle-plastic transition, plastic-regime grinding, molecular dynamics simulation of nanoscale machining, *etc*. [86–92]. The development of machining technology is rapid. In recent years, there have occurred many high-quality, high-efficiency, low-cost machining technologies. Grinding technologies have changed from diamond wheel grinding to mirror grinding, ELID ultra-precision grinding and nanoscale machining [93–95]. There are also changes from traditional cutting and grinding to laser machining, electrical discharge machining, ultrasonic vibration machining, high-pressure abrasive waterjet machining and heat-assisted cutting, as well as a change from single machining operation to composite machining with an integration of sound energy, light energy, electricity and chemical energy [96–100]. Research methods have developed from hypothetical reference, theoretical modeling and qualitative analysis to combination of theoretical analysis and experimental verification, combination of technological test and simulation and combination of multidisciplinary integration and technological innovation.

To date, much research on the machining mechanism and technology of ceramics has been conducted. However, there has not yet been a widely recognized, complete theory that can reveal the removal mechanism and machining process of ceramic materials and guide the high-efficiency, low-cost manufacturing and machining of ceramic materials.

1.2.3 High-speed ceramic spindle motor design and drive technology

High-speed variable frequency motor is the heart of motorized spindle. It is different from constant frequency motor, which is an ideal sinusoidal voltage source. Instead, it uses inverter to supply power, so its electromagnetic design is different from that of ordinary constant frequency motor. Currently, ideal sin wave is assumed in motor design theory, which is different from the situation of power supply by inverter. The non-sinusoidal output of inverter and the influence of modulation parameters should be fully considered in the construction of the design theory for high frequency motor. This can help comprehensively optimize the force and energy characteristics of high frequency motor so that it can achieve high speed and high power.

International research on the design of high-speed variable frequency motor mainly concerns the following aspects: electromagnetic loss mechanism and calculation method, electromagnetic design and motor simulation model.

Aldo Boglietti *et al* studied how the modulation waveform and carrier frequency of PWM inverter affected the iron loss of motor [101]. They found that modulation waveform and carrier frequency have insignificant influence on the iron loss of motor. However, the iron loss of motor can be significantly reduced by increasing amplitude ratio. On this basis, they proposed to calculate iron loss by a parameter estimation method, which improved the efficiency of calculating the iron loss of variable frequency motor. Larsson *et al* investigated the electromagnetic design of high-speed asynchronous spindle motor [102]. They thought that the output frequency of inverter has little influence on the inductance and magnetizing inductance of the stator and rotor of spindle motor. As the output frequency of inverter increases, the resistance of stator and rotor experience fluctuation for a while, then increase gradually and finally reach a stable level. Johansson *et al* studied the electromagnetic design of two high-speed asynchronous motors with different number of poles and analyzed the influence of motor pole number, modulation mode and inverter supply frequency on stator current. They found that a smaller number of poles is conducive to reducing the harmonic component of stator current and achieving high speed. Also, they thought that square wave modulation should be the optimum modulation mode. Above-mentioned research provides basic principles and methods for the electromagnetic design of high-speed spindle motor and provides reference for the design of high-performance spindle motor.

Drive control technology is the prerequisite of achieving spindle function. There are three drive control methods for asynchronous spindle motor: scalar control, vector control and direct torque control. Since Prof. Depenbrock in Ruhr-Universität Bochum (Germany) proposed direct torque control (DTC or DSC) based on hexagonal flux trajectory in 1985 [103], there has been more and more research on the direct torque control of alternating current (AC) motor. Specifically, the research is focused on the identification of motor parameters, accurate observation of stator flux linkage, direct torque control of speedless sensor, and torque pulsation in low-speed domain, speed adjustment, *etc*. The research aims to solve theoretically the problem of applying direct torque control in systems with requirements including lower power, small inertia, low speed, and high performance of speed adjustment. Currently, direct torque control has been applied in inverter products and the main drive systems of high-power high-speed electric locomotive, subway and trolleybus. In 1995, ABB Group (Switzerland) applied direct torque control in ACS600 and the torque responsive speed was even lower than 2 ms. Recently, ABB Group launched ACS800 and ACS1000 series based on direct torque control. Many other companies also aim to apply direct torque control in their products. Although direct torque control is simpler and requires no complicated decoupling operation compared with vector control, the application of direct torque control is in its initial stage and there are many problems remain to be solved.

1.2.4 Analysis and optimization of the dynamic characteristics of high-speed ceramic spindle-bearing system

The dynamic characteristics of spindle-bearing system is one of the most important factors affecting the reliable and stable operation of motorized spindle. In order to improve the dynamic characteristics of spindle-bearing system as well as the stability and reliability of motorized spindle during high-speed machining, the dynamic characteristics of spindle-bearing system should be analyzed and its structure should be optimized. There are many methods for analyzing and optimizing the dynamic characteristics of spindle system, such as finite element method, transfer-matrix method, structural analysis, genetic algorithm, neural networks, *etc*. Because of the development of finite element analysis software, finite element method is most frequently used for analyzing the dynamic characteristics of spindle system. It can be used not only in dynamics modeling of spindle-bearing system but also in the optimization and design of its structure. The error between the finite element calculation results and the experimental results in terms of low-order natural vibration mode and natural frequency of spindle system is within 5%, indicating high calculation accuracy.

In recent years, there has been more and more research on the analysis and optimization of the dynamic characteristics of high-speed spindle-bearing system. For example, Cao *et al* built up a spindle system model which includes the centrifugal force of bearing rolling bodies and gyro effect [104]. They also considered the influence of bearing contact angle, the dynamic characteristics of preload spindle, *etc*. Altintas *et al* considered the influence of actual machining operations on the dynamic characteristics of spindle in their spindle system model [105]. Kim *et al* studied the influences of bearing assembly, thermal deformation, working condition, using condition, *etc*. in their spindle system model [106].

Li *et al* built up a dynamic model for mechanical-thermal spindle-bearing system on the basis of the integration of mechanical-dynamic and thermal characteristics [107,108]. Researchers in Hunan University, Chongqing University and Southeast University studied the dynamic analysis methods and the mechanical-electric-hydraulic-thermal-magnetic coupled modelling of high-speed motorized spindle system [109]. They have built a system of simulation and virtual experiments for motorized spindle system, which can be used to reveal the coupling mechanism of NC machine tool and motorized spindle and influencing factors. In above-mentioned research, most factors influencing spindle system haven been considered. However, there has not yet been an agreement on the coupling mechanism among these factors. Especially, more research is needed on the complex nonlinear friction mechanism and closed loop thermoelastic coupling characteristics of spindle-bearing system during high-speed rotation. In terms of the design and optimization of machine tool spindle, expert spindle design system developed by Maeda *et al*. is the most representative [110]. This system can be used to optimize the position of bearing and spindle motor under certain cutting depth. Also, it can be used for optimizing the dynamic characteristics such as natural frequency and vibration of spindle. However, this system is only suitable for specific spindle system with only one kind of tool. In terms of structural improvement of spindle system, most research adopts theoretical modeling methods and then studies the influences of main parameters such as spindle span, bearing type, tool weight, tool overhang length, *etc*. Generally, the research on the improvement of the overall structure of spindle is rare [111,112].

1.2.5 Reliability technology of high-speed ceramic motorized spindle

The reliability of motorized spindle unit is one of the comprehensive indicators of its kinetic performance. This reliability directly affects the working stability and reliability of the whole machine tool. Ceramic materials have many good properties such as light weight, high strength, high temperature resistance, wear resistance, chemical stability, *etc*. However, they also have some disadvantages including high brittleness, low fracture toughness, high elastic modulus, *etc*. Therefore, it is necessary to ensure the reliability and a relatively long lifetime of various parts of motorized spindle made of ceramic materials. Reliability model of spindle unit and reliability engineering are the best choice to improve the reliability of ceramic motorized spindle unit.

In China, the research on the reliability of motorized spindle for NC machine tool is still in an initial stage. Agreement has not yet been reached on the indicators for evaluating the reliability of motorized spindle system. Currently, the reliability of motorized spindle for NC machine tool is mainly evaluated in terms of mean time between failures (MTBF), average repair time, reliable degree, precision duration, failure rate, malfunction rate, average lifetime, *etc*. In 1999, Yang *et al* analyzed the insulation reliability and failure of stator windings of motorized spindle [113]. They developed for the first time a model for the insulation reliability of stator windings. Then they revealed the insulation failure mechanism of motorized spindle using system analysis and proposed corresponding improvement measures. In 2001, Qin *et al* analyzed the reliability of motorized spindle under the influence of multiple factors. After developing a mathematical model for the reliability of motorized spindle, they used it for prediction and concluded that factors influencing the reliability of motorized spindle include the reliability of electronic components and parts, the ways that motorized spindle system is used, environmental conditions, *etc*. In 2004, Yu *et al* also developed a mathematical model to effectively predict the reliability of motorized spindle and proposed some measures to improve the reliability [114]. Wu *et al* proposed to apply fuzzy reliability design in the check of the stiffness of spindle and they used actual cases to explain the process and results of the fuzzy reliability design of spindle [115]. In 2009, Wei *et al* considered the interval uncertainty of structural design parameters of machine tool spindle based on non-probabilistic reliability theory and optimization design methods. They built a non-probabilistic reliability model for machine tool spindle and proposed optimization design methods.

Above-mentioned research is mainly focused on ordinary machine tool spindle or motorized spindle unit. Because of the high brittleness of engineering ceramics, the structural design, manufacture and control of ceramic motorized spindle unit face many technological challenges such as precision machining of various parts of ceramic spindle, cooling of spindle, dynamic balance, drive control and precision assembly, *etc*. All of these have significant influences on the dynamic performance and working reliability of ceramic motorized spindle. In design and manufacturing, these problems need to be solved to ensure the stability and reliability of the high-speed rotation of ceramic motorized spindle.

1.2.6 Precision assembly of high-speed ceramic motorized spindle and comprehensive performance testing technology

The precision assembly of spindle unit consists of the assembly between shaft and front/rear bearings, the assembly between shaft and motor rotor, the assembly between shaft and tool, the assembly between shaft and bearing spacer as well as positioning inference set, the assembly between shaft system and bearing seat, and the assembly between bearing seat and shell. The precision assembly needs to ensure the stiffness and dynamic balance accuracy of the whole motorized spindle, which are two most important indicators. Precision machining and assembly technology are factors determining the performance of motorized spindle. Currently, motorized spindle manufacturers tend to publish the design methods and structures of motorized spindles. However, precision machining and assembly technology, as the core technologies of companies, have been studied extensively and at the same time kept as business secrets.

Testing and evaluating the performance of motorized spindle is the final step and also one of the most important steps of designing and manufacturing high-quality motorized spindle. However, there is still not a systematic, complete technology or regulation for testing and evaluating the comprehensive performance of motorized spindle. Particularly, research on the comprehensive performance of spindle system faces challenges in rotational accuracy testing and error separation, dynamic stiffness testing, micro-displacement and thermal deformation testing, reliability testing, lifetime prediction, *etc*. [116–119]. Therefore, it is important to develop a platform or system for testing and evaluating the comprehensive performance of ceramic motorized spindle for NC machine tool. Also, the load characteristics, temperature rise characteristics, vibration characteristics, stiffness, precision duration and reliability of ceramic motorized spindle should be investigated and analyzed under different working conditions. These are significant for improving the quality and performance of ceramic motorized spindle, upgrading subsequent products and enhancing market competitiveness.

1.3 Contents of this book

Although ceramic spindles have many advantages and great application potential, there are still some theoretical and technological problems due to the special properties of ceramics. These problems mainly concern material preparation, precision machining, nonlinear dynamic characteristics, reliability optimization design, motor design and numerical control. Therefore, further research is needed.

(1) The main parts of ceramic motorized spindle are made of ceramic materials, which are brittle and hard to machine. Their toughness, machinability and machining accuracy should be improved by studying and using basic theories in dynamics, thermology, molecular dynamics, metallography and other fields.

(2) Since the physical properties (thermal conductivity, thermal expansion, density, *etc*.) of ceramic materials are different from those of metal materials, the coupling mechanism of the thermal and dynamic characteristics of ceramic motorized spindle remains unclear. There should be in-depth research on the dynamic performance and reliability of ceramic motorized spindle.

(3) Ceramic materials are used to fabricate the bearings and shaft of motorized spindle motor. Their influences should be investigated from perspectives of motor design and control.

(4) Manufacturing industry is developing towards high intelligence, high efficiency, energy saving and greenness. In terms of intelligent NC machine tool or intelligent functional parts such as spindle unit, related research mainly focuses on the application and perception of various sensors. In fact, current NC machine tools and spindle units still have limited decision-making ability, as well as limited deduction and self-learning abilities. Clearly, these products are far different from the intelligent products in a real sense, indicating a large room for further development.

This book analyzes in depth the research on the technology of NC machine tool spindle and the technology of machining engineering ceramics. Then, this book clarifies the main problems and the direction for the design and manufacture of NC machine tool spindle unit

[120–150]. The significance of further research aimed at solving these problems is stressed. According to above-mentioned goals and problems, this book mainly concerns the following research aspects.

(1) Considering the material properties of ceramics, this book explores the design of ceramic motorized spindle system and investigates the lubrication technology, cooling technology, tool interface technology, high-speed dynamic balance, precision assembly, *etc.*

(2) In order to ensure the stability of the high-speed rotation of ceramic spindle system, this book analyzes the damage mechanism, kinematics and dynamic performance of ceramic ball bearings, and optimizes the internal structural parameters of them. Further, we study the assembly of full ceramic ball bearing without inner ring and the problem of preload optimization.

(3) In order to improve the drive control performance of ceramic motorized spindle, this book optimizes the main design parameters of motor stator and rotor. In addition, relying on direct torque control theory, we design a direct torque control system based on PMAC for ceramic motorized spindle and perform simulation analysis.

(4) This book investigates the manufacturing processes of various spindle parts according to the requirements of these parts for the performance of ceramic materials. The aim is to obtain high-strength, high-toughness and high-density semifinished ZrO_2 ceramic spindle parts as well as semifinished ZrO_2 and Si_3N_4 ceramic bearing rings.

(5) In order to obtain high-accuracy spindle parts, this book studies the machining mechanism of ceramic materials, quality control of machining surface and optimization of processing parameters. By analysis and experiments on the precision machining of ceramic balls, ceramic bearing rings and ceramic spindle, we achieve the high-efficiency, high-precision machining of ceramic spindle parts.

(6) This book tests and evaluates the comprehensive performance of ceramic motorized spindle without inner ring. The experiments include load characteristics testing, temperature rise testing, vibration testing, noise testing, precision and stiffness testing, *etc*. This ceramic motorized spindle is also applied in NC machine tool.

(7) In order to make the NC machine tool motorized spindle intelligent, this book explores in depth the intelligent prediction of temperature rise, intelligent fault diagnosis, intelligent dynamic balance, intelligent adjustment of bearing preload and other intelligent technologie