Fabrication and service of all-ceramic ball bearings for extreme conditions applications

S Li¹, C Wei¹* and Y Wang¹

¹Mechanical Engineering College, Shenyang Jianzhu University, Shenyang 110168, China

*E-mail: panda_way@126.com

Abstract. Hot isostatic pressing silicon nitride material has properties that most metal materials do not have, such as low specific gravity, high strength, high stiffness, wear resistance, corrosion resistance, extreme temperature resistance, electrical insulation, no magnetic permeability, and excellent dimensional stability performance, self-lubricating performance, etc. It is one of the ideal alternative materials for the manufacturing of bearings applied to various extreme conditions. This manuscript focuses on the practical needs of bearings for environmental equipment such as extreme temperature and marine corrosion. These bearings are used to improve the ultimate speed and load capacity of the whole steel bearing design system in ultra-high speed applications (such as machine tool spindle and gas turbine engine); to eliminate corrosion and reduce friction under extreme temperature or corrosion conditions, so as to improve system performance. In this paper, from the preparation of ceramic bearing materials to the ultra-precision machining process of ceramic bearing components, the development status of ceramic bearings in recent years is introduced, and the future development and application prospect of ceramic bearings are prospected.

1. Introduction

Bearing is the key basic component in the field of industrial machinery, known as “joint of equipment” [1]. The quality of bearing performance directly affects and determines the key indicators of high-end equipment, such as accuracy, life, ultimate speed, bearing capacity, temperature resistance, stability, reliability and dynamic performance. With the development of high-end technology, higher requirements are put forward for the limit of equipment, especially the performance of bearings of rotating parts (such as large-scale cryogenic wind tunnel and liquid rocket turbine pump) under extremely complex working conditions is particularly important. With the diversification of the use environment of bearings, the performance requirements of bearings are also improved [2, 3]. At present, some bearing steel can’t meet or fully meet the requirements of the main engine for bearings. Due to the limitation of materials and the lack of high temperature and corrosion resistance, the application limitations of steel bearings in high-speed machine tools are gradually expanded. A series of new strengthening technologies for bearing parts, including ion implantation, enhanced ion-plating, nano-coating, functional gradient coating and laser surface treatment, have not been widely used in bearing research and manufacturing [4, 5]. The first set of ceramic bearings in the world was made by NASA in 1972, major industrial countries in the world are competing to develop a new generation of high-performance ceramic bearings, which have achieved good application results in high-speed, high-temperature, corrosion, insulation, vacuum and other industries [6, 7]. For example, in the spindle unit of high-speed machine tool, the $Dn$ value of ceramic bearing is more than 3 million, in the high-
temperature field, ceramic bearing can still maintain the material stability under the harsh conditions higher than 1273K, it can work stably in some high corrosive media such as strong acid, strong alkali and salt for a long time. Engineering ceramic materials, including silicon nitride (Si$_3$N$_4$), silicon carbide (SiC), zirconia (ZrO$_2$), alumina (Al$_2$O$_3$), etc., have the excellent characteristics of low density, high strength, high hardness, wear resistance, high temperature resistance, corrosion resistance, good self-lubrication, etc. Among them, hot isostatic pressure silicon nitride (HIPSN) is currently considered to be the most suitable for manufacturing high-performance rolling shaft ceramic materials for bearing [8, 9, 10].

2. Service behaviour of bearing in extreme temperature environment

Extreme temperature environment includes ultra-high temperature, ultra-low temperature and wide temperature range environment which alternates between high temperature and low temperature. The long-term stable service of bearing in extreme temperature environment is a new research hotspot with the continuous expansion of bearing application range. When the bearing is operated in the environment of 73K~1273K, new requirements are put forward for bearing materials, lubrication, structural parameters and many other aspects [11].

Low temperature and ultra-low temperature environment generally refers to the service environment of bearings in low temperature fluid medium, including liquid hydrogen, liquid oxygen, liquid nitrogen, etc. For example, the internal core bearing parts of large-scale low-temperature wind tunnel and liquid rocket turbine pump built for large-scale aircraft simulation experiment need to operate in the nitrogen atmosphere of ultra-low temperature and wide temperature range (110K-323K) and normal temperature atmosphere for a long time. In the extreme temperature environment, the complexity of the operation conditions and the high requirements of the service performance of the bearing are far different from the traditional ordinary bearing [12, 13]. The traditional metal bearing cannot work in the ultra-low temperature environment, and the conventional lubricating oil and grease cannot meet the use requirements.

Taking 9Cr18 bearing steel as an example, cold welding occurs between the rolling body and raceway due to the rupture of the metal oxide film, which results in bearing failure. Through the surface modification of bearing materials, such as vapour deposition, ion implantation, plasma spraying and other methods, researchers can obtain a modified layer of bearing rolling surface [14, 15]. Among them, tungsten disulfide (WS$_2$) and molybdenum disulfide (MoS$_2$) are the most important solid anti cold welding lubrication molds in the liquid oxygen environment. They are widely used in the field of low temperature bearing lubrication. The performance comparison is shown in table 1.

| Table 1. Comparison of basic properties of WS$_2$ and MoS$_2$ films. |
|---------------------------------------------------------------|
| **Project** | **WS$_2$** | **MoS$_2$** |
| Colour | Silver grey | Blue silver grey |
| Density (kg.m$^{-3}$) | 7500 | 5060 |
| Melting point (K) | 1523-1533 (decompose) | 1458 (decompose) |
| Thermal stability in air | Friction factor $<$ 0.1(867K) | Friction factor $<$ 0.1(587K), Friction factor = 0.1(867) |
| Operating temperature range (K) | 0~923 | 88~623 |
| Coating thickness ($\mu$m) | 0.5-1 | 0.2-2 |
| Plated material | Iron, steel, aluminum, copper and other alloys, plastics and synthetic solids, etc. |
The ideal solid lubricating film can be obtained by modifying the surface of metal materials, but it is difficult to form a wide range of applications because of its complex manufacturing process and high equipment cost. At present, solid lubricating materials have developed from single micro powder, adhesive film, etc. to composite materials with complex components [16].

Polymer based self-lubricating materials have good wear resistance and are used in the design and manufacture of cage at low temperature. Based on this, the researchers start with the solid lubrication of materials and transfer the film produced by the friction between the polymer material cage and the rolling body to the surface of the rolling body to form the polymer transfer film. Under the condition of ultra-low temperature and lack of oil lubrication, they can keep the basic lubrication behaviour of the bearing, such as PTFE, PEEK, NYLON and other materials [17, 18].

High performance HIPSN all ceramic ball bearing has the excellent performance that traditional material bearing does not have, such as wear resistance, high and low temperature resistance, corrosion resistance, high stiffness, good accuracy retention, long service life, electrical insulation, non-magnetic, light weight, good self-lubricating performance. It has a wide application prospect in aerospace, national defence and military industry, energy and chemical industry, equipment manufacturing and other fields. In particular, for applications requiring service in extreme temperature environment (extremely high temperature, extremely low temperature and extremely wide temperature range), all ceramic ball bearing will become an indispensable core and key basic component [19, 20]. For example, in a large ultra-low temperature wind tunnel, the ambient temperature for bearing operation is below 93K, in a liquid rocket engine turbine pump, the ambient temperature for bearing operation in liquid hydrogen or liquid oxygen and other media is below 20K, as shown in figure 1. All kinds of spacecraft bearings used in space must not only bear the environment of large temperature change of 73K~323K, but also face extreme space environment such as vacuum and electromagnetic radiation. Bearings used in aircraft engines and accessory casings are required to work stably in a wide temperature range of 223K~673K, as shown in figure 2. For bearings used in these fields, first of all, it is required that bearing materials have excellent adaptability to extreme temperature environment, which can realize long-term stable operation in extremely low temperature and high temperature without brittle fracture, softening or extreme wide temperature environment without rapid wear, scratch, adhesion, bite and other phenomena.

![Figure 1. Application of low temperature bearing in liquid rocket turbine pump.](image1)

![Figure 2. Application of high temperature bearing in aero engine.](image2)

The traditional bearing steel, even the new steel processed by strengthening the material properties, has already failed [21, 22, 23]. Secondly, conventional oil lubrication or grease lubrication is difficult to apply, new solid self-lubrication or oil-free lubrication will be the main form, which requires the bearing material to have better self-lubricating performance and wear resistance; in addition, it also requires the accuracy retention and long-term operation reliability of the bearing in extreme temperature environment. Because the thermal deformation coefficient of HIPSN ceramic material is only 1/4~1/5 of that of bearing steel, all ceramic ball bearing shows good thermal shock resistance, stable service
performance and long service life under the working conditions of high temperature, low temperature and large temperature difference. Moreover, the ceramic material has small density, strong bearing capacity, good wear resistance and low failure rate under high-speed environment, so its working life increases greatly. At present, the limit working temperature of all ceramic bearing has been able to exceed 1273K, and the continuous working time can be more than 100h, and it has self-lubricating characteristics, which can still ensure the working accuracy and service life under the condition of lack of oil lubrication. In conclusion, ceramic bearing may be one of the best choice [24, 25).

3. Development and application of ceramic materials in bearing field

Common bearing materials include GCr15, 9Cr18, etc. however, with the requirements for ultra-high and low temperature resistance, corrosion resistance, ultra-high speed, high reliability, etc. in aerospace, marine shipping, military industry and other fields, bearing materials are also developed from traditional metal materials to non-metal materials with better performance. A large number of experimental studies show that the engineering ceramic materials, including silicon nitride (Si3N4), silicon carbide (SiC), zirconia (ZrO2), alumina (Al2O3), etc., have the excellent characteristics of low density, high strength, high hardness, wear resistance, high temperature resistance, corrosion resistance, good self-lubricating as bearing materials. Figure 3 shows the comparison of common performance parameters between Si3N4 ceramic shaft material and common bearing material 9Cr18 [26, 27, 28].

![Figure 3. Comparison of basic parameters of Si3N4 and 9Cr18 bearing materials.](image-url)

The synthesis of silicon nitride (Si3N4) material was first completed by German scientists in 1896 by carbon reduction synthetic method, and it was found that it has the advantages of high hardness, wear resistance, corrosion resistance and low low temperature creep. By the 1950s, silicon nitride has been widely used in the field of high temperature refractories. In the 1960s and 1970s, the application of silicon nitride materials in the field of high temperature has been fully and in-depth studied. Scientists focus on replacing metal materials with silicon nitride materials in higher precision equipment parts in order to achieve better reliability. In this period, ceramic materials began to be applied in the field of bearings. From the 1970s to the 1980s, with the United States, Japan, Germany and other countries as the representatives, research began in the field of hybrid ceramic bearings. In the late 1980s, silicon nitride hybrid ceramic bearings have formed large-scale production and application. Since the 1990s, with the improvement of the requirements of high-end bearings in different fields, and the rapid development of research on extreme working conditions and even intelligent bearings, higher requirements have been put forward for the performance of silicon nitride materials themselves. Through continuous efforts, researchers have carried out in-depth research in the fields of basic unit structure transformation of silicon nitride, toughening mechanism of brittle materials, sintering process and
processing technology [29, 30, 31]. The sintering process of silicon nitride materials is complex, because the internal silicon nitride molecules are easily transformed in different sintering processes. A silicon nitride molecule consists of a silicon nitride molecule with four N atoms of a Si nucleus combined in the form of a covalent bond to form a Si-N4, tetrahedral structure unit. Each silicon nitride molecule consists of three Si-N4 tetrahedrons sharing the same N atom plane to form a Si3N4 continuous and solid network structure, as shown in figure 4 [32].

![Figure 4. Basic structural unit of silicon nitride.](image)

Silicon nitride (Si3N4) has three crystal forms, two crystal forms are common. One is $\alpha$ - Si3N4, acicular crystal, white or gray white, the other is $\beta$ - Si3N4, dark color, dense granular polyhedron or short prism. Both of them are hexagonal. The longer stacking sequence results in higher hardness of $\alpha$ phase than $\beta$ phase. However, compared with $\beta$ phase, $\alpha$ phase is chemically unstable. Therefore, at high temperature of liquid phase, $\alpha$ phase always changes into $\beta$ phase. Therefore, $\beta$ - Si3N4 is the main form used in silicon nitride ceramics [33].

Silicon powder is one of the basic raw materials for the preparation of silicon nitride ceramic materials. The shrinkage of high-quality silicon nitride powder is much smaller than that of ordinary silicon nitride powder, which helps to control the size of precision ceramic parts in the sintering process, and the preparation of high-quality silicon nitride powder has a strict process flow. Reaction sintering silicon nitride process is usually divided into two steps, including silicon powder nitriding and silicon nitride powder densification. Because the reaction temperature of silicon powder nitriding is about 1400°C, close to the melting temperature of silicon powder, the difficulty of silicon powder nitriding is to prevent silicon powder from melting before nitriding. In the nitriding process of silicon powder, in order to avoid the melting of silicon powder, many researchers add different kinds of catalysts to the nitriding reaction to promote the nitriding of silicon powder at low temperature, such as Cr, CA, Cu, Au, Zr and other metal oxides [34].

Silicon nitride materials are easy to crack and break because of its brittleness, so it is difficult to process. As a bearing material, it has limited its further development to a higher precision level. Therefore, in order to improve the processing performance of silicon nitride materials and improve the brittleness defects in the process of processing, through microstructure engineering, from the perspective of improving the toughness of materials, by controlling the growth and transformation of silicon nitride grains, the cracks deflect according to the different shapes and directions of grains, thus forming the mechanism of controlling the direction of cracks.

4. Development status of ceramic bearing technology

Ceramic ball bearing has the excellent performance that traditional material bearing does not have, such as wear resistance, high and low temperature resistance, corrosion resistance, high stiffness, good precision retention, long service life, electrical insulation, non-magnetic conduction, light weight, good self-lubricating performance. It has a wide application prospect in the fields of aerospace, national defense and military industry, energy and chemical industry, equipment manufacturing, etc. Full ceramic ball bearing will become an indispensable core and key basic component in the application field
of service in extreme temperature environment (extremely high temperature, extremely low temperature and extremely wide temperature range). Although ceramic bearing is a kind of basic bearing spare parts, it is also a kind of particularly important mechanical spare parts in the process of mechanical operation. When compare ceramic bearing with bearing steel, it is not difficult to find that the characteristics of ceramic bearing itself provide a considerable role for the development of ceramic bearing, and at the same time promote the ceramic bearing to mature [35, 36].

Ceramic bearing manufacturing process is mainly divided into raw material proportioning, molding and sintering, component processing, assembly testing and other parts, in which component processing involves ultra-precision processing technology of hard and brittle materials, which is the technical difficulty of the whole bearing manufacturing technology, and also the technical bottleneck limiting the development of ceramic bearing to P4 or P2 level. The ultra-precision processing technology of ceramic bearing components includes the processing and manufacturing of the rolling body and inner and outer rings. There is a big gap between the processing method and the processing difficulty. Therefore, the initial ceramic bearing product is a hybrid ceramic bearing, the rolling body is made of silicon nitride, and the inner and outer rings are made of metal, as shown in figure 5.

![Figure 5. Hybrid ceramic ball bearing.](image)

The inner and outer raceways of metal bearings are relatively simple in processing technology compared with silicon nitride materials, with good accuracy retention. With the development of ultra-precision machining technology, researchers design all ceramic bearings. Both the rolling body and the inner and outer ferrules are ceramic materials, and the rolling body is silicon nitride ceramic. The inner and outer ferrules can be made of silicon nitride or zirconia materials, which greatly improves the performance of ceramic bearings, as shown in figure 6 [37, 38].

![Figure 6. All ceramic bearing.](image)
4.1. Manufacturing technology of silicon nitride rolling element
The rolling body of ceramic bearing includes ceramic ball and ceramic roller. The processing and manufacturing of ceramic ball has relatively mature theoretical basis and processing methods in the world. The classification of processing equipment mainly includes single disc grinding equipment and multi disc grinding equipment, among which single disc grinding equipment is the most widely used, mainly including traditional V-shaped grinding method and conical grinding method. Compared with the V-shaped grinding method, the rotation angle of the ceramic ball cannot be changed, the conical grinding method increases the rotation angle, the grinding trajectory can achieve the entire envelope of the whole spherical surface, and the efficiency of the conical grinding is improved by 30%, and the grinding quality is improved by 20% [39, 40].

The machining method of ceramic roller is similar to that of metallic roller, and the centreless grinding method is generally adopted. Ceramic roller itself is hard and brittle material, and it is easy to produce micro cracks, scratches and other uniform defects in the process of processing, so the development of ceramic roller bearing lags behind that of ceramic ball bearing [41, 42].

4.2. Manufacturing technology of silicon nitride ceramic inner and outer rings
Compared with metallic bearing, the manufacturing of ceramic inner and outer rings is very difficult. At present, diamond wheel grinding is the most commonly used and effective processing method for ceramic bearing rings, accounting for 80% of all processing technologies, and its grinding cost accounts for about 90% of the production cost of the whole bearing. The key technologies involved include high-speed and ultra-high-speed grinding technology, clamping technology, diamond grinding wheel arc repair technology, bearing ring ultra-precision machining accuracy guarantee technology, experimental detection technology, etc. Compared with the traditional metallic bearing, the service life of the ceramic bearing is greatly improved, but the ceramic bearing still has a certain service life. In the service process, there are fatigue failures of rolling elements, inner and outer rings, cages, etc., such as surface wear, surface pitting and peeling off [43, 44]. The main reasons for the failure of the surface integrity of the bearing components are the defects of ceramic materials, the residual stress and micro cracks on the surface of the components after ultra-precision machining. The improvement of service life of ceramic bearing is mainly considered from two aspects: material preparation and component processing.

![Surface wear](image1)

![Surface spalling](image2)

**Figure 7.** Fatigue failure of ceramic bearing components.

5. Development trend and Prospect of ceramic bearing
The development of ceramic bearing technology is closely related to the development needs and application fields of the industry. With the international hot research fields such as aerospace, naval industry and so on, the service behaviour of the bearing is constantly put forward higher use needs, which promotes the continuous progress of the bearing industry. The ceramic bearing officially develops...
rapidly under such special needs. The excellent performance of ceramic bearings has become an important basic guarantee for the development of high-end equipment [45].

In the future, in the face of extreme working conditions, the development trend of ceramic bearing technology mainly includes:

Self toughened high strength ceramic materials. In the sintering process of silicon nitride ceramic materials, the high purity and particle size distribution of the powder are selected, and the processes of deoxidization and decarbonization are adopted. Hot isostatic pressing sintering is adopted in the sintering process. The growth trend of silicon nitride grain length diameter ratio is controlled by microstructure engineering, the mechanism of surface crack growth is improved, and the controllability of crack growth is mastered.

Design standard for structural parameters of ceramic bearings. The properties and mechanical properties of ceramic materials are quite different from that of bearing steel. From the perspective of bearing structure design, the current bearing design theory is based on metallic materials. The related key technologies, such as bearing contact theory, thermodynamics theory, tribology theory and dynamic characteristics, need to be accurately analysed and designed in combination with the characteristics of ceramic materials.

Service state and long-term performance prediction of ceramic bearing under extreme working conditions. In view of the service requirements of ceramic bearing under extreme working conditions, the effects of environmental temperature, load and speed on the macro and micro morphology, contact lubrication state and friction and wear state of ceramic bearing components, as well as the law of heat accumulation and transfer inside the bearing are studied. Further develop the model and analysis method that combine the ceramic bearing test and simulation experiment research under real working condition, so as to realize the effective prediction of the long-term performance development or failure performance of ceramic bearing under real working condition.

Bearing testing machine for extreme conditions. For the extreme temperature, wide temperature range of ceramic bearing experimental equipment is the technical guarantee for large-scale application and mass production of ceramic bearings. At present, all kinds of bearing testing machines are designed to test bearing capacity, vibration, noise, temperature rise and service life of bearings under normal temperature and pressure. They cannot provide service parameters of bearings under extreme conditions, so they hinder the application of ceramic bearings in high-end equipment.

6. Conclusion
With the development of high-end equipment, high-performance ceramic bearing has been widely used in aero engine, high-end CNC machine tool spindle, marine military industry and other fields because of its advantages of light weight, wear resistance, high hardness and high performance. In this manuscript, the development status of ceramic bearings is reviewed, especially the excellent performance of high performance engineering ceramics under extreme working conditions. The necessity and feasibility of ceramic bearing used in liquid turbine pump bearing of rocket engine and large wind tunnel bearing in ultra-low temperature environment are mainly introduced. The present situation of ultra-precision machining technology and common bearing failure forms of engineering ceramic bearing components are summarized, and the development direction of ceramic bearing technology in the future is prospected. Compared with metallic bearing, ceramic bearing has excellent performance in dynamic characteristics, temperature rise, speed, life and other service performance, especially its self-lubricating characteristics can ensure the normal service of equipment in extreme temperature environment, and can greatly improve the application field of high-end equipment. At the same time, it can also promote the progress of engineering ceramic materials and bearing design and manufacturing.

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