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The Development and Progress of High-Performance Ceramics in Mechanical Engineering Applications

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Abstract. High-performance ceramics, due to their high hardness, high-temperature resistance, corrosion resistance and low density, have become key materials for high-end mechanical equipment to break through the limits of metals. With the development of technology, high-performance ceramics have been applied in batches in typical mechanical components such as bearings, gears and seals. However, brittle dispersion, high cost and precision processing of complex shapes remain the bottlenecks restricting large-scale production. This article mainly adopts the research method of literature review to explore and summarize the current situation and challenges of the development of high-performance ceramic materials from aspects such as their characteristics, preparation methods, and specific applications. At the same time, it also provides reasonable insights into the future development trend of this material and offers some practical and feasible suggestions. This research shows that the systems, preparation techniques and application fields of high-performance ceramics have developed relatively maturely nowadays, but there is still much room for improvement and development prospects.

Keywords: High-performance ceramics, Mechanical Engineering, Al_2O_3, bearing balls, nanomaterials, development, large-scale

1. Introduction

High-performance new ceramic materials, due to their excellent mechanical properties, thermal stability and corrosion durability, have broad application potential in aerospace, deep-sea exploration, electronic devices and biomaterials fields. As high-end equipment rapidly iterates towards "high power density, extreme working conditions, long service life, and maintenance-free", the performance ceiling of traditional metal materials is increasingly prominent: when the temperature exceeds the tempering point of steel, the load approaches the fatigue limit, and the corrosion rate of the medium rises exponentially, the service life of parts will be rapidly shortened [1].

To highlight the superiority of high-performance ceramic materials, recent reserch shows that the HV of ceramics is approximately 80 to 100 times that of metals and drops slowly at high temperatures. Oxidation wear at 600°C is three orders of magnitude lower than that of metals. Its density is only 40% to 50% of that of metals. Therefore, it has gained the favor of the majority of people.

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However, the brittle dispersion, high cost and complex morphology manufacturing bottlenecks of ceramics still restrict their large-scale engineering application. This paper systematically reviews the research progress of the entire chain of high-performance ceramics for extreme mechanical working conditions, explores the path for the coordinated improvement of brittleness, reliability and economy, and provides data boundaries and decision-making frameworks, further promoting the application scope of this material in high-end equipment.

2. High-performance ceramic material systems for mechanical engineering

Oxide ceramics have become the most widely used ceramic materials due to their characteristics of low raw material cost, mature technology, easy production of large-sized and complex shapes, and high cost performance. Among them, the most typical one is Al_2O_3. And 995 alumina ceramics with an Al_2O_3 content of approximately 99.5% have higher mechanical properties, better chemical stability, electrical insulation, thermal conductivity and other comprehensive properties. Moreover, they have high cost performance and are suitable for relatively high-end application fields. Such as precision semiconductor components, precision wear-resistant mechanical parts, ceramic substrates, high-end structural and functional ceramic materials for new energy equipment, and bio-ceramic joints, etc. The material performance parameters of Al_2O_3 are shown in Table 1.

Table 1. Al_2O_3 some performance parameters

Items	Reference data
Three-point bending strength	≥420 MPa
Vickers hardness	≥16 GPa
Heat conductivity	≥20 W·m–1 ·K –1
Crystal grain size	≤2 μm
The roughness of the surface finishing	≤0.2 μm

The scanning electron microscope image of Al_2O_3 is shown in Figure 1. This indicates that Alumina powders all have the characteristics of small original crystals, high activity and easy sintering, and can achieve dense sintering of ceramic materials with Al_2O_3 content ≥99.5% at low temperature (≤ 1,650 °C) [2,3].

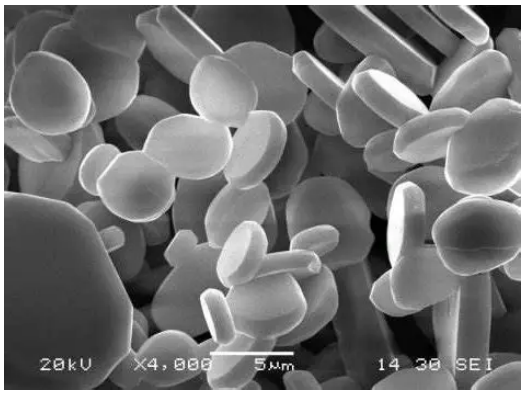

Figure 1. Scanning electron microscope image of Al_2O_3 [4]

Nitride ceramics have great high-temperature strength and strong resistance to corrosion and erosion. Take silicon nitride (Si_3N_4) as an example; it has the highest possibility of attaining the

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high-temperature structural parts. Their rigidity, thermal stability, high-temperature hardness, and resistance toward thermal shock as well as thermal shock and oxidative conditions will contribute to these factors.

Boride ceramics have the highest melting point among the three(>3000°C), with electrical and thermal conductivities close to those of metals, making them the ultimate choice in extreme thermal-force-electrical environments. Orthorhombic Ti_3B_4, hexagonal TiB_2, and orthorhombic Ti-B are the three major compounds used in titanium boride ceramics. Ti-B composites are promising ceramic materials due to the strong Ti-B covalent bonding. In titanium metal matrix composites, Ti-B has been frequently employed for reinforcement [5].

3. Preparation and processing technology

The preparation of high-performance ceramic materials can be divided into three key steps: separate synthesis and modification, forming technology and sintering technology. This article explores the representative technical features of each of these three main projects.

Vapor deposition is an important technology in the powder synthesis stage, which can be either physical or chemical. Physical Vapor Deposition (PVD) refers to a process in which, under vacuum conditions, coating materials are vaporized into atoms, molecules or ions by heating or high-energy beam bombardment, and then deposited on the substrate surface to form a coating through the action of low-pressure gas or plasma. Another one is Chemical Vapor Deposition (CVD). The process of obtaining the desired coating by means of chemical reactions on the surface of heated parts with multiple gases. Due to the flow of the reaction gas, the coating elements can reach any part of the complex parts or cavity parts. Therefore, the most prominent feature of this process is its extremely high surface coating rate.

Dry pressing is a forming method that, under the influence of external force, firmly connects each particle together through internal friction and maintains the corresponding shape. Dry pressing molding has advantages such as simplified processes, easy operation, short production cycles, quick results, and easy realization of automated manufacturing. Moreover, the produced green compact has a high density, accurate dimensions, a small shrinkage area, high machine hardness and good thermoelectric performance. In contrast, another method, hydrostatic pressure forming, has the following advantages: first, it can produce complex-shaped, large or slender products, and the forming quality is relatively high. Second, it has a high forming pressure and a good effect of pressurization. Third, the density of the compact is high and uniform, and it has a small shrinkage after firing, making it less prone to deterioration. Meanwhile, the mold manufacturing is relatively simple, has a long service life and low production costs. Additionally, there is less or no adhesive that can be used [6].

The temperature and pressure of sintering are the key factors affecting the performance of ceramic materials. High temperatures can promote the densification and grain growth of materials, thereby enhancing their mechanical properties. And enhancing pressure promotes the contact and bonding of ceramic particles, increases the density of the material and reduces porosity, thereby optimizing its mechanical properties and durability. However, excessively high temperatures and pressures can affect the strength and structure of materials. Therefore, how to control the sintering environment well has become the key to improving the performance of new ceramic materials. For instance, microwave sintering technology uses electromagnetic fields to achieve uniform temperature distribution, reduce minute internal defects in materials, and further enhance material performance [1].

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4. Application of mechanical components

High-performance ceramics are widely used in the field of mechanical engineering, including in bearings, gears, mechanical sealing rings and bushings, cutting tools and wear-resistant liners, as well as high-temperature molds and fixtures.

In high-speed bearing balls and rollers, Si_3N_4 is widely used in the manufacturing of ball bearings, as shown in Figure 2. The advantages are as follows: Its hardness is significantly higher than that of steel; thus, it has stronger wear resistance and a longer service life. With a lower density, the overall weight of the bearing is reduced, enabling a higher rotational speed. These bearings have stronger corrosion resistance, making them highly suitable for harsh environments exposed to dampness and chemicals. Its smoothness reduces friction, thereby minimizing heat generation and energy loss during use [7].

Figure 2. Picture of Si_3N_4 ceramic bearing [7]

Taking oil drilling as another example, the high-pressure mud pump is a key part of the drilling work platform, among which the cylinder liner is the most important component of the mud pump. It has to withstand working conditions such as high pressure, high wear, strong corrosion and complex temperatures. A comprehensive analysis shows that the Sicer-312 series 995 alumina ceramic material has high comprehensive performance and has achieved good results in practical applications. The Sicer-312 series 995 alumina ceramic cylinder liner achieves an average service life of $\geq$ 3,000 hours. At present, approximately ten thousand products are applied in drilling operation sites around the world [8].

5. Current challenges and future development trends

New ceramic materials face many obstacles and problems in low-cost mass production, and meticulous operation is required in each production link. The production process is quite complex, with very high control standards. Each step needs to be repeatedly checked and adjusted, so the production difficulty keeps increasing [1]. The supply status and quality of raw materials have also become important influencing factors. The acquisition and guarantee of high-purity nanomaterials are both the core and the difficulty. Furthermore, the fracture toughness of metals is still 2 orders of magnitude higher than that of high-performance ceramic materials, which is the main bottleneck for ceramic substitution of steel.

In the future, the rise of high-entropy ceramic materials will become a research hotspot in the field of ceramics due to their excellent physical and chemical properties and single crystal structure. High-entropy ceramics are usually composed of five or more metal cations and possess characteristics such as high strength, high toughness, high-temperature resistance and corrosion resistance. In recent years, research has focused on the development of high-entropy oxides,

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carbides, nitrides and other materials, which have shown great potential in fields such as transparent ceramics, functional ceramics and structural ceramics [9,10].

Nano-ceramics and special production processes: Nano-ceramic materials exhibit outstanding performance due to their ultrafine powder and unique microstructure. Therefore, the preparation technology of nano-ultrafine powders should also be given due attention.

The standardized construction of high-performance ceramic materials is an important way to promote the large-scale production of materials. By formulating unified industry standards, promote the industrialization and large-scale application of high-performance ceramic materials.

In order to break through the bottlenecks of the existing characteristics of ceramic materials, research on ceramic fiber reinforced ceramic or metal composites is also constantly deepening to enhance the toughness and thermal stability of the materials [11].

6. Conclusion

This article reviews, organizes and summarizes the application and development of high-performance ceramic materials in mechanical engineering from five aspects: material system, material preparation, material application, challenges faced and development trends, providing some feasible suggestions for the subsequent development of this field.

However, due to the limitations of the current environment, this article is unable to provide sufficient and powerful experimental data and images for verification. It can only summarize the current development status in the form of a literature review. Most of the references are based on cases from China, while there are relatively few references from other countries, resulting in regional information gaps. Despite some shortcomings, one can still catch a glimpse of the development pattern in the field of high-performance ceramic materials. And this still holds great promise The properties of the material, such as fracture toughness, still need to be optimized urgently. The preparation process of materials needs to become simpler, faster and less costly, so as to adapt to the trend of large-scale material production in The Times. The application of materials should also be expanded by reducing costs and increasing scale, enabling more fields and devices to adopt advanced material technologies, thereby promoting the development of the entire industry.

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