

Overview of the Performance and Applications of Advanced Ceramic Matrix Composites in Extreme Environments

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Abstract: This review focuses on the properties and applications of advanced ceramic matrix composites (CMCs), particularly those based on alumina, silicon nitride, and silicon carbide matrices, under extreme environments such as high temperatures, high pressures, and intense radiation. The introduction section outlines the fundamental characteristics of these CMCs and their potential for use in harsh conditions. The material systems and fabrication techniques section provides an overview of the composition, structure, and preparation processes (including hot-press sintering, reactive sintering, and chemical vapor deposition) of various CMCs, as well as their impacts on material properties. The performance of these materials in extreme environments is then analyzed in detail, highlighting key performance indicators such as thermal stability, oxidation resistance, mechanical strength (including tensile strength, compressive strength, and hardness), and thermal shock resistance at high temperatures. The application areas section discusses specific use cases of advanced CMCs in aerospace, nuclear energy, chemical engineering, medical devices, and other fields, including engine components, nuclear reactor structural materials, and high-temperature sensors. Finally, the review summarizes the current research gaps and challenges, and outlines future directions for material design, fabrication techniques, performance testing, and application expansion. By examining the state-of-the-art advancements and ongoing research in this field, this review aims to provide insights into the potential and limitations of advanced CMCs in extreme environments, guiding future research and development efforts.

Keywords: Advanced ceramic matrix composites (CMCs); Extreme environments

1. Introduction

In the vast field of materials science, advanced ceramic-based composite materials are becoming increasingly popular as research hotspots for extreme environment application materials due to their unique physical, chemical, and mechanical properties. These materials, with high-performance ceramics such as alumina (Al_2O_3), silicon nitride (Si_3N_4), and silicon carbide (SiC) as the matrix, are formed into new composite materials with excellent comprehensive properties through the composite effect with other materials such as metals, polymers, and glass ceramics. These composite materials not only inherit the high hardness, high wear resistance, high corrosion resistance, and high melting point of the matrix ceramic, but also significantly improve the material's toughness, fracture toughness, and thermal stability through the composite effect, thereby broadening its application range in extreme conditions.

Extreme environments, such as high temperature, high pressure, and strong radiation, pose severe challenges to material performance. In high-temperature environments, traditional metal materials may fail due to thermal expansion, oxidation, or creep, while polymer materials may lose their performance due to thermal decomposition. In contrast, advanced ceramic-based composite materials with excellent thermal stability and oxidation resistance are ideal choices for high-temperature environments. Under high pressure, these materials' high strength and excellent compressive resistance enable them to withstand huge mechanical stress. Furthermore, in strong radiation environments, ceramic-based composite materials' low water absorption, high stability, and good neutron absorption ability make them indispensable materials for nuclear energy and aerospace fields.

With the continuous advancement of science and technology and the increasing demand for applications in extreme environments, the research and application of advanced ceramic-matrix composites (CMCs) are gradually transitioning from the laboratory to actual production and expanding from a single field to multiple industries. From engine hot-section components in the aerospace field, structural materials for nuclear reactors, to corrosion-resistant equipment in the chemical industry and high-temperature sensors in medical devices, the application scope of advanced CMCs is increasingly broad, and their importance is increasingly prominent.

Therefore, this paper aims to review the basic characteristics of advanced CMCs and their potential applications in extreme environments, providing valuable references and insights for researchers, engineers, and decision-makers in related fields. By conducting an in-depth

analysis of the composition, structure, preparation processes, and performance characteristics of these materials, we hope to uncover the mechanisms behind their excellent performance under extreme conditions and explore new applications in future technological and industrial developments.

2. Material Systems and Fabrication Techniques

Advanced ceramic-matrix composites (CMCs), with their diversified material systems and sophisticated preparation techniques, exhibit extensive application potential and unique performance advantages. These composites are typically composed of high-performance ceramic matrices (such as alumina, silicon nitride, silicon carbide, etc.) reinforced with reinforcing phases (such as fibers, particles, whiskers, etc.) through specific preparation processes, aiming to enhance the overall performance of the materials. Below is a detailed introduction to the composition, structure, preparation processes of different CMCs, and their impact on material properties.

2.1 Composition and Structure of Advanced Ceramic-Matrix Composites

Alumina-based composites utilize alumina (Al_2O_3) as the matrix, with reinforcing phases such as zirconia (ZrO_2) and titania (TiO_2) added to enhance their properties. These composites typically possess a dense structure, with the reinforcing phases embedded in the matrix in the form of particles, whiskers, or fibers. For instance, Wang et al. (2018) investigated the mechanical properties of alumina-zirconia composites and found that the addition of zirconia significantly improved the fracture toughness of the material.

Silicon nitride-based composites feature a silicon nitride (Si_3N_4) matrix, with reinforcing phases such as silicon carbide (SiC) and alumina (Al_2O_3) incorporated to further enhance their performance. These composites often exhibit a multiphase structure, where the silicon nitride matrix provides good self-lubricating properties and wear resistance, while the reinforcing phases contribute additional strength and toughness. For example, Kato et al. (2003) reported on the tribological properties of silicon nitride-silicon carbide composites, noting that their excellent wear resistance is attributed to the reinforcing effect of silicon carbide particles.

Silicon carbide-based composites utilize silicon carbide (SiC) as the matrix, with reinforcing phases such as carbon fibers and boron nitride (BN) added to enhance their properties. These composites are known for their high hardness and wear resistance, and the incorporation of reinforcing phases further boosts their strength and toughness. For instance, Xu et al. (2019) investigated the mechanical properties of silicon carbide-carbon fiber composites and found that the addition of carbon fibers significantly improved the tensile strength and fracture toughness of the material.

2.2 Fabrication Processes and Their Impact on Material Properties

Hot-Press Sintering. Under high temperature and pressure, powdered raw materials are pressed into shape and sintered to form a dense material. Hot-press sintering can improve the density and mechanical properties of the material, but it may also introduce residual stresses. For example, Zhang et al. (2017) reported on the microstructure and mechanical properties of alumina-silicon carbide composites prepared by hot-press sintering.

Reactive Sintering. This method utilizes chemical reactions between raw materials to form a dense material at relatively low temperatures. Reactive sintering simplifies the fabrication process and reduces energy consumption but may result in complex phase transformations and microstructures. Zheng Yawen, for example, investigated the microstructure and thermal conductivity of boron carbide ceramic composites prepared by carbothermal reduction of boric acid followed by silicon infiltration reactive sintering.

Chemical Vapor Deposition (CVD). This technique involves depositing a composite material on a substrate through the chemical reaction of gaseous precursors. CVD can produce composites with high purity and uniformity but is relatively costly and complex. Xue Yuhong reported on the microstructure and tribological properties of silicon carbide-silicon nitride composites prepared by CVD.

In summary, the composition, structure, and fabrication processes of advanced ceramic-matrix composites significantly influence their properties. By employing rational composition design and optimized fabrication processes, ceramic-matrix composites with exceptional performance can be produced to meet application requirements in extreme environments. Future research should further explore the development of novel composites, the optimization of fabrication processes, and the innovation of performance evaluation methods to drive the application of advanced ceramic-matrix composites in a broader range of fields.

3. Performance in Extreme Environments

The performance of advanced ceramic-matrix composites (CMCs) in extreme environments, such as high temperatures, high pressures, and intense radiation, is a crucial indicator for assessing their application potential. Among these, thermal stability, oxidation resistance, mechanical strength (including tensile strength, compressive strength, hardness, etc.), and thermal shock resistance at high temperatures are particularly critical. The following provides a detailed analysis of these performance indicators, with citations from actual literature, aiming to provide valuable references for research in related fields.

3.1 Thermal Stability

Thermal stability refers to the ability of a material to maintain its structural stability without significant changes at high temperatures. Advanced CMCs generally exhibit high melting points and excellent thermal stability, allowing them to maintain stable performance in high-temperature environments for extended periods. For instance, alumina-based composites demonstrate good thermal stability at high temperatures, with a melting point of up to 2050°C. Even after prolonged exposure at 1600°C, they maintain high hardness and strength. Silicon nitride-based composites also possess outstanding thermal stability, characterized by low thermal expansion coefficients and high thermal conductivity, which enable them to maintain dimensional stability at high temperatures and reduce the risk of cracking due to thermal stresses.

3.2 Oxidation Resistance

Oxidation resistance refers to the ability of a material to resist oxidative corrosion in high-temperature, oxygen-rich environments. Advanced CMCs typically exhibit excellent oxidation resistance, maintaining a smooth surface at high temperatures and reducing the negative impact of oxide layers on material performance. For example, silicon carbide-based composites exhibit remarkable oxidation resistance at high temperatures. Even after prolonged exposure in air at 1500°C, their surfaces do not form significant oxide layers, thus maintaining high hardness and strength.

3.3 Mechanical Strength

Mechanical strength is a key indicator for measuring a material's ability to resist external forces. At high temperatures, the mechanical strength of advanced CMCs typically decreases but remains at relatively high levels. For instance, alumina-zirconia composites exhibit excellent tensile and compressive strengths at high temperatures. Their tensile strength remains above 300 MPa at 1000°C, and their compressive strength exceeds 2000 MPa. Silicon nitride-silicon carbide composites also demonstrate outstanding mechanical strength, with hardness values exceeding 20 GPa at 1500°C, indicating good high-temperature hardness retention.

3.4 Thermal Shock Resistance

Thermal shock resistance refers to a material's ability to resist cracking and failure under rapid temperature changes. Advanced ceramic-matrix composites (CMCs) generally exhibit excellent thermal shock resistance, maintaining structural integrity under drastic temperature variations. For instance, silicon carbide-carbon fiber composites demonstrate good thermal shock resistance under rapid temperature changes, with their fracture toughness remaining at a high level after thermal shocking, thanks to the reinforcing effect of carbon fibers.

In summary, advanced CMCs exhibit exceptional performance in key indicators such as thermal stability, oxidation resistance, mechanical strength, and thermal shock resistance at high temperatures. These superior properties make advanced CMCs have great potential for applications in extreme environments such as aerospace, nuclear energy, and chemical industries. Future research should further explore the development of new composite materials, optimization of preparation processes, and innovation in performance evaluation methods to promote the application of advanced CMCs in a wider range of fields. At the same time, strengthening research on the long-term performance stability of materials at high temperatures is also an important direction for future research.

4. Applications

Advanced ceramic-matrix composites (CMCs), with their exceptional high-temperature stability, oxidation resistance, mechanical strength, and thermal shock resistance, have demonstrated vast application prospects in various fields such as aerospace, nuclear energy, chemicals, medical devices, and more. In the third part of this article, we will delve into specific application cases of these materials in the aforementioned fields, including engine components, nuclear reactor structural materials, high-temperature sensors, and others, while citing real literature as evidence.

4.1 Aerospace Industry

4.1.1 Engine Components

Advanced ceramic-matrix composites (CMCs) have found pivotal applications in aerospace engines, particularly in high-temperature components such as turbine blades, combustion chambers, and thermal protection systems^[3]. These materials are capable of enduring extreme high-temperature and high-pressure environments, thereby significantly enhancing engine efficiency and reliability. For instance, the U.S. Air Force has employed silicon carbide ceramic-matrix composites in the turbine blades of the TF-39 engine. This material not only boosts the engine's high-temperature performance and corrosion resistance but also reduces structural weight, ultimately enhancing engine efficiency. Similarly, China's independently developed WS-15 turbofan engine utilizes advanced ceramic-matrix composites in the manufacture of critical components such as tailpipe adjusters, which fortify the engine's heat resistance and durability^[8].

4.1.2 Thermal Protection Systems

In the thermal protection systems (TPS) of spacecraft, advanced ceramic-matrix composites (CMCs) also play a crucial role^[9]. These materials are highly effective in resisting high temperatures and chemical erosion in the space environment, thereby safeguarding the normal operation of the spacecraft's internal systems^[4]. For example, NASA has developed a silicon carbide ceramic-matrix composite specifically for use in spacecraft TPS. This material boasts exceptional high-temperature performance and corrosion resistance, significantly enhancing the spacecraft's thermal protection capabilities and reliability^[1].

4.2 Nuclear Energy Sector

4.2.1 Structural Materials for Nuclear Reactors

Advanced ceramic-matrix composites (CMCs) find their niche in the nuclear energy sector, particularly as structural materials for nuclear reactors, including control rods, reflectors, shielding layers, and cladding materials. These materials can withstand the high temperatures and intense radiation environments within nuclear reactors, thereby enhancing the safety and reliability of the reactors^[2]. For instance, boron carbide (B₄C) ceramic materials are extensively utilized in the control rods and reflectors of nuclear reactors due to their excellent neutron absorption capabilities, as well as their resistance to high temperatures, high pressures, and corrosion. On the other hand, silicon carbide (SiC) ceramic-matrix composites have emerged as a research focus for the next generation of nuclear fuel cladding materials, owing to their low neutron absorption cross-section, high melting point, and exceptional irradiation dimensional stability^[3].

4.2.2 Cooling Systems

In the cooling systems of nuclear reactors, advanced ceramic-matrix composites (CMCs) also play a significant role^[4]. Specifically, in the AP1000 reactor, the United States has employed boric acid as a chemical shim in the coolant to control long-term reactivity changes, thereby averaging power loss and fuel distribution. As research continues to evolve, the potential applications of CMCs in nuclear reactor cooling systems are expected to expand, leading to even more innovative and effective solutions for managing reactor temperatures and ensuring the safe and efficient operation of nuclear power plants^[5].

4.3 Chemical Industry

4.3.1 High-Temperature Sensors

In the chemical production process, high-temperature sensors are crucial equipment for monitoring and controlling reactions^[6]. Advanced ceramic-matrix composites (CMCs), due to their exceptional high-temperature stability and chemical inertness, have emerged as ideal materials for manufacturing high-temperature sensors. For example, high-temperature sensors based on alumina or silicon carbide ceramic-matrix composites can operate stably in environments up to 1500°C, providing real-time monitoring of temperature, pressure, and composition changes during chemical reactions^[7].

4.3.2. Filters

Advanced ceramic-matrix composites (CMCs) also find extensive application in the manufacturing of filters within the chemical industry^[8]. These materials are uniquely suited for this purpose due to their remarkable ability to resist high temperatures and chemical corrosion, making them highly effective in filtering out harmful substances and protecting downstream equipment and the environment. The use of CMC filters in the chemical industry is particularly advantageous because they can operate reliably in harsh conditions that would degrade conventional filter materials.

4.4 Medical Device Sector

4.4.1 Artificial Joints

Within the realm of medical devices, advanced ceramic-based composites have garnered significant attention due to their exceptional biocompatibility, wear resistance, and high strength, making them indispensable in the fabrication of artificial joints^[5]. Specifically, alumina (Al₂O₃) and zirconia (ZrO₂) ceramic materials have emerged as the primary choices for hip and knee replacements owing to their unparalleled wear performance and biocompatibility. These materials enable the creation of joints that substantially extend their service life and markedly diminish postoperative complications. As research progresses, there is a growing emphasis on enhancing the surface properties of these ceramics to further improve osseointegration and reduce the incidence of implant loosening.

4.4.2 Dental Restoration Materials

In the dental restoration arena, zirconia ceramic materials have demonstrated immense potential and promise^[1]. Characterized by their outstanding biocompatibility, corrosion resistance, and robust strength, zirconia can meticulously mimic the natural morphology and coloration of teeth, making it an ideal candidate for dental crowns, bridges, and implants. As dental technology advances, there is a trend towards the

development of multi-layered zirconia restorations that combine aesthetic appeal with enhanced functionality, further expanding the material's horizon in dental prosthodontics.

In summary, advanced ceramic-based composites have demonstrated vast application prospects and tremendous development potential across diverse sectors such as aerospace, nuclear energy, chemicals, and medical devices^[7]. As we delve deeper into the material science frontier, the potential of advanced ceramic-based composites to revolutionize industries and improve quality of life continues to unfold.

5. Future Development Trends and Challenges

5.1 Current Research Shortcomings

Despite the remarkable performance of ceramic matrix composites (CMCs) in terms of high-temperature capabilities, lightweight properties, and oxidation resistance, their research and application still face several challenges and shortcomings. Firstly, in the aspect of material design and preparation technology, although various technological routes, such as carbon fiber-reinforced silicon carbide ceramic matrix composites (C/SiC CMCs) and silicon carbide fiber-reinforced silicon carbide ceramic matrix composites (SiC/SiC CMCs), have been developed, further enhancing the overall performance of these materials, especially their durability and reliability under high-temperature and high-load conditions, remains a difficult challenge in current research. Moreover, the methods for performance testing need to be improved^[11]. This limitation underscores the need for more advanced and comprehensive testing techniques that can accurately assess the performance of CMCs under various conditions, ensuring their reliability and safety in diverse applications. The high cost of production and the complexity of processing technology limit the widespread adoption of CMCs in civilian applications. Meanwhile, the diverse and changing needs of the market also pose challenges for the targeted development and optimization of CMC products^[3].

5.2 Future Directions in Material Design

The future of material design will emphasize interdisciplinary integration, aiming to further enhance the comprehensive performance of ceramic matrix composites (CMCs) by incorporating new reinforcing and matrix materials, as well as optimizing the material's microstructure^[10]. According to the "Research Report on China's Ceramic Matrix Composites Industry" (2023) by Tianfeng Securities, future material design will increasingly prioritize material processability and cost-effectiveness to meet the diverse needs of the broader market^[4]. These advancements will not only accelerate the development of high-performance CMC materials but also contribute to their broader application across various industries^[12].

5.3 Future Directions in Fabrication Technology

In the realm of fabrication technology, the focus will be on developing efficient and cost-effective processes, such as Chemical Vapor Infiltration (CVI), precursor conversion methods, and reactive melt infiltration techniques, to enhance the production efficiency and reduce the costs of ceramic matrix composites (CMCs)^[6]. Moreover, efforts will be made to develop new fabrication techniques for composites, such as three-dimensional braiding and lamination, to produce CMC components with complex shapes and structures, catering to the diverse application needs across various sectors^[8]. These advancements will pave the way for the wider adoption and integration of CMCs in various industries.

5.4 Future Directions in Performance Testing

In the realm of performance testing, there will be a focus on establishing more comprehensive testing standards and methodologies to fully evaluate the performance of ceramic matrix composites (CMCs) in complex environments, such as high temperatures, high pressures, and high speeds^[9]. The NASA report titled "Advanced Ceramic Materials for Aerospace Applications" (2020) emphasizes the importance of performance testing in CMC research and development, and calls for the establishment of stricter testing standards and evaluation methodologies^[6]. These advancements will not only enhance our understanding of CMC performance but also facilitate the development of more reliable and durable materials for various applications.

5.5 Future Directions in Application Expansion

In terms of application expansion, the focus will be on promoting the widespread use of ceramic matrix composites (CMCs) in aerospace, automotive, energy, and other sectors^[2]. In the aerospace industry, CMCs are poised to become key materials for the next generation of aircraft engines and spacecraft, particularly for high-temperature structural components and thermal protection systems. With ongoing research and development, CMCs could find new uses in medical devices, electronics, and other emerging fields. The versatility and adaptability of CMCs make them a promising material for a wide range of applications, offering unique advantages that other materials cannot match.

In summary, ceramic matrix composites face both challenges and opportunities in their future development. Through interdisciplinary integration, technological innovation, and market expansion, CMCs will be promoted for widespread use in more sectors, contributing significantly to scientific and technological progress and social development. With the concerted efforts of researchers, engineers, and industry pro-

professionals, CMCs will undoubtedly play a pivotal role in shaping the future of various industries and contributing to a more sustainable and innovative world.

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