
**ULTRA HIGH TEMPERATURE CERAMICS FOR HYPERSONIC VEHICLE
APPLICATIONS**

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ABSTRACT

Ultra High Temperature Ceramics (UHTCs) are advanced ceramic materials capable of withstanding extremely high temperatures and severe thermal environments encountered in hypersonic vehicle applications. This project focuses on the development and analysis of Hafnium Diboride (HfB_2) and Zirconium Diboride (ZrB_2) based ceramic composites reinforced with Silicon Carbide (SiC) for thermal protection systems used in hypersonic and reentry vehicles. Conventional thermal protection materials fail under temperatures exceeding 2000°C , whereas UHTCs possess very high melting points above 3200°C , excellent oxidation resistance, high thermal conductivity, and superior mechanical strength. The project investigates the processing, microstructure, thermal properties, oxidation behavior, and mechanical performance of HfB_2 -SiC and ZrB_2 -SiC composites prepared using hot pressing techniques at 2000°C and 5000 psi. Different compositions containing 0% to 20% SiC were fabricated and analyzed using Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), thermal diffusivity testing, and flexural strength measurements. The experimental results showed that the addition of SiC improved densification, oxidation resistance, and thermal stability of the ceramics. The developed UHTCs achieved high fracture toughness values, excellent thermal conductivity, and flexural strengths up to 500 MPa at elevated temperatures. Thermal diffusivity decreased with increasing temperature and porosity, while SiC additions enhanced oxidation protection through borosilicate layer formation. The project successfully demonstrates that HfB_2 -SiC and ZrB_2 -SiC composites are promising materials for advanced aerospace thermal protection systems and hypersonic vehicle applications due to their outstanding thermal and mechanical properties.

KEYWORDS : *Ultra High Temperature Ceramics, Hypersonic Vehicles, Thermal Protection Systems, Hafnium Diboride, Zirconium Diboride, Silicon Carbide, Thermal Conductivity, Oxidation Resistance, Thermal Diffusivity, Mechanical Properties, Hot Pressing, Aerospace Materials.*

I.INTRODUCTION

Hypersonic vehicles operate at extremely high velocities and experience severe aerodynamic heating during atmospheric reentry and hypersonic flight conditions. Conventional thermal protection materials are unable to withstand temperatures exceeding 2000°C , which creates the need for advanced high temperature materials with superior thermal and mechanical properties [1][2]. Ultra High Temperature Ceramics (UHTCs) such as Hafnium Diboride (HfB_2) and Zirconium Diboride (ZrB_2) are considered promising materials for aerospace thermal protection systems because of their extremely high melting points above 3200°C , excellent oxidation resistance, high thermal conductivity, and good mechanical strength [3][4]. This project focuses on the development and analysis of HfB_2 -SiC and ZrB_2 -SiC ceramic composites for hypersonic vehicle applications. Silicon Carbide (SiC) is added to improve densification, thermal stability, and oxidation resistance during high temperature exposure [5]. The project investigates processing methods, microstructural behavior, thermal diffusivity, thermal conductivity, and mechanical performance of these UHTCs under severe operating conditions [6][7].

The processing and characterization of Ultra High Temperature Ceramics play an important role in determining their performance in thermal protection systems used in aerospace vehicles [8]. In this project, HfB_2 -SiC and ZrB_2 -SiC composites are fabricated using hot pressing techniques at high temperature and pressure conditions to achieve nearly full density ceramics [9]. The powders are prepared using ball milling and attritor milling processes before sintering in graphite dies under argon atmosphere [10]. The developed ceramic composites are analyzed using Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), thermal diffusivity testing, and mechanical strength evaluation [11]. Microstructural analysis

helps identify grain growth, porosity, inclusion phases, and grain boundary structures responsible for densification and thermal behavior [12]. The project also investigates oxidation mechanisms and phase stability at elevated temperatures. The addition of SiC forms protective borosilicate layers during oxidation, which significantly improves oxidation resistance and thermal protection capability of the ceramics during hypersonic flight conditions [13][14].

The thermal and mechanical properties of Ultra High Temperature Ceramics are critical for designing reliable thermal protection systems in hypersonic vehicles and reentry spacecraft [15]. This project evaluates thermal diffusivity, thermal conductivity, specific heat, thermal expansion, fracture toughness, and flexural strength of HfB₂-SiC and ZrB₂-SiC composites at temperatures up to 2000°C [16]. Thermal diffusivity measurements are carried out using laser flash analysis methods, while flexural strength and fracture toughness tests determine the mechanical reliability of the developed materials [17]. Experimental results indicate that the addition of SiC improves densification, oxidation resistance, and high temperature stability of the ceramic composites [18]. The developed UHTCs achieved high thermal conductivity and flexural strengths up to 500 MPa under elevated temperature conditions [19]. The project demonstrates that HfB₂-SiC and ZrB₂-SiC based UHTCs are highly suitable for advanced aerospace thermal protection systems because of their excellent thermal resistance, oxidation behavior, and mechanical durability under extreme hypersonic operating environments [20].

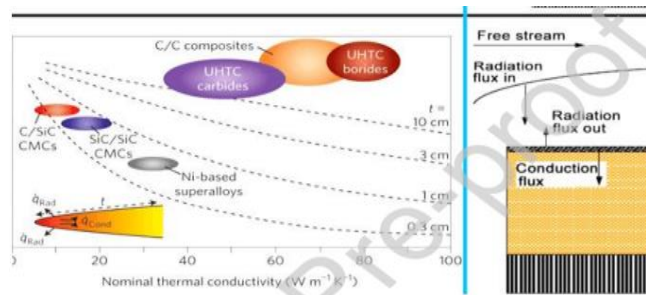


Fig1: Ultrahigh Temperature Ceramic Material Properties

The above figure compares various high temperature materials used for hypersonic vehicle applications based on their thermal conductivity and thermal protection capability. Materials such as Carbon/Carbon composites, Ceramic Matrix Composites (CMCs), Silicon Carbide composites, Nickel-based superalloys, and Ultra High Temperature Ceramics (UHTCs) are represented in the graph. The figure shows that UHTC borides and carbides possess high thermal conductivity and can withstand extremely high temperatures compared to conventional materials, making them highly suitable for aerospace thermal protection systems. The graph also indicates that lower material thickness is required for UHTCs to provide effective thermal protection. The right side of the figure explains the heat transfer mechanism occurring on the surface of a hypersonic vehicle. During hypersonic flight, intense radiation heat enters the material surface, while some heat is radiated outward and the remaining heat transfers through conduction. UHTCs reduce heat penetration and protect internal structures from severe thermal damage during high speed atmospheric reentry conditions.

II SURVEY OF RESEARCH

1. Kaufman and Clougherty conducted one of the earliest detailed studies on Hafnium Diboride (HfB₂) and Zirconium Diboride (ZrB₂) ceramics for high temperature aerospace applications. Their research mainly focused on investigating the thermal, electrical, and mechanical properties of diboride ceramics prepared through hot pressing techniques. The authors reported that both HfB₂ and ZrB₂ possess extremely high melting points above 3000°C and excellent oxidation resistance, making them suitable for thermal protection systems used in hypersonic vehicles. They also observed that the addition of Silicon Carbide (SiC) significantly improved oxidation resistance and high temperature stability of the ceramics. The study measured properties such as thermal expansion, electrical resistivity, and microhardness under elevated temperatures. Their work provided important experimental data related to the phase behavior and thermal stability of UHTCs. This research became a foundation for the development of modern Ultra High Temperature Ceramics for aerospace and hypersonic vehicle applications [1][2].

2. Upadhyya et al. investigated the thermal and oxidation properties of Ultra High Temperature Ceramics for advanced aerospace thermal protection systems. Their study focused on the oxidation behavior of HfB₂ and ZrB₂ ceramics and the effect of high temperature exposure on material performance. The authors reported that oxidation products such as HfO₂ and ZrO₂

formed protective oxide layers that improved resistance against severe thermal environments. However, they also observed that phase transformations occurring in these oxides could generate cracks and structural damage during thermal cycling conditions. To overcome this problem, Silicon Carbide was added to stabilize the oxide layer and improve oxidation resistance. The study also discussed the advantages of high melting temperatures and low vapor pressure characteristics of diboride ceramics. Their experimental results demonstrated that UHTCs possess excellent thermal stability and can survive severe hypersonic flight environments. This work significantly contributed toward the understanding of oxidation mechanisms in thermal protection materials [3][4].

3. Berkowitz-Mattuck carried out detailed research on the oxidation mechanisms of HfB_2 and ZrB_2 ceramics under high temperature conditions. The study analyzed oxidation behavior in the temperature range between 1400°C and 2100°C using controlled oxygen environments. The author reported that oxidation of diboride ceramics generated gaseous products and porous oxide layers that affected thermal protection performance. The research also identified the importance of boric oxide evaporation and diffusion mechanisms during high temperature oxidation. Silicon Carbide additions were found to improve oxidation resistance by forming borosilicate glass layers that reduced oxygen penetration into the material surface. The study measured oxidation kinetics and parabolic rate constants to evaluate material stability under severe aerospace operating conditions. Their work provided important information regarding oxygen diffusion behavior, thermal degradation, and protective oxide formation in UHTCs. The research became an important reference for designing oxidation resistant ceramics for hypersonic vehicles and reentry systems [5][6].

4. Tripp et al. investigated the thermal and oxidation properties of ZrB_2 -SiC ceramic composites for aerospace thermal protection systems. Their research focused on understanding the role of Silicon Carbide additions in improving oxidation resistance and thermal shock performance. Experimental studies showed that the addition of SiC produced protective glassy oxide layers during oxidation, which minimized oxygen diffusion and improved thermal stability at temperatures above 1100°C . The authors also reported that oxidation behavior followed diffusion controlled mechanisms under elevated temperature conditions. The thermal conductivity and thermal diffusivity of the ceramic composites were measured at different temperatures to evaluate their suitability for hypersonic applications. The results indicated that UHTCs retained high thermal conductivity even under severe thermal loading conditions. Their study demonstrated that SiC reinforced ZrB_2 ceramics provide better thermal protection and oxidation resistance compared to pure diboride materials. This research significantly contributed to the development of advanced UHTC composites for aerospace engineering applications [7][8].

5. Zhang et al. studied the reactive hot pressing and microstructural behavior of ZrB_2 -SiC composites used for Ultra High Temperature Ceramic applications. The research mainly focused on powder processing techniques, densification behavior, and microstructural evolution during high temperature sintering. The authors used hot pressing methods to fabricate dense ceramic composites with different percentages of Silicon Carbide additions. Their experimental analysis revealed that SiC improved densification and reduced porosity in the ceramic structure. Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) studies identified grain growth behavior, inclusion phases, and grain boundary structures in the developed composites. The researchers also observed that fine grain microstructures improved thermal conductivity and mechanical strength. Their study demonstrated that proper control of processing conditions and SiC content significantly enhanced the thermal and structural performance of UHTCs. This work provided valuable information regarding fabrication methods and microstructural optimization of aerospace ceramic composites [9][10].

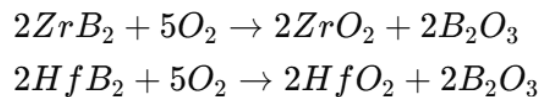
6. Barger et al. performed research on the mechanical and thermal properties of HfB_2 based Ultra High Temperature Ceramics for hypersonic vehicle applications. The study focused on fracture toughness, thermal conductivity, thermal diffusivity, and flexural strength evaluation at elevated temperatures. The authors reported that HfB_2 -SiC composites exhibited fracture toughness values between $5\text{--}6\text{ MPa}\sqrt{\text{m}}$ and flexural strengths around $450\text{--}500\text{ MPa}$ under high temperature conditions. Thermal diffusivity measurements were performed using laser flash analysis methods up to 2000°C . The results showed that thermal diffusivity decreased with increasing temperature and porosity, while fully dense ceramics maintained excellent heat transfer characteristics. The research also explained that grain boundary phases and microstructural impurities influenced high temperature mechanical performance. Their study confirmed that HfB_2 based UHTCs possess outstanding thermal stability, oxidation resistance, and mechanical strength required for thermal protection systems in hypersonic vehicles and aerospace structures [11][12].

III. WORKING METHODOLOGY

The working methodology begins with the identification and selection of suitable ceramic materials capable of withstanding extreme thermal and aerodynamic conditions experienced during hypersonic flight and atmospheric reentry.

Hafnium Diboride (HfB_2) and Zirconium Diboride (ZrB_2) are selected as the primary ceramic materials because they possess melting points above 3200°C , excellent thermal conductivity, superior oxidation resistance, and good mechanical strength [1][2]. Silicon Carbide (SiC) is added as a reinforcement material to improve densification, thermal stability, fracture toughness, and oxidation resistance during high temperature exposure. Initially, high purity powders of HfB_2 , ZrB_2 , and SiC are collected according to the required composition percentages ranging from 0% to 20% SiC additions [3]. The powders are then mixed thoroughly using ball milling and attritor milling processes to achieve uniform particle distribution and reduce particle size. Hexane is used as the milling medium, while zirconia and silicon carbide balls are used as grinding media during milling operations [4]. The prepared powder mixtures are dried and loaded into graphite dies lined with graphite foil to prevent reactions between the die and powder materials during sintering. The ceramic composites are fabricated using hot pressing techniques at 2000°C and 5000 psi under an argon atmosphere. The sintering process is carried out using a controlled heating rate of $20^\circ\text{C}/\text{min}$ followed by one hour holding time at the maximum temperature before furnace cooling. This process produces highly dense ceramic composites with reduced porosity and improved thermal performance suitable for aerospace thermal protection systems [5][6].

The second stage of the methodology focuses on microstructural characterization, phase analysis, and oxidation behavior of the developed Ultra High Temperature Ceramics. After fabrication, the sintered ceramic samples are cut, polished, and prepared for microscopic examination. Scanning Electron Microscopy (SEM) is used to study grain size, porosity, inclusion phases, grain boundaries, and distribution of Silicon Carbide particles within the ceramic matrix [7]. Transmission Electron Microscopy (TEM) and spectral image analysis techniques are employed to identify thin silicate grain boundary phases formed during the sintering process. The microstructural analysis helps determine the relationship between grain growth, densification, and mechanical properties of the composites [8]. Oxidation behavior is analyzed under elevated temperature conditions to evaluate the suitability of UHTCs for hypersonic applications. During oxidation, HfB_2 and ZrB_2 react with oxygen to form protective oxide layers represented by the following reactions:



At elevated temperatures, Silicon Carbide forms borosilicate glass layers that minimize oxygen penetration and improve oxidation resistance. Phase diagrams, oxidation kinetics, and thermal stability are analyzed to understand the effect of temperature and SiC content on ceramic performance [9][10]. The oxidation studies confirm that the addition of SiC significantly enhances thermal protection capability during severe aerospace operating conditions. The final stage of the methodology involves evaluating the thermal and mechanical properties of the developed ceramic composites under extreme temperature conditions. Thermal diffusivity measurements are performed using laser flash analysis methods according to ASTM standards over a temperature range of 250°C to 2000°C [11]. Thermal conductivity is calculated using the relation:

$$\alpha = \frac{k}{\rho C_p}$$

where α represents thermal diffusivity, k is thermal conductivity, ρ is density, and C_p is specific heat. Specific heat measurements are carried out using Differential Scanning Calorimetry (DSC), while thermal expansion tests are conducted using dilatometer equipment [12]. Mechanical properties such as fracture toughness, flexural strength, and thermal shock resistance are evaluated using chevron notch testing and four-point bending methods at elevated temperatures. The fracture toughness values obtained range between 5–6 $\text{MPa}\sqrt{\text{m}}$, while flexural strengths reach up to 500 MPa under high temperature conditions [13]. The experimental results are compared for different SiC contents to analyze the influence of porosity, grain size, density, and temperature on thermal conductivity and mechanical performance. The developed HfB_2 - SiC and ZrB_2 - SiC composites demonstrate excellent thermal stability, oxidation resistance, high thermal conductivity, and superior mechanical durability. The methodology successfully proves that Ultra High Temperature Ceramics are highly suitable materials for hypersonic vehicle thermal protection systems, leading edges, nose cones, and advanced aerospace applications operating under extreme thermal environments [14][15].

IV RESULTS EXPLANATIONS

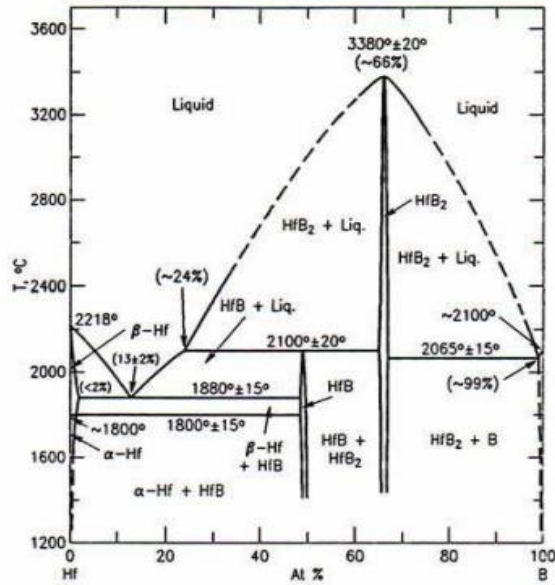


Figure 2. Hf-B syst

Fig. 2 represents the Hafnium–Boron (Hf-B) phase diagram, which shows the phase stability and compound formation between hafnium and boron at different temperatures and atomic percentages. The horizontal axis represents atomic percentage composition, while the vertical axis represents temperature in degrees Celsius. The diagram indicates the formation of phases such as α -Hf, β -Hf, HfB, and HfB₂ under different thermal conditions. Among these phases, HfB₂ is the most important Ultra High Temperature Ceramic because it possesses an extremely high melting point of approximately 3380°C and excellent thermal stability. The diagram also shows liquid phase regions formed at very high temperatures. Understanding this phase diagram is important for selecting proper processing temperatures and controlling the microstructure during fabrication of HfB₂ ceramics. The HfB₂ phase is widely used in hypersonic vehicle thermal protection systems because of its excellent oxidation resistance and high temperature performance.

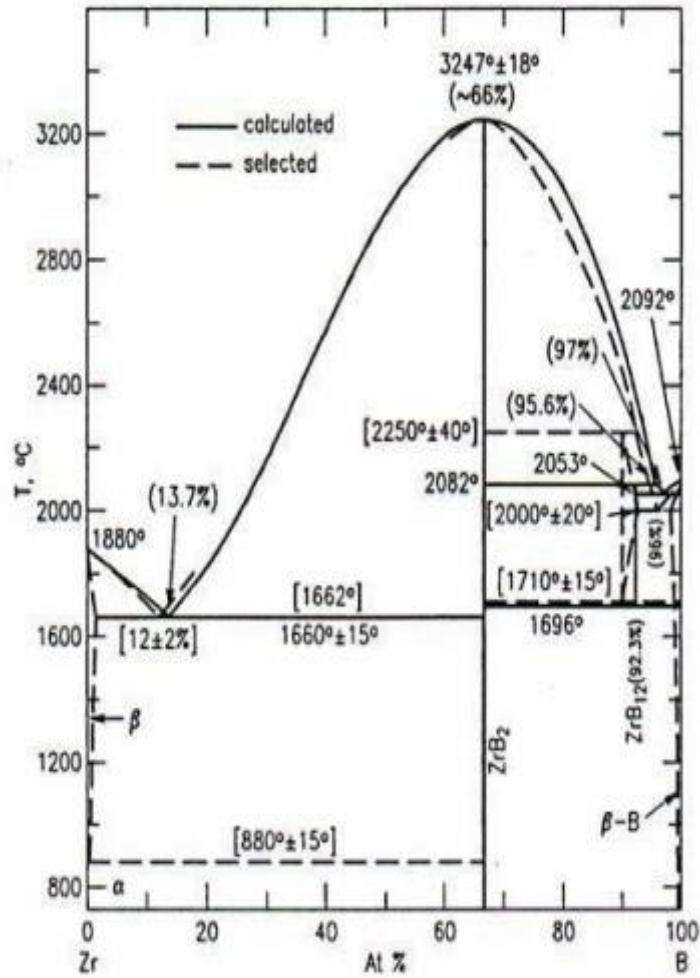


Figure 3. Zr-B system

Fig. 3 represents the Zirconium–Boron (Zr-B) phase diagram, which explains the relationship between temperature and atomic percentage composition of zirconium and boron. The diagram shows various phases such as ZrB, ZrB₂, and ZrB₁₂ formed under different temperature conditions. The vertical axis represents temperature in degrees Celsius, while the horizontal axis indicates boron composition. ZrB₂ is the dominant phase in the zirconium-boron system and has a melting point above 3200°C, making it highly suitable for Ultra High Temperature Ceramic applications. The phase diagram also shows liquid regions and phase transformation boundaries occurring during heating and cooling processes. The narrow homogeneity range of ZrB₂ indicates that precise composition control is required during material processing. This phase diagram helps researchers understand sintering behavior, phase stability, and microstructural development of ZrB₂ ceramics used in aerospace thermal protection systems and hypersonic vehicles.

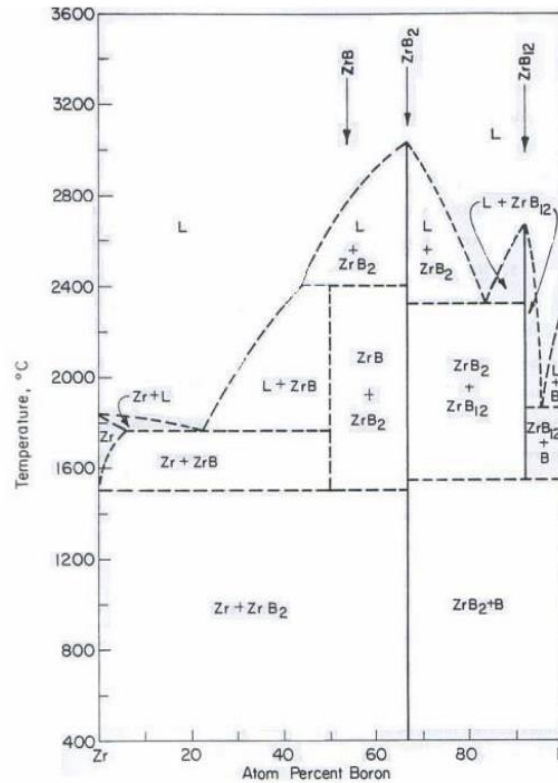


Figure 4. Zr-B system

Fig. 4 shows another representation of the Zirconium–Boron (Zr-B) phase diagram illustrating additional phase transformation behavior and stability regions of zirconium boride compounds. The figure explains the formation of intermediate phases such as ZrB and ZrB₁₂ along with the stable ZrB₂ phase at elevated temperatures. The diagram demonstrates how temperature and boron concentration influence the stability of various zirconium boride compounds during ceramic processing. Liquid phase regions and eutectic reactions are also represented in the figure, which are important for understanding high temperature sintering and densification behavior of Ultra High Temperature Ceramics. The diagram confirms that ZrB₂ possesses a very high melting temperature and excellent structural stability under extreme thermal conditions. This information is useful for optimizing fabrication methods, controlling grain structure, and improving thermal resistance of ZrB₂ based ceramics used in hypersonic vehicle leading edges, nose cones, and thermal protection systems for aerospace applications.

V.CONCLUSION

The project “Ultra High Temperature Ceramics for Hypersonic Vehicle Applications” successfully demonstrated the development, processing, and analysis of HfB₂-SiC and ZrB₂-SiC ceramic composites for advanced aerospace thermal protection systems. The study confirmed that Ultra High Temperature Ceramics possess excellent thermal stability, oxidation resistance, high thermal conductivity, and superior mechanical strength required for hypersonic flight and atmospheric reentry conditions. The ceramic composites were successfully fabricated using hot pressing techniques at high temperature and pressure conditions, achieving nearly full density structures with reduced porosity. The addition of Silicon Carbide significantly improved densification, oxidation resistance, thermal stability, and mechanical performance of the ceramics. Microstructural analysis using SEM and TEM revealed fine grain structures and thin grain boundary phases responsible for improved sintering and thermal behavior. Thermal diffusivity and thermal conductivity measurements showed stable heat transfer characteristics even at temperatures up to 2000°C. Mechanical testing demonstrated fracture toughness values of 5–6 MPa√m and flexural strengths up to 500 MPa under elevated temperature conditions. The developed UHTCs effectively resisted oxidation and thermal degradation during severe thermal exposure. Overall, the project proved that HfB₂-SiC and ZrB₂-SiC Ultra High Temperature Ceramics are highly suitable materials for hypersonic vehicle leading edges, nose cones, and thermal protection systems operating under extreme aerospace environments.

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