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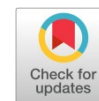
Synthesis and Sintering

ISSN 2564-0186 (Print), ISSN 2564-0194 (Online)



Review article

Ceramic coatings for extreme environments and energy systems: A review



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ABSTRACT

This paper provides a comprehensive review of wear-resistant ceramic coatings used in extreme environments, such as oil and gas operations, thermal barrier coatings, energy, and industrial applications. It explores various material classes, including oxides, carbides, nitrides, and borides, focusing on their thermal stability, mechanical strength, and resistance to oxidation and wear. The study discusses different deposition techniques, including chemical vapor deposition (CVD), physical vapor deposition (PVD), and plasma spraying, highlighting their advantages and challenges. Key challenges, including brittleness, adhesion issues, and high-temperature oxidation, are explained in detail, along with emerging solutions like high-entropy ceramics, self-healing materials, and computational modeling. The integration of smart monitoring systems and advanced fabrication methods is demonstrated as a promising way for optimizing the durability and performance of ceramic coatings. This review also aims to bridge the existing knowledge gaps, offering insights into the latest advancements and future directions in the development of high-performance ceramic coatings for extreme environments.

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KEYWORDS

Ultra high temperature ceramic coating
Wear-resistant coatings
Extreme environments
Energy systems



1. Introduction

The main considerations underlying the selection of materials today are the preservation of current natural resources as well as their efficient and economical use in the design and production of all high-temperature equipment. Given these factors, researchers have focused on increasing the equipment's energy production efficiency while also lowering its harmful emissions (mainly CO₂ and NO_x) through a careful raw material selection [1]. This can be accomplished, for example, by reducing the size and weight of the engines and turbines while maintaining high temperatures. This creates a high-temperature environment without any cooling systems nearby [2]. Because less fuel would be used, fewer harmful gases will be released, which will

contribute to the creation of ultra-high thrust. Research on the use of materials at high temperatures has hitherto mostly concentrated on super alloys like silicon carbide (SiC) and silicon nitride (Si₃N₄). Nevertheless, these alloys exhibit certain drawbacks in such operational settings, necessitating the use of superior materials, such as ceramics and composites, for these applications. Researchers have experimented with several transition metals and their derivatives to find appropriate materials for high-temperature applications [1, 3]. The study demonstrates that transition metal carbides, nitrides, and borides may be used as appropriate materials for high-temperature applications. Many industries can use ceramic metal composites (CMCs), thermal and environmental barrier coatings, etc., in high-temperature applications. By using these coatings in fuel cells, power production

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Received 20 May 2025; Received in revised form 26 June 2025; Accepted 26 June 2025.

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<https://doi.org/10.53063/synsint.2025.52289>

efficiency is increased, and harmful gas emissions are reduced. Solid oxide fuel cells made of ceramic metal composites may run on fuels like hydrogen or light hydrocarbons at high temperatures while producing ultraclean energy and exhibiting a low rate of performance degradation [4].

Also, large ships, airplanes, and the generation of electricity have all made extensive use of high-performance gas turbines as sources of electricity. Thermal barrier coatings (TBCs) can offer efficient protection for the hot-end components of gas turbines, which must withstand complicated and severe conditions during operation, including high-temperature oxidation, erosion, and corrosion. TBCs are typically made up of a metal bond coat and a top ceramic coating that work together to create a naturally occurring, synergistic system. The primary mechanical properties of TBCs that impact their service effect and lifespan are their thermal conductivity, high temperature stability, fracture toughness, and thermal expansion coefficient [5, 6].

There are currently over 3,000 materials with high melting points, often exceeding 2,273 K, such as SiC, a widely used high-temperature material. Refractory metals (Hf, Ir, Nb, etc.), oxides of Hf, U, Th, and Zr, and a broad class of transition metal borides, carbides, and nitrides and their composites are among the other high-temperature materials of interest. Because of their superior oxidation resistance, refractory diboride compounds based on group IV and V elements have drawn more attention from researchers. The diborides of Hf and Zr are the most promising contenders among these materials for applications involving extremely high temperatures [7, 8].

The materials used to construct gas turbines for aviation engines include steel, composite materials, nickel-based superalloys, titanium alloys, and aluminum alloys. The selection of materials and component manufacturing procedures is necessary to enhance engine performance and longevity for turbine parts that are subjected to harsh operating conditions, such as high temperatures and stress. Since nickel-based superalloys like Nimonic or Inconel[®] have superior heat resistance, they have supplanted the numerous stainless-steel kinds that were initially employed in Frank Whittles' gas turbine engines [7, 9].

The study of lubrication, wear, and friction on interacting surfaces is known as tribology. Wear has a significant impact on the lifespan of mechanical components from the nanoscale to the macroscale since it is one of the important tribological domains and a recurring phenomenon of deformation and damage at contact surfaces [10]. This review explores advanced ceramics, their various types, and synthesis methods, focusing on their applications in wear resistance within energy systems and turbine blades. Additionally, recent studies in this field are categorized and analyzed, highlighting key factors influencing wear. Furthermore, the impact of novel materials and advanced techniques in mitigating corrosion is examined.

2. Material classes for wear resistance in extreme environments

Materials must be able to tolerate wear processes such as oxidation, erosion, and thermal fatigue in addition to thermal stress in harsh settings with temperatures above 1,000 °C. In ultra-high temperature (UHT) settings, the following material classes are frequently used for wear-resistant applications:

2.1. Oxide-based ceramics

Ceramics based on oxides are used in applications where resistance to wear at very high temperatures is necessary. These materials are appropriate for demanding applications because they provide a variety of qualities [11].

2.1.1. Zirconia-based ceramics

Zirconia, commonly known as zirconium dioxide (ZrO_2), is a chemically inert mineral that is found in baddeleyite. At room pressure, ZrO_2 possesses three different phases and a polymorphic structure in its pure state. Up to 1170 °C, the monoclinic phase is stable at ambient temperature. While the cubic fluorite phase is stable at extremely high temperatures from 2370 °C to its melting point (2750 °C), tetragonal ZrO_2 with a deformed fluorite structure is stable at intermediate temperatures between 1170 and 2370 °C [12]. The significant characteristics of ZrO_2 , including its high ionic conductivity, low density, chemical inertness, good wear resistance, high mechanical strength, and stability at high temperatures, have made it possible for its widespread use in a variety of difficult structural, tribological, and multifunctional applications. ZrO_2 -based nanocomposites are among the most extensively researched and technologically potent ceramic materials, with applications in advanced engineering systems such as aircraft engines, thermal barrier coatings, and energy systems [13–15]. The increasing demand for TBCs in components exposed to high-temperature oxidation, corrosion, and wear necessitates a deeper understanding of material behavior under extreme conditions. Atmospheric plasma-sprayed (APS) yttria stabilized zirconia (YSZ) coatings are commonly employed as TBCs due to their thermal stability and low thermal conductivity [16]. For instance, Franco et al.'s [17] study addresses a critical gap in the literature by investigating the tribological behavior of YSZ coatings with varying microstructures under abrasive conditions at temperatures up to 1000 °C. Based on their study, Yttria-stabilized zirconia (YSZ) coatings exhibit temperature-dependent wear behavior. At room temperature (25 °C), ductile deformation results in low wear rates. However, at intermediate temperatures (500 °C and 750 °C), increased thermal stresses promote cracking and particle detachment, leading to higher wear rates associated with brittle deformation. Notably, at 1,000 °C, a transformation to the t'-zirconia phase increases coating hardness, improving wear resistance. This phase transformation shifts the damage mechanism back to ductile deformation, with resulting wear rates similar to those observed at room temperature. Specifically, wear rates at 25 °C and 1000 °C were found to be low due to ductile deformation, while significantly higher wear rates were observed at 500 °C and 750 °C due to brittle fracture.

2.1.2. Alumina (Al_2O_3) and its derivatives

One common example of engineering ceramics is alumina (aluminum oxide, Al_2O_3). Its qualities make it appealing for use in cutting tools, vehicles, aerospace, biomedical, and structural applications, especially in harsh climatic circumstances. Two primary techniques have been used to make aluminum-based composites: liquid state processing (such as stir casting) and solid-state processing (such as mechanical alloying and powder metallurgy). The matrix and reinforcement are combined in the powder metallurgy process to compact the material, which is then sintered to gain strength. The process of mechanical alloying is when components react to generate reinforcement. The most

traditional and economical technique for producing aluminum composites is stir casting [18, 19].

Alumina is widely utilized in ultra-high temperature applications due to its exceptional hardness, oxidation resistance, and thermal stability. With a melting point exceeding 2,000 °C, it serves as a critical material for wear-resistant coatings in extreme environments, such as turbine blades, rocket nozzles, and industrial cutting tools. In aerospace and energy systems, Al_2O_3 is applied as a protective layer to prevent thermal degradation and mechanical wear, particularly in components exposed to high-speed particle erosion and oxidative damage. Additionally, alumina-based coatings are extensively used in thermal barrier coatings and high-temperature structural components, where they enhance the longevity of underlying metallic substrates by mitigating corrosion and thermal fatigue [20, 21].

Beyond monolithic alumina, composite derivatives such as $\text{Al}_2\text{O}_3\text{-ZrO}_2$ and $\text{Al}_2\text{O}_3\text{-TiO}_2$ offer enhanced wear resistance and mechanical toughness. The incorporation of zirconia (ZrO_2) improves fracture toughness through transformation toughening, making the composite suitable for impact-resistant applications in extreme thermal conditions [22]. Meanwhile, $\text{Al}_2\text{O}_3\text{-TiO}_2$ coatings, commonly produced via plasma spraying, provide superior adhesion and resistance to abrasive wear, making them ideal for industrial machinery and engine components. Furthermore, rare earth-doped alumina has shown promise in improving high-temperature phase stability and reducing grain growth, leading to better mechanical integrity in prolonged service conditions. These advancements in alumina-based ceramics continue to drive their application in next-generation aerospace, energy, and manufacturing technologies [23, 24].

2.1.3. Rare earth oxides

The group commonly designated as rare earth elements (REEs) comprises fifteen lanthanides, spanning atomic numbers 57 to 71 on the periodic table, along with scandium (Sc, atomic number 21) and yttrium (Y, atomic number 39). These elements are further classified based on their atomic and chemical properties: the light rare earth elements (LREEs) include lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), and promethium (Pm); the medium rare earth elements (MREEs) encompass samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), and dysprosium (Dy); while the heavy rare earth elements (HREEs) consist of holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu) [25].

Lanthanum oxide (LaO_3), yttrium oxide (YO_3), and cerium oxide (CeO_2) are examples of rare earth oxides (REOs) that are essential for improving thermal stability and wear resistance in applications involving extremely high temperatures [26, 27]. These oxides are perfect for usage in TBCs for gas turbines, aerospace components, and hypersonic vehicles because of their exceptional phase stability, oxidation resistance, and low thermal conductivity. One of the most used TBC materials, yttria-stabilized zirconia, depends on Y_2O_3 to preserve its high-temperature phase stability and avoid early coating breakdown. Similarly, to increase durability in harsh conditions, LaO_3 and CeO_2 have been added to sophisticated TBC formulations to strengthen their resistance to sintering and thermal cycling [28].

Rare earth oxides are used in wear-resistant composites and high-temperature structural ceramics in addition to thermal barrier coatings. By preventing grain formation and enhancing fracture toughness, REOs are added to ceramics based on alumina and zirconia to improve their mechanical integrity. La_3O_3 -doped Al_3O_3 , for example, has shown

enhanced hardness and resilience to heat shock, which makes it appropriate for protective coatings in industrial processing equipment and high-speed cutting tools. CeO_2 is also utilized in self-healing ceramic coatings, where its redox characteristics and dynamic surface chemistry enable in situ microcrack and wettability repair. This self-healing behavior is primarily driven by the reversible adsorption and removal of atmospheric hydrocarbons, which modulate surface energy and restore superhydrophobicity after environmental or mechanical damage [29–31]. Because of these special qualities, rare earth oxides are essential for creating next-generation materials for high-temperature industrial, energy, and aerospace applications.

2.2. Carbide-based ceramics

Because of their remarkable hardness, resistance to wear, and thermal stability, carbide-based ceramics are frequently utilized in ultra-high temperature applications. Excellent resistance to oxidation, erosion, and thermal stress makes materials like silicon carbide (SiC), tungsten carbide (WC), and hafnium carbide (HfC) perfect for industrial, energy, and aerospace applications. The subsequent section provides a detailed examination of the most prominent carbide-based ceramics, highlighting their properties in extreme environments and effectiveness in wear resistance [32–34].

2.2.1. Silicon carbide (SiC)

A well-known structural ceramic material, silicon carbide has long been utilized in industries because of its special set of qualities, which include high temperature strength, high modulus, high hardness, excellent wear resistance, good oxidation resistance, good thermal shock resistance, and high thermal conductivity [35].

Silicon carbide (SiC) is renowned for its exceptional hardness, reaching up to 2800 HV0.1 (Vickers hardness scale), making it a highly effective material for abrasive applications. Its superior thermal properties, including high thermal conductivity ($110 \text{ W m}^{-1} \text{ K}^{-1}$ at room temperature) and a low thermal expansion coefficient ($4.6 \times 10^{-6} \text{ K}^{-1}$ from ambient temperature to 1000 °C), contribute to its outstanding resistance to thermal shock. These characteristics make SiC an ideal candidate for high-temperature environments, such as kiln linings, industrial furnaces, and crucibles. Additionally, its durability and thermal efficiency have led to its widespread use in energy-related applications, including SiC linings in gas-fired rotary kilns, SiC-based heat exchangers in solar thermal plants, and burner nozzles in high-efficiency gas turbines, where material stability under extreme thermal and mechanical conditions is crucial [35, 36].

Sintered silicon carbide is a substance with superior high-temperature characteristics. Sintering additives are the only way to achieve a significant pressure-less densification for SiC. Usually, additives that contain boron or aluminum are utilized because they create silicon vacancies in the SiC lattice and increase diffusion rates. Graphite is also added to the powders to lessen the silica layer, which lowers surface diffusion and encourages densifying sintering processes. Pressure-assisted sintering techniques like hot pressing and hot isostatic pressing (HIP) can further improve the characteristics [37].

2.2.2. Tungsten carbide (WC)

Tungsten carbide (WC) is renowned for its exceptional hardness, ranking between 8.5 and 9 on the Mohs scale, which makes it highly effective in wear-resistant applications. Its high melting point of

approximately 2870 °C ensures stability under ultra-high temperature (UHT) conditions. Incorporated into cutting tools, WC maintains sharpness and performance during high-speed machining operations, outperforming traditional high-speed steels [38]. Additionally, WC is utilized in wear-resistant coatings, often applied through thermal spray processes, to protect components exposed to abrasive and erosive environments. However, it is important to note that WC's performance can be limited at elevated temperatures due to oxidation, as tungsten in WC reacts with oxygen to form volatile tungsten oxides (e.g., WO_3), which degrade the material's structural integrity. Therefore, protective coatings or the use of alternative materials like chromium carbide may be considered for applications exceeding 510 °C [39].

Air-plasma spray (APS) and high-velocity oxygen fuel method (HVOF) can be applied to tungsten carbide and titanium carbide, which are typically utilized in gas turbine components. These coatings are used in conjunction with molten binders, such as copper and nickel, to facilitate rapid melting using thermal-spraying processes. Both WC and TiC exhibit extremely high hardness (up to 700 HV) and a titanium-carbide coated surface cross-section. WC's restricted ability to operate at moderate temperatures up to 600 °C is its primary drawback. Up to 1100 °C, CrC and TiC coatings work exceptionally well [33].

2.2.3. Hafnium carbide (HfC)

A refractory ceramic material with remarkable qualities that make it appropriate for applications requiring extremely high temperatures is hafnium carbide (HfC). It has a density of 12.76 g cm⁻³ and crystallizes in a face-centered cubic (FCC) structure with a lattice parameter of around 4.638 Å. Superior wear resistance is a result of HfC's exceptional hardness, which usually exceeds 9 on the Mohs scale. Nevertheless, oxidation begins at temperatures as low as 430 °C, indicating poor oxidation resistance. These properties make HfC useful in applications where resistance to wear and tolerance to high temperatures are crucial, such as cutting tools, high-temperature coatings, and rocket nozzles; however, in highly oxidizing environments like rocket engines, HfC must be used with protective coatings or in reducing atmospheres to prevent degradation [40, 41].

2.3. Nitride-based ceramics

Ceramics based on nitride, such as silicon nitride (Si_3N_4) and aluminum nitride (AlN), are well known for their remarkable mechanical qualities and resistance to wear at elevated temperatures. For instance, silicon nitride has a high fracture toughness (6.5–7 MPa m^{1/2}), outstanding thermal shock resistance (up to 800 °C), and the ability to maintain strength and hardness up to 1200 °C. Likewise, aluminum nitride has exceptional wear resistance, high-temperature strength, and improved thermal shock resistance. Because of these characteristics, nitride-based ceramics are perfect for uses where resilience in harsh mechanical and thermal environments is required [42].

AlO_3 and other oxide-based ceramics, in contrast, show strong wear resistance but often lack the fracture toughness and thermal shock resistance of nitride-based ceramics. Although alumina has superior hardness and is stable at high temperatures, it is often more brittle than silicon nitride. This restricts how well it performs in situations with significant mechanical loads or abrupt temperature changes. Compared to nitrides, oxide-based ceramics are less suited for demanding high-temperature conditions, despite their widespread usage because of their affordability and chemical stability [42, 43].

SiC and other carbide-based ceramics function well at high temperatures as well; their maximum working temperatures can approach 1900 °C. They have great heat conductivity, remarkable toughness, and resilience to wear. However, silicon carbide is more likely to fail brittly under mechanical stress because it has a lower fracture toughness than silicon nitride. SiC may fall short of nitride-based ceramics in terms of overall toughness and thermal shock resistance, despite being a great option for applications needing exceptional hardness and thermal conductivity. In contrast to oxide coatings, nitride-based coatings, such as TiAlN or CrAlN, offer better wear resistance at higher temperatures [44]. For example, the creation of protective oxide layers such as AlO_3 and CrO_3 allows CrAlN coatings to maintain exceptional wear resistance up to 900 °C. However, compared to multi-component nitride coatings, these oxide layers could not provide the same degree of hardness or durability. At temperatures between 700 °C and 900 °C, advanced multi-component nitride coatings, including Ti-TiN-(Ti, Al, Nb, Zr)N, show improved wear resistance and decreased friction [45, 46].

2.3.1. Silicon nitride (Si_3N_4)

The unique ceramic substance silicon nitride (Si_3N_4) is well-known for its great wear resistance and extraordinary characteristics at extremely high temperatures. This material's unique blend of mechanical, chemical, and thermal properties has drawn a lot of interest from a variety of sectors. The ability of silicon nitride to retain mechanical strength and structural integrity at very high temperatures is one of its most remarkable characteristics. With a melting point of about 1900 °C, it can tolerate extreme heat without suffering appreciable deterioration [47]. Because of its high-temperature stability, silicon nitride is a perfect fit for parts used in gas turbines, automobile engines, and aircraft, where extreme heat exposure is frequent. Extremely high wear resistance is another important characteristic that distinguishes silicon nitride from other ceramic materials. The reason for its exceptional resistance to erosion and abrasion is its great hardness, which places it slightly below diamond on the Mohs scale. When paired with its low coefficient of friction, this characteristic makes silicon nitride a great material for cutting tools, bearings, and other parts that are exposed to extreme wear [48].

2.3.2. Boron nitride (BN)

Boron nitride (BN) is a versatile ceramic material with unique properties that make it highly suitable for applications in extreme environments, particularly at high temperatures. Hexagonal boron nitride (h-BN) is the most commonly employed of the several crystalline forms of BN because of its layered structure, which provides superior lubrication, chemical, and thermal stability. In inert atmospheres, BN can withstand temperatures of up to 3000 °C, which is far greater than that of Si_3N_4 , which breaks down at 1900 °C. Because of its remarkable thermal stability, BN is ideal for high-temperature applications such as thermal insulators, crucibles, and protective coatings. Additionally, its anisotropic structure contributes to good machinability and moderate hardness. However, due to its relatively low mechanical strength compared to Si_3N_4 , BN is more suitable for non-load-bearing applications in high-temperature environments [49, 50].

Because of its great wear resistance and exceptional fracture toughness (up to 11.1 MPa m^{1/2}), silicon nitride is better suited for structural applications that are subjected to abrasive or severe mechanical

stresses. For instance, because Si_3N_4 can tolerate high loads without failing, it is frequently used in cutting tools, bearings, and engine components [51].

2.4. Boride-based ceramics

The complex combination of entropy-driven, multi-component disordered solid solutions is what makes high-entropy borides strong candidates. They stand out because of their significant bandgap and distinctive single-crystal architectures. They differ from traditional transition metal diborides in that they are uniquely positioned among materials due to their structural versatility. Because of the novel concept of "high-entropy ceramics", researchers have long been captivated by the allure of high-entropy borides.

2.4.1. Titanium diboride (TiB_2)

TiB_2 -based materials have been considered viable UHTCs because of their appealing blend of chemical, mechanical, tribological, and thermophysical characteristics. Despite its outstanding mechanical, physical, and chemical properties, TiB_2 presents significant challenges in densification. Furthermore, it exhibits insufficient fracture toughness. Investigations into this material are further complicated by the difficulties in assessing its properties under extreme temperatures and severe environmental conditions. For instance, flexural creep testing is generally restricted to temperatures of 1500 °C or lower due to interactions between the testing fixtures and the specimens, which prevents accurate evaluation of TiB_2 's mechanical performance at the higher temperatures relevant to its intended applications [52]. Recently, an innovative noncontact mechanical testing approach has been introduced to analyze the high-temperature creep and fatigue behavior of electrically conductive materials. Despite research efforts dating back to the 1960s and continuing to the present, the challenges preventing the widespread application of TiB_2 remain unresolved [53]. In recent years, extensive research has focused on addressing the high sintering temperatures required for TiB_2 . Various approaches, including the use of metallic and ceramic additives, advanced and conventional sintering techniques, and optimized processing parameters, have been explored. However, the addition of secondary phases presents significant challenges. For instance, metallic additives can compromise the high-temperature stability and corrosion resistance of diborides. To enhance densification and mechanical properties, ceramic additives such as MoSi_2 and TiSi_2 have been introduced. Another critical area of research involves improving the fracture toughness of UHTCs through microstructural engineering and the incorporation of various reinforcements. Nonetheless, the composition and microstructural modifications must be carefully designed to avoid detrimental effects on high-temperature performance [54, 55].

2.4.2. Zirconium diboride (ZrB_2)

Zirconium diboride (ZrB_2) based UHTCs are the most important for particular applications such as aerospace and nuclear industry, where the components face extreme environments of both thermal and chemical nature. Pure ZrB_2 requires high temperatures and pressure for its densification [56].

Zirconium diboride (ZrB_2)-based UHTCs are among the most critical materials for demanding applications in aerospace and nuclear industries, where components are subjected to extreme thermal and chemical environments. However, pure ZrB_2 requires high

temperatures and pressure to achieve densification. The incorporation of SiC significantly enhances both its fracture toughness and oxidation resistance [1]. The ZrB_2 -SiC composite demonstrates superior oxidation resistance compared to monolithic ZrB_2 at elevated temperatures due to the formation of a protective silica-rich surface layer, which acts as a diffusion barrier against further degradation. The remarkable performance of this composite is largely attributed to its refined grain structure and the homogeneous dispersion of SiC within the matrix. Traditionally, densification has been achieved using spark plasma sintering (SPS) or hot pressing; however, pressureless sintering has gained prominence in recent years due to its cost-effectiveness and simplicity in large-scale processing [57]. The properties of the materials mentioned above, along with other materials exhibiting high-temperature characteristics and applications, are illustrated in Fig. 1.

3. Fabrication and deposition techniques

The development of wear-resistant coatings dates back to the 1960s, coinciding with the emergence of chemical vapor deposition (CVD) and physical vapor deposition (PVD) techniques. These deposition methods have since become integral to numerous industrial sectors, significantly enhancing component longevity, operational efficiency, and overall cost-effectiveness. Thin film coatings represent a crucial category of surface modifications, with the choice of deposition technique dictated by the specific service conditions and functional requirements. Thin film fabrication technologies enable the production and manipulation of coatings ranging from nanometric layers to several microns in thickness. PVD is widely recognized as a versatile deposition method employed in diverse applications, including tribological performance improvements, optical enhancements, and aesthetic modifications. Compared to conventional electroplating, PVD coatings generally exhibit superior mechanical strength and corrosion resistance. Common materials used in PVD deposition include titanium, zirconium, aluminum, stainless steel, and copper, while gold coatings are increasingly utilized in aerospace electronics. PVD coatings can be applied to a broad spectrum of substrates, such as ceramics, polymers, glass, and various metals, including aluminum and stainless steel. This method is instrumental in fabricating semiconductor components, optical devices, display coatings, and high-performance cutting tools that enhance machining efficiency and wear resistance.

Plasma spraying is a high-temperature deposition process in which powdered coating materials are injected into a plasma jet, rapidly heated, and propelled onto the substrate. Upon impact, the molten particles solidify, forming a protective layer with enhanced mechanical and chemical properties. This versatile technique finds applications across multiple industries, including aerospace, automotive, medical devices, marine engineering, electronics, and petrochemical processing. Plasma-sprayed coatings improve substrate performance by imparting high-temperature stability, oxidation resistance, electrical insulation or conductivity, and superior wear and corrosion resistance.

High-velocity oxygen fuel (HVOF) spraying is a key advancement in surface engineering, enabling the restoration and protection of critical components. By prolonging service life and reducing environmental impact, HVOF coatings contribute to sustainability in industries such as energy, petrochemicals, aerospace, mining, and manufacturing. The primary applications of HVOF coatings include corrosion and wear resistance, as well as component refurbishment, providing cost-

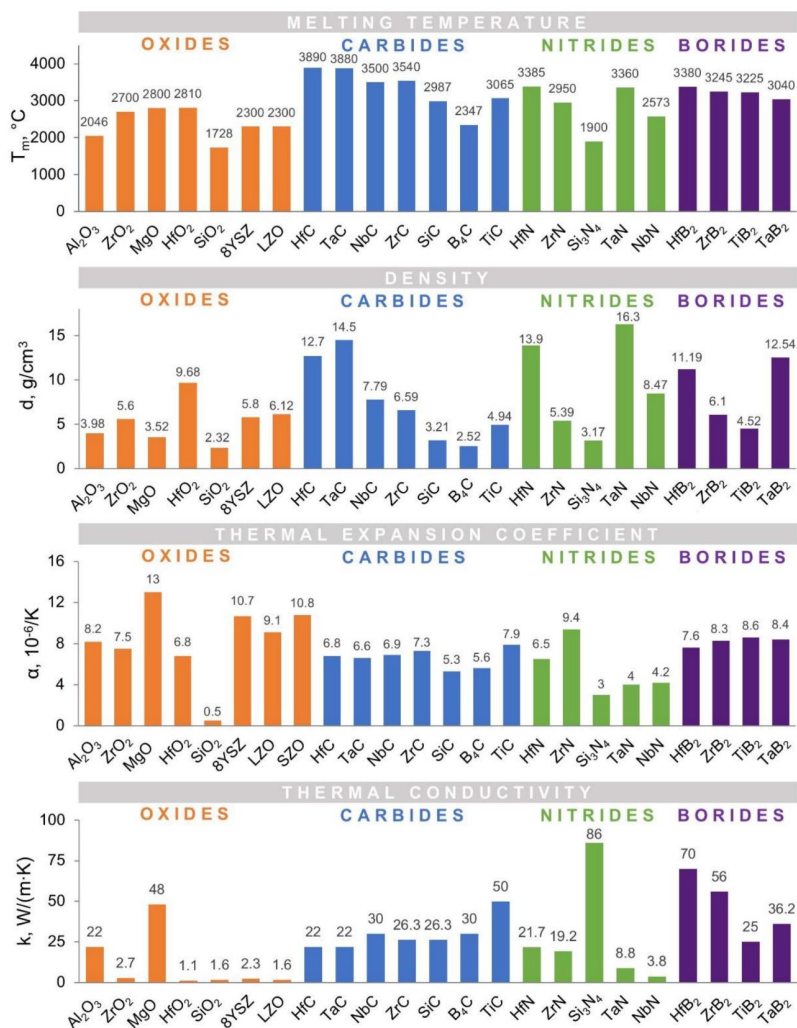


Fig. 1. The properties of oxides, carbides, nitrides, and borides needed for thermal barrier coatings (TBCs) include melting temperature (T_m), density (d), thermal expansion coefficient (α), and thermal conductivity (k). Reproduced from Ref. [58]. Copyright © MDPI.

effective and technically advanced solutions for industrial machinery. Magnetron sputtering has gained prominence as an advanced technique for depositing functional coatings tailored to industrial applications. This process is employed to produce hard coatings, low-friction surfaces, corrosion-resistant layers, and coatings with specialized optical or electrical properties. The ability of magnetron sputtering to deliver uniform, high-purity films has established it as a preferred method for engineering high-performance protective coatings in demanding environments. In this section, we will discuss the aforementioned coverage methods in more detail and also discuss their challenges or limitations.

3.1. Chemical vapor deposition (CVD)

Chemical Vapor Deposition is a widely used technique for producing high-quality ceramic coatings through chemical reactions of gaseous precursors on a heated substrate. The effectiveness of this process depends on several critical parameters. The substrate temperature, usually between 800 and 1200 °C, plays a central role in enabling the necessary surface reactions and determining the microstructure of the

coating. The gas flow rate influences the uniformity and thickness of the deposited layer by controlling how precursor molecules reach the surface. Chamber pressure also affects the reaction dynamics; lower pressures can enhance film quality by promoting more controlled deposition and reducing unwanted side reactions. Additionally, the type and concentration of precursor gases directly determine the composition, purity, and growth rate of the resulting coating. By optimizing these parameters, the CVD process can be tailored to produce coatings with desirable properties such as high adhesion, uniformity, and thermal stability, making it suitable for applications in harsh environments [59].

Because of its excellent production efficiency and comparatively low fabrication cost, the CVD technique is the most widely used layer deposition method for ceramic nanocomposite coatings in industrial production. The CVD technique is a method that uses heat, light, and plasma to break down or react chemically with gaseous reactants. A stable-solid layer is created by such a breakdown. Highly pure stand-alone materials or coatings with properties controllable down to the atomic or nanometer scale can be produced using CVD [60].

Over the past few years, CVD technology has seen a substantial expansion in its applications. Materials science and engineering have made extensive use of CVD technology, which is based on the deposition components of the process. The CVD technology is a very attractive and significant coating process because of its many applications, which range from extraction to precipitation. For instance, thin film semiconductor and nanocomposite ceramic coatings with significantly enhanced surface qualities, including abrasion resistance, corrosion/oxidation resistance, chemical reactions, thermal stress, and neutron absorption, are widely produced using the CVD technique. In terms of history, CVD technology made significant strides in producing electronic semiconductors and protective coatings for electronic circuits in the early 1970s [61].

In most conventional systems, the chemical vapor deposition (CVD) method operates by introducing reactive gases or precursor vapors into a controlled chamber. Inside this chamber, one or more heated substrates serve as the deposition surface. As these gases interact with the heated substrate, chemical reactions take place, leading to the formation of a thin film, either crystalline, amorphous, or a mixture of both. However, one drawback of this process is the generation of chemical byproducts. Unreacted precursor gases, along with waste materials, exit the chamber as residual emissions. The deposition temperature for CVD typically ranges from 900 °C to 1400 °C [62]. Unlike physical vapor deposition (PVD), which primarily relies on physical processes such as evaporation, dispersion, and sublimation, CVD is fundamentally a chemically driven technique where reactions occur between precursor molecules. The CVD process is governed by three primary phenomena: surface reaction kinetics, mass transfer or diffusion mechanisms, and desorption reactions. A schematic representation of the key stages in the CVD process is provided in Fig. 2. The initial phase involves transporting the precursor gases to the deposition site, facilitated by convective flow. The second and fifth steps are interconnected, as they are influenced by the infiltration rate and the stoichiometric balance of the reactants. The third and fourth steps are particularly intricate, involving multiple simultaneous processes such as surface reactions, adsorption-desorption cycles (both chemical and physical), and nucleation events on the substrate. The slowest step in this sequence typically dictates the overall reaction rate. If the substrate temperature exceeds the decomposition temperature of

the precursor materials, the deposition rate is primarily controlled by mass transport. Under such conditions, the reactants decompose more rapidly, and the growth rate of the coating is determined by the efficiency of reactant delivery to the substrate. Conversely, if the substrate temperature is significantly higher than the reaction temperature of the gaseous precursors, the deposition process becomes limited by temperature-dependent heterogeneous nucleation rates and kinetic constraints. In this scenario, the reaction kinetics dictate the initial growth rate. If the precursor supply remains sufficient, the deposition rate becomes independent of the chamber temperature and instead follows an exponential dependence on the temperature of the reactant materials. Thus, in CVD, reaction kinetics govern deposition rates at lower temperatures, whereas diffusion processes become the dominant rate-controlling factor at higher temperatures [62, 63].

3.2. Physical vapor deposition (PVD)

Physical vapor deposition (PVD) is a vacuum-based technique used to deposit thin films of ceramic materials through the physical transfer of material from a solid source to the substrate. Common PVD methods include sputtering and thermal evaporation. The substrate temperature during PVD typically ranges from room temperature up to 500 °C, depending on the material and application, which is generally lower than that in CVD processes. The chamber pressure is kept in the low vacuum range (around 10^{-3} to 10^{-6} Torr) to facilitate controlled deposition. In sputtering, an inert gas such as argon is introduced to generate a plasma, which dislodges atoms from a target material that then condense on the substrate. The type of target material and working gas directly affect the film composition and deposition rate. Layer thickness and growth rate can be controlled by adjusting parameters such as deposition time, target power, and gas flow rate. Although PVD often results in coatings with high purity and good adhesion, it may produce films with less conformality compared to CVD. Nonetheless, its relatively low processing temperature and flexibility in coating various substrates make PVD a valuable technique in high-performance ceramic applications [64].

Physical vapor deposition (PVD) is a well-known technique that is frequently used to produce thin films for a variety of purposes, such as improving optical performance, tribological characteristics, and aesthetics. In many businesses, this method is already well-established.

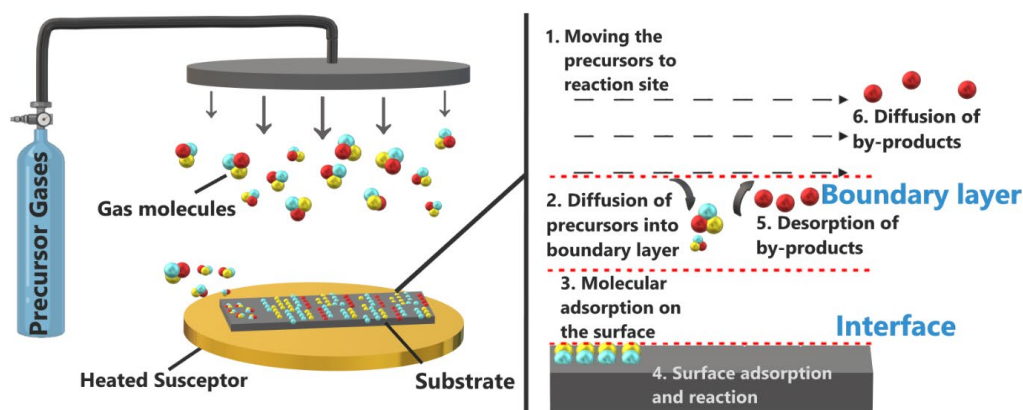


Fig. 2. Schematic of the CVD process and the mechanism and stages of the coating process. Redesigned from Ref. [62]. Copyright © MDPI.

PVD is widely used in machining tools, where it is frequently combined with CVD to improve thermal characteristics, decrease friction, and increase tool longevity. However, CVD only works in situations when such high-temperature processing is necessary since it operates at higher temperatures, which raise tensions in the coating and substrate. Increasing plasma ionization, reducing deposition-free zones inside the reactor, increasing target utilization, improving atomic bombardment efficiency, increasing deposition rates, and choosing the best gases are just a few of the important parameters that have been optimized in several studies to improve the PVD method. These developments demonstrate the enormous potential of optimizing processing parameters to enhance thin film quality and fortify substrate adherence [65].

Beyond aesthetic uses, PVD-coated parts are regularly exposed to high levels of wear, which causes surface abrasion and the coating layer to gradually peel off. Because of this deterioration, components are less resistant to erosion and are therefore more susceptible to adverse conditions [66]. A schematic depiction of several electron beam PVD devices is shown in Fig. 3. Physical evaporation is the main force behind coating deposition in this technique, and thermal energy is provided by a variety of sources, including electron beams, heating wires, laser beams, and molecular beams. The source material's atoms, which may be solid or liquid, are heated to their evaporation point by this thermal energy. The atoms that have been vaporized move through the vacuum and land on the substrate.

3.3. Plasma spray method

This method is used to produce UHTC coatings with significant thickness, typically in the range of 4–5 mm. It also allows for the creation of free-standing UHTC coatings by detaching them from the substrate. The overall quality of the resulting coating is largely determined by the characteristics of the starting powders used in the preparation of the UHTCs in powder form. Applying the vacuum plasma spray technique enhances the oxidation resistance of UHTC coatings. In a particular study, researchers successfully applied a UHTC coating of HfC and TiC onto a substrate using the plasma spray technique. These materials demonstrated exceptional hardness and mechanical properties. The HfC coating exhibited a hardness of

1650.70 HV, while the TiC coating had a hardness of 753.60 HV. For a multilayer sample containing both HfC and TiC layers, the hardness values were 1563.50 HV and 1059.20 HV, respectively. The surface roughness was measured at 5.710 μm for the HfC coating, 4.300 μm for the TiC coating, and 3.320 μm for the combined HfC/TiC coating [1, 68].

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4. Applications and case studies

As mentioned in the previous sections, ultra-high temperature ceramics and their coatings are used in many fields. In this section, we briefly discuss the main fields that have harsh environments and where the use of advanced ceramic materials is essential to prevent wear, erosion, and degradation.

4.1. Oil and gas operations

Oil and gas production presents some of the most challenging environments for materials due to the combination of severe erosion, corrosion, high temperatures, and pressures. These conditions are particularly detrimental to components such as piping, tubing, pumps, valves, and downhole tools, which are critical to the extraction and

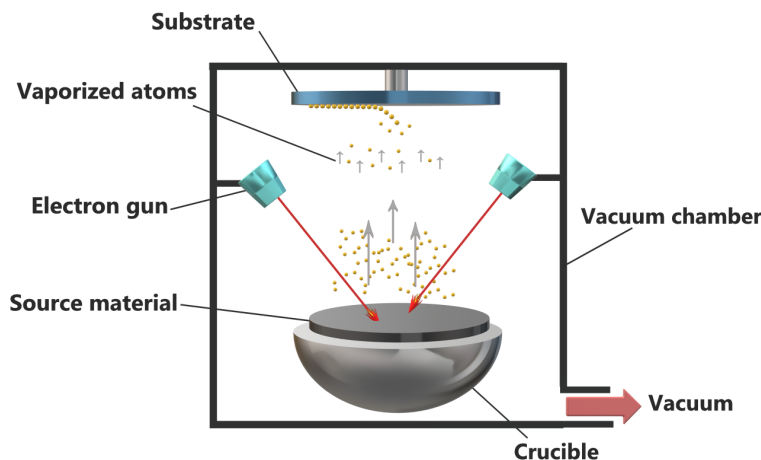


Fig. 3. Schematic illustration of a physical vapor deposition (PVD) system. Redesigned from Ref. [67]. Copyright © MDPI.

transportation of hydrocarbons. Traditional materials like steels and alloys, while widely used, often suffer from rapid degradation under these harsh conditions, leading to frequent failures, unscheduled downtime, and escalated maintenance costs. Advanced ceramic coatings have emerged as a promising solution to mitigate these issues, offering superior hardness, chemical inertness, and thermal stability. This section reviews the application of ceramic coatings in oil and gas production, focusing on their role in enhancing the durability and performance of critical components [69].

In oil and gas production, erosion and corrosion are pervasive problems, exacerbated by the presence of abrasive particles such as sand, calcite, and clay-sand mud, as well as corrosive agents like chlorides, sulfates, and bacteria in the processing fluids. For instance, in downhole operations, components like sucker rod pumps and progressing cavity screw pumps are subjected to reciprocating and rotational movements that cause wear through mechanical contact and the entrainment of abrasive particles. Additionally, the well trajectory, especially in deviated or horizontal wells, can lead to increased contact between the rod and tubing, further accelerating wear. Ceramic coatings provide a protective barrier that can significantly reduce wear and corrosion, thereby extending the service life of these components. Materials such as oxide ceramics (e.g., alumina, zirconia), non-oxide ceramics (e.g., silicon carbide), and ceramic-metal composites (e.g., tungsten carbide with cobalt or nickel binders) are particularly effective due to their high hardness and resistance to chemical attack [70].

The selection of an appropriate ceramic coating depends on several factors, including the specific type of erosion (e.g., sliding or impact), the corrosivity of the environment, and the operating temperature. For example, in applications where sliding erosion is predominant, such as in pump impellers or tubing, coatings with high hardness and low friction coefficients are preferred. Conversely, in scenarios involving high-impact erosion, such as in choke valves or elbows where flow direction changes abruptly, coatings with enhanced toughness are necessary to prevent brittle fracture. Ductile materials perform better at high impingement angles (75–90 °), while brittle materials like ceramics excel at low impingement angles (below 45 °). Therefore, understanding the erosion mechanism and the impingement angle is crucial for selecting the optimal coating material [32, 69].

Manufacturing processes for ceramic coatings in oil and gas applications must be tailored to the component's size, shape, and required properties. Common techniques include thermal spraying, chemical vapor deposition (CVD), and physical vapor deposition (PVD). Thermal spraying, such as high-velocity oxygen fuel (HVOF) spraying, is widely used for applying carbide-based coatings like tungsten carbide or chromium carbide, which provide excellent wear resistance. However, thermal spraying is limited in its ability to coat internal surfaces of long tubing or complex geometries. In contrast, CVD and related processes, such as boronizing, are more suitable for coating the inner surfaces of tubing and complex components. Boronizing, for instance, involves the diffusion of boron into the steel substrate to form iron boride layers, which offer high hardness and corrosion resistance. This process is particularly advantageous for protecting long production tubing strings used in artificial lift systems [71].

The performance of ceramic coatings in oil and gas applications has been demonstrated through various case studies. For example, coated tubing and pump parts have shown significantly longer service lives compared to their uncoated counterparts, reducing the frequency of

replacements and associated downtime. In one instance, pump impellers coated with ceramic materials lasted several months longer than those made from traditional high-chromium irons or duplex stainless steels. Similarly, boronized steel components have exhibited enhanced resistance to erosion-corrosion in downhole environments, where the combination of abrasive particles and corrosive fluids is particularly aggressive [32, 69].

Despite their advantages, ceramic coatings also present challenges that must be addressed to ensure their effective application. One major limitation is their inherent brittleness, which can lead to cracking or spalling under high-impact conditions or when subjected to thermal cycling. To mitigate this, composite coatings that incorporate ductile phases or multi-layered structures can be employed to improve toughness. Additionally, achieving strong adhesion between the coating and the substrate is critical for preventing delamination, especially in environments with high mechanical stresses. Surface preparation techniques, such as grit blasting or phosphating, are often used to enhance coating adhesion. Furthermore, the cost of ceramic coatings can be higher than traditional materials, but this is often offset by the extended service life and reduced maintenance requirements [72].

4.2. Turbine blades

Turbine blades operate in some of the most extreme environments, facing high temperatures, oxidative and corrosive atmospheres, and intense mechanical stresses. In gas turbines used for aerospace propulsion and power generation, the combustion process generates temperatures that often exceed the melting points of conventional metallic materials [73]. To withstand such conditions, turbine blades must possess exceptional thermal stability, oxidation resistance, and mechanical integrity. Additionally, the presence of corrosive species such as sulfur, vanadium, and alkali metals in fuel can lead to hot corrosion, further accelerating material degradation. The combined effects of thermal fatigue, erosion, and oxidation demand advanced protective solutions to extend blade longevity and maintain efficiency [74].

Blade tip protective coatings are primarily classified into two main categories: single-layer coatings and composite coatings. Single-layer coatings are typically composed of metal or ceramic particles, such as alumina coatings, MCrAlY coatings, and ZrO₂ ceramic coatings. However, their uniform structure limits their overall protective performance. In contrast, composite coatings can be divided into three subtypes: laminated composite coatings, metal/ceramic particle composite coatings, and laminated/ceramic particle composite coatings. Compared to single-layer coatings, composite coatings offer a more advanced structural design, enhancing the overall protection of blade tips. Consequently, the development and optimization of composite coatings have attracted significant research interest [75].

To enhance the durability of turbine blades under extreme conditions, UHTCs have been extensively researched and developed. These coatings provide superior thermal insulation, oxidation resistance, and wear protection, significantly improving blade performance. Among the most commonly used ceramic coatings are zirconia-based thermal barrier coatings TBCs, which have low thermal conductivity and excellent phase stability at high temperatures. However, for applications exceeding 1500 °C, novel UHTCs such as HfC, ZrB₂, and TaC have been explored due to their exceptional refractory properties and resistance to ablation. These ceramics not only act as thermal

shields but also prevent rapid oxidation and erosion, thereby extending the service life of turbine blades. Continuous advancements in coating deposition techniques, such as plasma spraying, CVD, and electron beam physical vapor deposition (EB-PVD), are further enhancing the effectiveness and reliability of UHTC systems in modern gas turbines [76].

4.3. Nuclear reactors

Fossil-fuel-based thermal power plants currently account for the majority of global electricity production. However, their dependence on non-renewable fossil fuel reserves and their substantial greenhouse gas emissions present significant environmental and sustainability concerns. The ongoing depletion of coal, oil, and natural gas resources underscores the need for alternative energy sources that can provide long-term energy security while reducing environmental impact. Among the available options, nuclear power represents a technically viable and efficient solution capable of supplying large-scale energy without contributing to carbon dioxide emissions. Its high energy density and potential for continuous, stable power generation make it a strategic component in future energy systems aimed at decarbonization [77]. Currently, various nuclear fission reactor designs, such as light water reactors (LWRs), boiling water reactors (BWRs), and pressurized water reactors (PWRs), are in operation across different countries, providing a stable and large-scale power generation capacity. Despite their widespread use, concerns regarding the structural resilience of conventional fission reactors have intensified, particularly in light of catastrophic nuclear incidents like the Fukushima Daiichi disaster. This accident, triggered by a powerful earthquake and subsequent tsunami, highlighted critical vulnerabilities in existing reactor materials—especially zirconium-based alloys used in fuel claddings—which contributed to severe hydrogen explosions and radiation leakage. To address these concerns and enhance the safety of next-generation nuclear reactors, significant research efforts have been directed toward the development of advanced materials with superior thermal, mechanical, and radiation-resistant properties [78]. One of the most promising alternatives is silicon carbide (SiC)-based ceramic matrix composites (CMCs), particularly SiC/SiC composites, which exhibit exceptional high-temperature stability, oxidation resistance, and reduced hydrogen generation compared to traditional zirconium alloys. These advanced materials are being explored for implementation in future reactor concepts, including gas-cooled fast reactors (GFRs), lead-cooled fast reactors (LFRs), molten salt reactors (MSRs), sodium-cooled fast reactors (SFRs), very-high-temperature reactors (VHTRs), supercritical water-cooled reactors (SCWRs), and even nuclear fusion reactors. Beyond their application in nuclear fission and fusion energy systems, UHTCs and ceramic-based composites are also being considered for wear-resistant coatings in various high-temperature energy applications.

In concentrated solar power (CSP) plants, for example, advanced ceramic coatings help improve the efficiency and longevity of receiver tubes and heat exchangers by resisting oxidation, corrosion, and thermal fatigue. Similarly, in plasma-facing components of fusion reactors, UHTC coatings such as ZrB₂ and HfC play a crucial role in mitigating erosion and radiation-induced material degradation [79]. As the global energy sector continues to evolve, the development and integration of advanced ceramic materials in nuclear and renewable energy systems will be instrumental in enhancing safety, efficiency, and long-term sustainability. These innovations not only offer viable

solutions for overcoming the limitations of conventional structural materials but also pave the way for the next generation of high-performance energy technologies capable of operating under extreme conditions [80].

4.4. Aeroengine components

The use of UHTCs in aeroengines is driven by their high thermal conductivity and resistance to thermal shock, which allows them to maintain structural integrity under sudden and extreme temperature changes. However, their brittleness and difficulty in machining pose significant challenges. Despite these limitations, ongoing research focuses on improving processing techniques and mechanical properties, such as incorporating ceramic matrix composites (CMCs) to enhance durability and performance [4]. For instance, ZrB₂ and HfB₂-based composites are being developed for their high melting points and thermal conductivity, making them suitable for sharp leading-edge applications in hypersonic vehicles. In aeroengine applications, UHTCs can be used as coatings or monolithic structures, depending on the specific requirements of the component. For example, in combustion chambers, aluminosilicate CMCs are used for their tensile strength and environmental stability [81]. Meanwhile, ZrB₂-ZrC-SiC coatings are explored for their oxidation resistance and thermal stability, which are essential for components exposed to high-temperature oxidative environments. The integration of UHTCs into aeroengines not only enhances component lifespan but also contributes to improved engine efficiency and reduced weight, critical factors in modern aerospace engineering [82]. Despite the promising properties of UHTCs, their application in aeroengines is still evolving. Challenges such as poor oxidation resistance and low fracture toughness need to be addressed through advanced material processing and design strategies. Ongoing research aims to overcome these limitations by developing hybrid coatings and composites that combine the high-temperature capabilities of UHTCs with improved mechanical properties. As aeroengine technology continues to advance towards higher efficiency and performance, the role of UHTCs in protecting critical components will become increasingly important [83].

Ultra-high temperature ceramic materials have been applied across various fields, with a wide range of coating methods and materials used. Table 1 categorizes coatings or materials used, the synthesis or coating method, and their application are categorized by anti-wear properties in ultra-high temperature environments, including turbine blades or other areas related to energy production and optimization.

5. Challenges and future perspectives

Despite substantial progress in the development of wear-resistant ceramic coatings, several critical challenges continue to hinder their widespread application and long-term reliability in harsh environments. These challenges can be categorized into three main areas: material-related limitations, processing complexities, and economic constraints. From a materials perspective, oxidation resistance at ultra-high temperatures remains a major concern, particularly for carbide- and boride-based coatings. Exposure to high temperatures often results in the formation of porous oxide layers, which significantly reduce the mechanical strength and service life of the coatings. Practical failures, such as coating degradation observed in jet engine components and gas turbines, highlight the importance of addressing this issue. In addition, the inherent brittleness of ceramic materials makes them susceptible to

Table 1. Materials, coating methods, and applications of UHTCs.

Materials	Coating method	Application	Key advantages	Ref.
(TaNbHfTi)C based composite	Pulsed electro-spark deposition	Thin protective coating	<ul style="list-style-type: none"> Wear resistance High hardness (4.5 times more than substrate) 	[84]
Cf/C-UHTC carbon fabric composites	Hot pressing	High-speed high-enthalpy air plasma flow	<ul style="list-style-type: none"> Oxidation resistance Ablation resistance 	[85]
Cf/C-SiC-TiC-TaC CMC	Melt infiltration	Aerospace applications	<ul style="list-style-type: none"> Significant improvement in ablation/oxidation resistance 	[86]
ZrB ₂ -based UHTC composite	Spark plasma sintering	Wear-resistant coatings	<ul style="list-style-type: none"> A high wear resistance Improved microstructural bonding and reduced porosity 	[87]
(Ta, Nb, Hf, Ti)C-based MC-UHTC	Spark plasma sintering	Wear-resistant applications under high mechanical loading	<ul style="list-style-type: none"> Dominant wear mechanisms shift from micro-cracking/delamination to grain deformation Improved wear resistance (49% higher in quaternary UHTCs compared to binary) 	[88]
ZrB ₂ -based UHTC composite	Conventional sintering (1600 °C, 1700 °C) & spark plasma sintering	Wear-resistant coatings and structural applications	<ul style="list-style-type: none"> Enhanced mechanical properties in SPS-sintered samples (flexural strength: 336.3 MPa, fracture toughness: 7.32 MPa m^{1/2}, modulus of elasticity: 249 GPa). Reduced porosity, improving flexural strength and hardness 	[57]
SiC, VC, ZrC-based UHTCs	-	Reactor core applications (CANDU, PWR, VVER)	<ul style="list-style-type: none"> High melting point and low density for improved reactor performance Alternative to conventional zircaloy cladding 	[89]
ZrB ₂ -based UHTC	-	Neutron irradiation study for fusion reactor first-wall structures	<ul style="list-style-type: none"> High-temperature stability with potential for first-wall applications 11B enrichment mitigates helium production, improving irradiation resistance 	[90]
SiC/UHTC/SiC triple-layer coating	Chemical vapor deposition (CVD) & brushing-sintering	Oxidation protection for C/SiC composites	<ul style="list-style-type: none"> Long-term oxidation resistance at high temperatures Low mass loss rates at 1100–1500 °C Synergistic protection from ZrB₂-based UHTC and SiC layers 	[91]
ZrB ₂ -based coatings with secondary phases (SiC, MoSi ₂ , TaC)	Air plasma spraying (APS)	High-temperature oxidation and ablation resistance	<ul style="list-style-type: none"> Enhanced ablation resistance (2.4 MW/m², 60 s) Insights into thermally sprayed non-oxide ceramic coatings 	[92]
SiC-ZrC-based composite coatings	Polymer precursor pyrolysis (PPP) + gaseous reactive infiltration (GRI)	Ablation-resistant coatings for carbon/carbon composites	<ul style="list-style-type: none"> Enhanced ablation resistance (-0.3 mg/s, -0.53 μm/s) Increased UHTC (ZrC) content via ZrSi₂ infiltration 	[93]
(Ta,Nb,Hf,Ti)C-based MC-UHTCs	Spark plasma sintering	High-temperature applications, thermal protection systems for hypersonic flight	<ul style="list-style-type: none"> Improved hardness (up to 34.8 GPa) Enhanced resistance to indentation damage (72% at 200 N load) 	[77]
C/C-UHTC composites with dual-layer UHTCs oxidation coating	Arc-heated wind tunnel exposure	Oxidation resistance in high-temperature environments	<ul style="list-style-type: none"> Excellent ablation resistance with mass ablation rate of -1.9×10^{-2} mg/cm²s 	[94]
ZrB ₂ -10 vol% SiC UHTC reinforced with 0/90 ° carbon fiber	Self-designed dynamometer test	Braking and sliding conditions, tribological applications	<ul style="list-style-type: none"> Stable friction coefficients (0.86 and 0.40 at 1 MPa and 3 MPa with steel disk) Enhanced wear resistance under braking conditions 	[95]

cracking under thermal or mechanical stress. Enhancing fracture toughness without compromising wear resistance remains a key research objective. Another persistent issue is the weak adhesion between ceramic coatings and underlying metallic or composite substrates, which can lead to delamination and premature failure, especially under cyclic thermal or mechanical loading [96]. Another major challenge is understanding the wear behavior of ceramic coatings under real-world conditions, such as thermal cycling, high-speed erosion, and complex mechanical loading. Addressing

these challenges requires continued research and innovation in material science, fabrication techniques, and application methods [97].

Processing-related challenges are associated with the complexity and sensitivity of deposition methods. Techniques such as chemical vapor deposition (CVD), physical vapor deposition (PVD), and plasma spraying require precise control over parameters including temperature, gas flow rate, and pressure. These processes are often energy-intensive and expensive, which limits their scalability. Emerging methods, such

as atomic layer deposition (ALD), offer better control at the atomic level and improved uniformity. ALD is a gas-phase technique that relies on sequential, self-limiting surface reactions to deposit conformal thin films with high precision. However, its integration into large-scale industrial applications remains limited due to high costs and processing time [98]. Economic limitations also present significant barriers to broader implementation. The high cost of raw materials, specialized equipment, and the energy required for deposition processes contribute to the overall expense of ceramic coatings. Furthermore, maintaining consistency and performance at industrial scales is challenging. To address these issues, researchers are investigating advanced material systems such as high-entropy ceramics and multi-principal element ceramics, which exhibit superior thermal stability and mechanical robustness compared to traditional single-phase ceramics. Functionally graded coatings, where the composition or structure gradually changes across the coating thickness, help reduce thermal mismatch and improve adhesion. Nanostructured coatings are also being developed to enhance hardness and thermal resistance. Another promising direction is the incorporation of self-healing mechanisms using reactive additives such as rare earth oxides or borosilicate glasses, which can facilitate microcrack repair under operating conditions. In parallel with materials innovation, computational modeling and machine learning are increasingly being used to predict the behavior of ceramic coatings under various service conditions. These tools accelerate the design and optimization process. The integration of real-time monitoring systems through embedded sensors is also gaining attention, offering the possibility to track coating health in critical applications such as aerospace, nuclear reactors, and energy systems [99].

6. Conclusions

Wear-resistant ceramic coatings play an essential role in extending the operational life of components exposed to extreme environments, particularly in high-temperature energy systems, aerospace applications, and industrial machinery. This review has highlighted the significant progress made in the development of oxide-, carbide-, nitride-, and boride-based ceramics, emphasizing their superior mechanical, thermal, and chemical properties. The evolution of deposition techniques such as CVD, PVD, and plasma spraying has further enhanced the applicability and efficiency of these coatings in demanding conditions. However, several challenges, including oxidation resistance, fracture toughness, and processing complexities, remain significant obstacles to widespread adoption. Looking ahead, emerging innovations such as high-entropy ceramics, self-healing coatings, and advanced computational modeling offer promising avenues for overcoming these challenges. The integration of smart monitoring technologies and data-driven material design will further optimize the performance and longevity of ceramic coatings. Continued research and interdisciplinary collaboration will be key to unlocking the full potential of these materials, paving the way for next-generation solutions in energy, aerospace, and other high-performance industries. As technology advances, wear-resistant ceramic coatings will continue to play a pivotal role in enhancing efficiency, sustainability, and reliability across various engineering applications.

CRedit authorship contribution statement

Farrokhfar Valizadeh Harzand: Investigation, Writing – original draft, Writing – review & editing

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Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

Declaration of competing interest

The authors declare no competing interests.

Funding and acknowledgment

The authors would like to express their sincere gratitude to Jaddeh Construction Company for providing research resources and facilities, as well as for their insightful input on emerging industrial trends and future application needs. Their support played a key role in enhancing the depth and relevance of this review.

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