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Review

# Expanding the members of ultra-high temperature ceramics and their maximum service temperature exceeding 3000 °C

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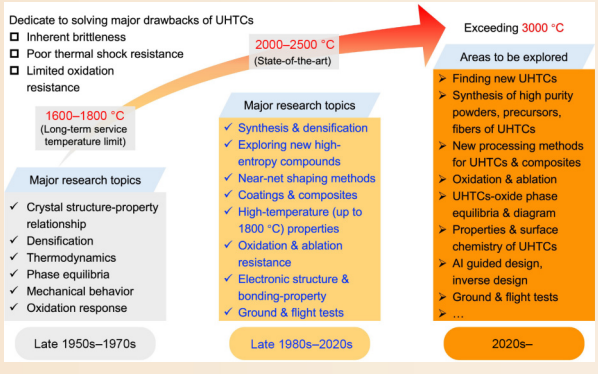
**ABSTRACT:** Aerodynamic heating, oxidation, ablation, and high dynamic pressure represent the extreme environments that aerospace vehicles must withstand during high-Mach atmospheric or trans-atmospheric flight. The temperature of critical components on the vehicles can reach 3000 °C or higher. Such an extreme environment imposes stringent requirements on thermal protection materials, such as ultrahigh temperature ceramics (UHTCs) and their composites. The formation of a dense oxide scale with low oxygen permeability is crucial for ensuring the ablation resistance of UHTCs. As such, searching for oxides with melting points exceeding 3000 °C is one of the emerging directions. This perspective aims to briefly review the development of UHTCs and their composites over the past few decades. In addition, promising directions are proposed to meet extreme environments. Concurrently, the assistance of multiscale modeling techniques to accelerate the development and application of UHTCs and their composites is emphasized.




**KEYWORDS:** ultrahigh temperature ceramics (UHTCs); ceramic matrix composites; ultrahigh melting point oxide; oxidation resistance; ablation resistance; extreme environments; hypersonic vehicles

## 1 Introduction

3000 °C is an extremely high temperature. It is also a notable criterion for the melting point of materials, although arbitrary, that distinguishes ultrahigh temperature ceramics (UHTCs) from others [1]. Historically, three independent aspects of materials, i.e., melting temperature, ultimate use temperature, and chemical composition, have been applied to define UHTCs, providing three different definitions [1,2]. Currently, these three criteria are integrated to define UHTCs; that is, UHTCs are early transition metal carbides, borides, or nitrides with melting points above 3000 °C and are readily available for use in oxygen-containing atmospheres at temperatures over 2000 °C [1–4].

Historical research into UHTCs originated in the late 19th century, focusing on their synthesis and fundamental properties. The field gained significant traction in the mid-20th century due to the demand for materials suitable for extreme environments, such as rocket propulsion and atmospheric reentry [1,3,4]. Subsequently, extensive investigation and validation of UHTCs were conducted [5–9], which identified the benchmark UHTC systems, i.e., UHTCs incorporating SiC with a volume fraction of 20%. However, the practical implementation of UHTCs was hindered by unresolved issues concerning inherent brittleness and poor thermal shock resistance, possibly compounded by insufficient raw material purity [10]. The field experienced a revival toward the end of the last century, driven by the critical need for ultrahigh temperature nonablative thermal protection materials [11–17]. Conventional materials, such as refractory metals and carbon-based composites, are deemed inadequate due to their limited oxidation resistance under high-temperature and oxygen-containing atmospheres. Over the past quarter of a century, substantial progress has been made in UHTCs, encompassing bulk ceramics [18–23], porous ceramics [24–27], composites [28–30], and coatings [31–34]. Major research topics of UHTCs during different periods and their long-term service temperature limits are listed in Fig. 1. UHTC-based thermostructural components are now finding practical use in specific applications. As these applications push toward extreme environments, UHTCs face a new set of challenges.

The actual application environment is an ultrahigh temperature oxygen-containing atmosphere, wherein the oxidation of UHTCs is a problem that must be faced [13,35,36]. In such an extreme environment, the thermophysical properties (such as the melting point) of the oxidation products partially determine the upper temperature limit for the practical application of UHTCs [35]. It has been recognized that to realize the application of thermal

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protection materials surpassing the 3000 °C limit, not only the UHTCs but also their oxidation products must be able to withstand 3000 °C, and the oxidation products must be capable of preventing the UHTC matrix from further oxidation. These stringent requirements are not only challenging to materials science but also place the field of UHTCs at a critical junction. At the critical junction of the field, providing future directions based on historical achievements is of paramount importance. This perspective will briefly summarize the key advancements in bulk UHTCs and ultrahigh temperature ceramic matrix composites (UHTCMCs) over the past decades, discuss strategies for addressing current limitations, outline the future trajectory of UHTCs development, pose potential challenges that may arise, and present our perspectives on the field.

## 2 Bulk ultrahigh temperature ceramics

**Synthesis**. Powders are crucial raw materials for UHTCs. The synthesis methods for UHTC powders can be categorized into solid-state reactions, liquid precursor conversion synthesis, and vapor phase reactions [37–40]. Table 1 lists the advantages and disadvantages of these three methods. Solid-state reactions involve mixing raw material powders and then reacting them at high temperatures to obtain UHTC powders [37]. This method can produce large batches of ceramic powders. Liquid phase synthesis is a method that has rapidly developed only in this century [39,41–43]. Liquid precursor-to-ceramic conversion is basically a two-step process that involves the decomposition of the precursor to oxides with carbon upon pyrolysis and carbothermal or borothermal reduction reactions to form the target UHTCs. Liquid precursor methods can produce polymeric precursors for UHTCs, which can be directly converted into UHTC compositions upon pyrolysis. Vapor phase reactions involve gas-phase reactions [40], typically using easily vaporized metal halides as raw materials. High-purity, low-oxygen content UHTC powders are prepared by laser or plasma-induced high-

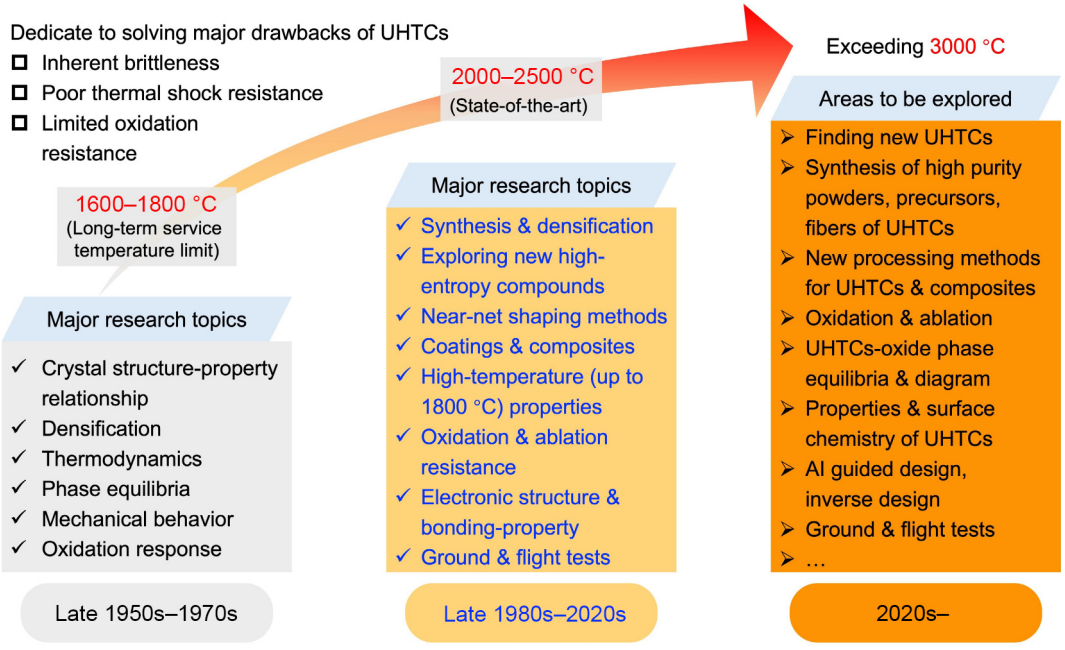


**Fig. 1** Timeline of UHTC research and developments dedicated to solving the major drawbacks of UHTCs. The chart outlines the major research topics explored across different periods and the future areas of exploration to break the 3000 °C service temperature limit.

**Table 1** Advantages and disadvantages of the synthesis methods for UHTC powders

| | Advantage | Disadvantage |
|---|---|---|
| Solid-state reaction | ⮝ Mass production<br>⮝ Broad applicability<br>⮝ Simple processes | ⮝ High processing temperature<br>⮝ Long reaction time<br>⮝ Impurities<br>⮝ Difficulty in microstructure control (shape and size)<br>⮝ High energy consumption |
| Liquid precursor conversion synthesis | ⌑ Atomic-level mixing<br>⌑ Low processing temperature<br>⌑ Complex shape fabrication (e.g., fibers, coatings)<br>⌑ High homogeneity | ⌑ Limited choice of precursors<br>⌑ Complex processes<br>⌑ High cost<br>⌑ Low ceramic yield<br>⌑ Porosity & shrinkage<br>⌑ Toxicity and safety |
| Vapor phase reaction | ✧ High purity and density<br>✧ Coatings and thin films<br>✧ Exceptional control over the crystallinity, texture, and anisotropy | ✧ Complex processes<br>✧ Slow deposition rate<br>✧ High cost<br>✧ Low yield<br>✧ Size restriction<br>✧ Toxicity and safety |

temperature reactions. This method is often used for the preparation of nitride and carbide coatings. It is of note that over the past quarter-century, research has primarily focused on exploring new powder synthesis techniques and designing new compositions [44–50]. The progress in the design and synthesis of polymeric UHTC precursors has been relatively slow, which may be ascribed to the high chemical activity and strong covalent bonding of transition metal cations (e.g., $Zr^{4+}$ and $Hf^{4+}$) of groups 4 and 5 with anions. These *d*-orbital transition metal cations prefer to form stable inorganic bonds or oligomers rather than forming long-chain polymer backbones.

**Densification**. UHTCs share common characteristics: high melting points, strong covalent bonding (Fig. 2(a)), and low self-diffusion coefficients [18,51], which make their densification difficult. Consequently, sintering techniques [52] such as field-assisted sintering, pressureless sintering, and flash sintering have been developed to obtain dense bulk UHTCs (Fig. 2(b)). A series of representative advancements in pressureless sintering were achieved at the beginning of this century [51,53,54]. The pressureless sintering mechanism focuses on an oxygen removal mechanism, which eliminates oxygen contamination from the surface of UHTC powders, thereby improving the material's sintering activity. $B_4C$ and WC are considered effective pressureless sintering aids [53,55], which enable densification via pressureless sintering at approximately 1900 °C without negatively affecting the high-temperature mechanical properties of the UHTCs. The development of pressureless sintering has also facilitated the preparation of high-quality powders and UHTCs with complex geometries [56]. More recently, liquid phase-assisted ultrahigh temperature fast sintering of UHTCs has been developed, enabling the fabrication of UHTCs with complex geometries [57]. However, the impact of the liquid phase in the grain boundaries on the high-temperature performance of UHTCs warrants attention.

**Mechanical properties**. Extensive research has been conducted on the mechanical properties (flexural strength, elastic modulus, fracture toughness, etc.) and thermophysical properties (thermal conductivity, coefficient of thermal expansion, etc.) of UHTCs, establishing composition-preparation-property relationships for these materials [1,3,18,47,58]. Taking zirconium diboride ($ZrB_2$) as an example, the reported elastic modulus values are all approximately 500 GPa. However, its room-temperature flexural strength (ranging from 300 to 1000 MPa) is significantly influenced by composition, sintering method, and microstructure. The relationship between room-temperature flexural strength and grain size adheres to the Hall-Petch relationship [59], meaning that the strength is approximately inversely proportional to the square root of the grain size. The addition of secondary phases such as SiC not only promotes the densification of $ZrB_2$ but also suppresses the grain growth of $ZrB_2$, thereby enhancing its flexural strength. However, when the volume fraction of SiC exceeds 20 vol%, no significant changes in the flexural strength have been made [59,60]. Regarding high-temperature strength, the fracture mode in UHTCs at high temperatures is generally intergranular fracture [11,61,62]. Clean grain boundaries positively impact the high-temperature strength and creep resistance of UHTCs. Multicomponent compositions can also significantly improve the creep resistance of UHTCs, with the steady-state creep rate of high-entropy ceramics being nearly one-tenth that of binary carbides [63]. Fracture toughness is critical for UHTCs in actual service environments. Improving fracture toughness is key to enhancing the damage tolerance and thermal shock resistance of UHTCs [64]. Various toughening methods have been developed, including particulate toughening and fiber reinforcing [3,16]. Among them, continuous fiber-reinforced UHTCs can effectively resolve the inherent brittleness of bulk UHTCs [65,66].

**Thermophysical properties**. During high Mach flight, hypersonic vehicles endure severe aerodynamic heating, and

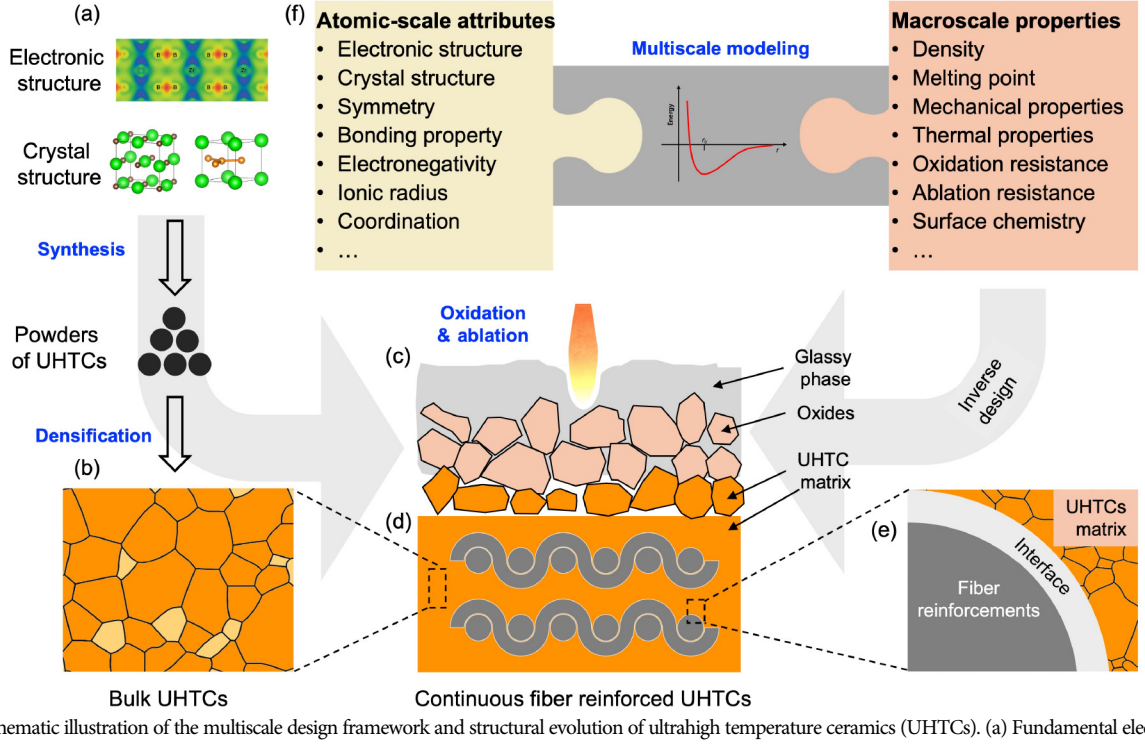


**Fig. 2** Schematic illustration of the multiscale design framework and structural evolution of ultrahigh temperature ceramics (UHTCs). (a) Fundamental electronic and crystal structures. (b) Microstructure of bulk UHTCs fabricated via powder synthesis and densification. (c) Cross-sectional schematic showing the oxidation and ablation behavior. (d) Designed architecture of continuous fiber-reinforced UHTCs, showing (e) critical fiber-matrix interface microstructure. (f) Material design strategy bridging atomic-scale attributes with macroscale properties through multiscale modeling and inverse design approaches.

critical components experience extreme thermal gradients, which can change from −170 to 3000 °C across distances on the order of 1 cm [17]. Thermophysical properties such as thermal conductivity, volumetric heat capacity, and coefficient of thermal expansion are among the key factors determining the successful application of UHTCs [35]. The mismatch in the coefficient of thermal expansion between UHTCs and the secondary phase is a problem that negatively affects high-temperature applications. The thermal conduction mechanism changes at high temperatures; for example, at 1800 °C or higher, electronic thermal conduction is the dominant heat transfer mechanism in $ZrB_2$–SiC ceramics [67]. Extensive research suggests that grain boundaries are one of the major factors influencing the high-temperature mechanical properties and thermal conductivity of UHTCs, and clean grain boundaries play an active role in enhancing these properties [62]. Therefore, it is believed that grain boundary engineering is an effective approach for improving the high-temperature properties of UHTCs [68,69].

**Oxidation resistance**. During atmospheric reentry, hypersonic vehicles encounter an ultrahigh temperature oxidizing environment. As such, the oxidation resistance of UHTCs is another critical indicator of their suitability. The initial oxidation temperatures of UHTCs are all below 800 °C [11,45]. Borides exhibit a slightly higher initial oxidation temperature than carbides and nitrides. Secondary phase additives, such as SiC, can significantly enhance the oxidation resistance of UHTCs [70]. The mechanism for enhanced oxidation resistance is primarily based on the formation of a high-viscosity B–Si–O glassy phase in an oxidizing environment [71–73], as schematically illustrated in Fig. 2(c). This glassy phase seals the pores in the oxidation products of UHTCs (e.g., $ZrO_2$ and $HfO_2$), acting as an oxygen barrier due to its low oxygen conductivity. However, most current results are obtained under laboratory static oxidation conditions, raising the question of their applicability to actual service environments [1]. For example, Parthasarathy *et al.* [74] compared laboratory static oxidation test results with simulated flight environments and concluded that differences exist in the oxidation behavior of UHTCs, a disparity that currently lacks a satisfactory explanation.

Thermodynamic calculations can guide the phase equilibrium of multicomponent UHTC oxidation products. Based on the Ellingham diagram, the composition of oxidation products in composite ceramics can be quantitatively calculated [75]. Thermodynamic calculations show that a large tendency toward preferential oxidation is expected in these materials, even for elements whose oxides exhibit a small difference in thermodynamic favorability. For instance, in the binary TiC–TaC system, the oxidation product mainly consists of $TiO_2$; even if the mole fraction of TaC is over 90%, the mole fraction of $Ta_2O_5$ in the oxidation products rarely exceeds 20% [75]. Thermodynamic calculations demonstrate a clear preferential oxidation sequence in binary systems. Nevertheless, whether this conclusion can be extended to high-entropy carbides and borides is still debated and requires further validation. The phase equilibria between high-entropy UHTCs and their oxidation products merit systematic investigation.

The phase stability and oxygen permeability of the oxide layer play a crucial role in protecting the substrate UHTCs from oxidation. Zirconia ($ZrO_2$) and hafnia ($HfO_2$) undergo phase transformations at high temperatures, with the monoclinic-tetragonal phase transition accompanied by a considerable volume change of ~3%. Doping with rare earth elements and alkaline earth metal elements effectively suppresses these phase transitions. Consequently, the use of rare-earth-doped UHTCs to enhance their oxidation and ablation resistance has been reported in the literature [76–78]. However, according to defect chemistry, doping with rare earth or alkaline earth metal elements generates abundant oxygen vacancies in $ZrO_2$ and $HfO_2$, which increases the oxygen ion conductivity of the oxides and thereby reduces their oxidation resistance to some extent. In sharp contrast, doping high-valence transition metal cations, such as $Ta^{5+}$, can suppress the formation of oxygen vacancies in these oxides [79], thus enhancing their oxygen blocking capacity and improving the oxidation resistance of the material. Based on these facts, it is of great significance to investigate the high-temperature phase stability of solid solutions of $ZrO_2$ and $HfO_2$ doped with high-valence cations. Meanwhile, developing glassy oxides with high melting points, high viscosity and low oxygen permeability holds significant importance. High-melting-point glassy phases could heal and fill the voids within the crystalline oxide framework, while the crystalline oxide framework could prevent the glassy phase from being eroded by high-velocity gas flows. Together, they may form a dense oxide layer that protects the substrate.

**Ablation resistance**. Ablation is a very complex process, and different evaluation methods influence the service performance of UHTCs [21,34,80,81]. A single report of negative evaluation does not always accurately reflect the intrinsic properties of the UHTCs. It is recommended to select an appropriate ablation evaluation method based on the specific application context. UHTCs first undergo oxidation, and the resulting oxide scale is the actual material that directly faces the external environment. The thermal response behavior of UHTCs is affected by a number of factors, including thermal conductivity, volumetric heat capacity, and catalytic coefficient [35,72,73]. The current consensus is that a dense, continuous, and low-oxygen-permeability oxide layer is essential to ensuring the ablation resistance of UHTCs, as schematically shown in Fig. 2(c). Current oxide scale systems are primarily based on the B–Si–O glassy phase generated from the oxidation of borides and carbides (typically SiC). The long-term service temperature of UHTC-SiC is limited to below approximately 1800 °C by the active oxidation of SiC [70]. During long-term ablation, attention must be paid to the change in surface chemistry of the oxide scale [35]. There is currently a lack of clear understanding regarding the fundamental properties of the B–Si–O glassy phase, such as its high-temperature viscosity and adhesion with the matrix. Moreover, the B–Si–O glassy phase is a low-melting-point phase, and its melting point determines, to some extent, the upper limit temperature of the use of UHTCs.

It is apparent that increasing the melting point of the oxidation product can raise the operational temperature limit. Therefore, developing new oxide ceramic systems with melting points exceeding 3000 °C has become an emerging research direction. Very recently, a group led by Zhou established a universal design paradigm for developing new oxide materials with ultrahigh melting points [82]. They concluded that oxides exhibiting high melting points possess high crystal structural symmetry, have valence electron concentrations between 2.4 and 2.7, feature coordination numbers of 8, and exhibit relatively small cation radii. This mechanism is verified in the Hf–Ta–O system, pushing the melting point past the 3000 °C mark and setting the highest record for nonradioactive oxides. The melting point of $Hf_{0.85}Ta_{0.15}O$ is reported as 3006 °C, making the oxide a new member of the UHTCs. Doping with high-valence Ta cations can also reduce the oxygen conductivity of the oxide [79]. It is worth noting that finding high-melting-point oxides is the very first step forward in oxide scale design toward 3000 °C application. The primary issue is to determine which nonoxide components yield

oxidation products that form high-melting-point oxides. Their comprehensive properties, including mechanical, thermal, and physical (e.g., viscosity, catalytic properties, emissivity, adhesion to the matrix) characteristics, also need to be investigated. Actual service conditions are highly complex. The operating temperature or response temperature (e.g., 3000 °C) represents only one parameter among many, accompanied by extremely high heat flux densities, high-pressure gas erosion, abrupt thermal gradients, and intricate gas phase compositions. The ablation resistance of a material reflects its dynamic response under extreme thermal-mechanical-chemical coupling fields.

**Phase equilibrium and diagram**. In the mid-to-late 20th century, researchers conducted extensive studies on the phase equilibrium relationships of UHTCs, mapping out numerous binary and ternary phase diagrams [8,83]. These phase diagrams remain widely used and play a crucial role in UHTC design. However, constrained by the technology available at the time, many phase diagrams contain undetermined regions, or some conclusions require further verification. Current theoretical calculation and experimental characterization techniques, such as neutron powder diffraction, can be used to refine or update these phase diagrams. One example is the Zr–C binary phase diagram [84,85]. In the widely accepted experimental phase diagrams, $ZrC_x$ is stable for x values ranging from 0.63 to 0.98. However, current theoretical phase diagrams and experimental results both confirm the existence of a new phase, i.e., $Zr_2C$, which has ordered carbon vacancies [85]. The ordered structure of carbon vacancies influences the sintering, mechanical, and thermal properties of $Zr_2C$ [86]. Furthermore, large undetermined regions exist in the high-temperature phase diagrams of some binary systems (such as $ZrO_2$–$Ta_2O_5$ and $HfO_2$–$Ta_2O_5$) that require in-depth investigation.

**Multiscale modeling**. Computational science has provided a powerful tool for the design, structural analysis, and performance simulation of UHTCs. It allows for the analysis of UHTCs at multiple scales by selecting appropriate computational methods [87]. Density functional theory (DFT)-based first-principles calculations can provide atomic-scale information for UHTCs, such as electronic structure, chemical bonding, and intrinsic elastic properties [1,86]. Molecular dynamics studies can be used to simulate the pyrolysis behavior of polymer precursors [88] and the dynamic oxidation process of UHTCs [89]. Phase-field modeling can be used to predict mesoscale phenomena of UHTCs, such as the microstructure evolution and fracture process of $ZrB_2$-based UHTCs [90]. Finite element analysis (FEA) can be used at the macroscale to predict the high-temperature mechanical properties of UHTCs [91] and heat transfer in UHTCMCs [92]. By integrating with new computational technologies such as artificial intelligence (AI) and machine learning (ML), multiscale simulation offers great promise for accelerating the development and application of UHTCs.

## 3 Ultrahigh-temperature ceramic matrix composites (UHTCMCs)

The inherent brittleness of UHTCs and the resulting poor thermal shock resistance are major obstacles limiting their application [64,66,93]. To tackle this issue, various UHTC toughening methods have been developed to enhance their fracture toughness, damage tolerance, and thermal shock resistance, including particle, whisker, and fiber reinforcement [3,29,65,66,94]. Among numerous reinforcements, continuous fiber toughening has been proven to be an effective means of addressing the brittleness of UHTCs. Figures 2(d) and 2(e) schematically show the microstructure of the continuous fiber-reinforced UHTCs, which can improve the fracture toughness from 3–5 $MPa{\cdot}m^{1/2}$ for monolithic UHTCs to 10–20 $MPa{\cdot}m^{1/2}$ for UHTCMCs. The basic structural elements of continuous fiber-reinforced UHTCs consist of three parts: the UHTC matrix, the fiber reinforcements, and the interface (Fig. 2(e)). The composition and structure of each part affect the performance of UHTCMCs. Research on UHTCMCs primarily focuses on these three components, leading to significant progress in their preparation, processing, performance testing, theoretical simulation, etc.

**UHTCMCs processing**. Multiple processing methods have been developed for UHTCMCs, including pressure sintering, slurry infiltration, precursor infiltration and pyrolysis (PIP), reactive melt infiltration (RMI), and chemical vapor infiltration/deposition (CVI/CVD) [3,66]. Each method has its own advantages and disadvantages, and the appropriate process is selected based on different application requirements. Generally, pressure sintering and RMI easily cause damage to the fibers. CVI/CVD is more suitable for preparing thin-shell composite structures. The liquid precursors for PIP are expensive, with limited selection, and the preparation cycle is long. Most processing methods involve precursor-to-ceramic conversion, which can lead to detrimental factors such as the formation of cracks, pores, and residual stress. Slurry infiltration directly uses UHTC powders as raw materials. However, challenges include uniformly filling the preform with ceramic powders, obtaining a uniform and stable slurry, and preventing ceramic particles from clogging the preform channels. A common challenge across all methods is that the UHTC matrix in UHTCMCs needs a certain degree of densification to function as expected. Achieving low-temperature densification of the UHTC matrix remains challenging.

The team led by Zhang [95–97] proposed the so-called "double continuous structure" based slurry infiltration strategy for UHTCMCs. This concept refers to a three-dimensionally continuous fiber reinforcement and a UHTC matrix with sufficiently high content to form a continuous structure. They achieved efficient compounding of UHTC powders and the carbon fiber preform. The volume content of the ceramic matrix in UHTCMCs can exceed 50%, and the sintering temperature can be reduced from 2000 to 1300 °C. The fracture toughness of the UHTCMCs was improved by an order of magnitude. Significantly, their UHTCMCs exhibited near-zero ablation in a strong oxidizing environment at temperatures up to 2500 °C [96].

**Oxidation and ablation resistance of UHTCMCs**. As with bulk UHTCs, the oxidation resistance and ablation resistance of UHTCMCs depend largely on the oxidation products of the ceramic matrix [29,30,94–96,98], as schematically shown in Fig. 2(c). However, it is worth noting that the fiber reinforcement and the interface are typically more susceptible to oxidation than the ceramic matrix. The channels left by oxidation of the fiber reinforcement and interface can become pathways for free oxygen diffusion. The issue of thermal mismatch caused by differences in the coefficient of thermal expansion also warrants attention. To overcome the oxidation and ablation resistance limits of UHTCs and their composites, multiscale modeling techniques can be employed to design oxide scales based on the requirements of their properties, as shown in Fig. 2(f). Subsequently, nonoxide UHTCs can be inversely designed according to the phase equilibrium between nonoxides and oxides. Such inverse design of UHTCs and their composites could reduce the high costs associated with the traditional trial-and-error paradigm in new material development.

All the above approaches are based on the logic of passive

thermal protection, which continuously improves the material's intrinsic properties, relying on its excellent physicochemical performance to endure the extreme service environment. Active thermal protection is also a very attractive way to break through the usage limits of existing materials. This involves designing the material's structure to dissipate a portion of the incoming heat flow, thereby lowering the response temperature. Hybrid active/passive thermal protection systems are complex to design and impose extremely high demands on the materials. This area is still in its infancy for UHTCs and their composites. Unpublished results show that hybrid active/passive thermal protection can significantly enhance the ability to cope with extreme environments.

## 4 Summary and outlook

The development of UHTCs is driven by the need to find materials applicable in extreme environments. The first wave of UHTC research began in the late 1950s to find materials usable in rocket propulsion systems. The second wave of UHTC research started in the late 1980s and continues to currently aim to meet the material demands of hypersonic vehicles. The investigation of UHTCs in the first stage centered on the properties deduced from their crystal structures, while in the second stage, it involved material design based on the understanding of their electronic structures. Due to the excellent comprehensive properties that UHTCs exhibit in extreme environments, their application scenarios are no longer limited to aerospace-related fields. They hold important prospects for widespread use in the fields of energy, materials processing, microelectronics, etc. Non-oxides have consistently been the central focus of UHTC research over the past few decades. However, it is recognized that their oxidation products play key roles in ensuring their application in oxidizing environments. To break through the temperature limit of existing UHTC systems, one feasible research direction is to design oxidation products, i.e., searching for oxides with melting points exceeding 3000 °C. Such oxides could be considered new members of UHTCs. This may open a third wave of UHTC research, marked by a service temperature exceeding 3000 °C. Perhaps when reviewing the history of UHTC development decades from now, the discovery of the first nonradioactive $Hf_{0.85}Ta_{0.15}O$ UHTC will be regarded as a milestone.

Future research on UHTCs is crucial for developing materials capable of withstanding extreme temperatures up to 3000 °C. Key opportunities and challenges motivate research across several areas in particular: discovering new UHTC compounds, including both oxides and nonoxides; synthesizing high-purity UHTC powders to enable low-temperature sintering and potentially enhance high-temperature performance; and developing polymeric precursors that can directly convert into UHTC compositions, which would facilitate the processing of UHTC fibers and UHTCMCs. Further efforts should also focus on exploring new processing methods for both UHTCs and UHTCMCs to lower production costs and shorten the preparation cycle. Fundamentally, research must also concentrate on understanding the room- and high-temperature properties of oxide UHTCs, including their surface chemistry and phase equilibrium with corresponding nonoxide UHTCs, and critically, clarifying the actual service environment and simulating it accurately in the laboratory. Harnessing artificial intelligence (AI) for establishing correlations between atomic-scale attributes and macroscopic properties enables the targeted design of material composition, microstructure, and properties, ultimately realizing the inverse design of UHTCs (Fig. 2(f)). For the practical application of UHTCs and their composites, integration with hypersonic vehicle design, aerodynamic design, manufacturing, processing, and assembly is needed, and each link is worthy of intensive effort.

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### Availability of data and materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

### Competing interests

The authors have no competing interests to declare that are relevant to the content of this article. The author Yanchun Zhou is the Editor-in-Chief of this journal. The authors Fei Li, Guo-Jun Zhang, and Xinghong Zhang are the Editorial Committee members of this journal.

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