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Different Approaches of Ultra-High temperature Ceramics Material in Various Industrial Production

By

Ajay Verma
(Assistant Professor), Department of Mechanical Engineering, Shivalik College of Engineering, Deharadun,
Email: ajay.verma@sce.org.in

Prerna Bhargav
(Assistant Professor), Shivalik Institute of Professional Studies, Dehradun,

Jyoti Sharma
(Assistant Professor), College of Pharmacy, Dehradun

Abstract

There are different compounds in nature having different compositions which affect their properties one such compound is ceramics. Ceramics are used since old times for various purposes as they have high heat and electrical resistance and also are brittle. Thus the focus of the study is to know the importance of a new type of ceramics which is Ultra-High Temperature Ceramics (UHTC) in various industrial applications. There are many studies made on the different properties of the UHTC and their application in industries for different purposes. Thus, the UHTC is brittle with high heat and electrical resistance due to its unique elemental compositions. The approach made towards the UHTC is useful and efficient for industries to implement such material in high-temperature applications. Further study in UHTC will help in developing the new scope of UHTC in high-temperature applications of industries.

Keywords: Carbon fiber, Ceramics, Industry, Temperature, UHTC.

1. Introduction

Soil and other inorganic, nonmetallic materials are shaped and then heated to high temperatures to create a wide variety of ceramics that are hard, brittle, and heat corrosion-resistant. Standard materials include brick, porcelain, and earthenware. The earliest ceramics created by humans included pottery (kettles or containers) or figurines formed of clay, either alone or when combined with additional elements like silica, and then solidified and annealed in the fire. Later, flexible, unstructured ceramic coatings were applied over the crystal ceramic substrates to reduce porosity, resulting in smooth, colorful surfaces for ceramics [1]–[3].

Ceramics include a broad range of materials used in everyday life and sophisticated ceramic technologies such as semiconductors and the construction of buildings. Ceramics are inorganic, nonmetallic materials such carbides, oxides, and nitrides. Some substances, like silicon or carbon, can be categorized as ceramics. Brittle, rigid, strong in compression, poor in shearing and stress, ceramic materials are. It can withstand conditions that would destroy most other materials, including those that are acidic or caustic. Ceramics often have a high heat tolerance, generally functioning at temperatures up to 1,600 degrees Celsius [4], [5].

Materials made of ceramic have a wide range of crystallinities. In most cases, fired ceramics, such as earthenware, stoneware, and porcelain, are either verified or semi-vitrified. The majority of ceramic materials are effective electrical and thermal insulators because of their varied crystallite and electron concentration in the covalent and ionic bonds. The materials of ceramic have such a wide variety of potential alternatives, making it challenging to define specific characteristics for the grouping as a whole. With recognized exceptions to each of these general laws, qualities like high melting point, impact strength, poor conduction, elastic modulus, and poor ductility are the norm. Despite incorporating ceramic components, many composites, like fiberglass and carbon fiber, are not regarded as belonging to the ceramic family [6]–[8].

The processing options for highly orientated crystallographic ceramic material are limited. It can be dealt with in one of two ways: either by reacting in situ to create the ceramics in the correct shape or by "shaping" particles into the shape you want, then sintering them to create a solid body. Hand shaping, slip cast, tape casts, injection molds, dry press, and other processes are used to manufacture ceramics [9], [10].

Although glassmaking involves many of the same processes as the ceramic process and has mechanical characteristics similar to ceramics, many ceramics specialists do not consider amorphous materials like glass to be ceramics. Glass may, however, undergo heat treatments to become glass-ceramic, a semi-crystalline substance. [16]. Clay minerals like kaolinite are used in traditional ceramic raw materials, whereas aluminum oxide, sometimes known as alumina, is used in more contemporary ceramics. Silicon carbide with tungsten carbide are examples of contemporary ceramic materials that are categorized as advanced ceramics.[17].

Both are used in applications like wear plates for breaking machinery in mining projects because they are appreciated for their abrasion resistance. In addition to body armor, advanced ceramics are employed in the medical, electrical, and electronic sectors. Since at least 26,000 years ago, it appears that humans have been producing their ceramics by applying extreme heat to clay and silica to fuse and create ceramic materials. [18]–[19]. The earliest artifacts discovered thus far weren't dishes but rather carved figurines from southern central Europe. Clay and animal byproducts were combined to create the oldest pottery, which was then cooked in a kiln at high to 800°C. While genuine pottery fragments dating back up to 19,000 years have been discovered, regular pottery did not start to become widespread until around ten thousand years later.

Corded Ware was an ancient civilization that once flourished throughout much of Europe. Pottery made by ancient Indo-Europeans was decorated with rope wrappings while still wet. The rope burnt off during the firing of the pottery but left behind a beautiful pattern of intricate grooves. [20]. The development of the wheel finally allowed for the creation of smoother, more uniform pottery utilizing the wheel-forming method. Early ceramics were permeable and readily absorbed water. With the development of glazing processes, pottery can be coated with materials like silica, bone ash, or even other substances that might melt or rather reform into a glassy surface, decreasing a vessel's water resistance. [21]–[23]. Researchers working in e-Science fields such as meteorology, connectomics, sophisticated physics simulations, biology, genomics, and environmental studies meet difficulties. [16]- [41].

2. Literature Review

Feilden et al. (2019) [11] discussed that robocasting, an additive manufacturing method, was used to create hafnium diboride for this study. It has been possible to effectively produce complex shapes and interior structures that would have been impossible using conventional production methods. The theoretical density of the monolithic components is achieved during pressure-less sintering, at 94-97%. These parts have the same bending strength as UHTC parts made using traditional techniques: 364±31 MPa at room temperature and 196±5 MPa up to 1950 °C. These mechanical tests on a 3D-printed object are the highest-temperature ones yet performed. A wide range of materials can be produced utilizing robocasting with Pluronic pastes, as shown by the successful printing of high-density HfB_2.

Sciti et al. (2021) [12] evaluated that in this study, for the first time, researchers show how to make and characterize huge discs of Ultra high-temperature ceramic matrix composite (UHTCMC) out of a ZrB2/SiC matrix and PyC-coated PAN-based carbon fibers. The research is the result of a concerted effort on the part of several academic institutions, and it shows that UHTCMCs can be successfully scaled up for the production of substantial components. Using filament winding and spark plasma sintering, 150 mm discs were fabricated, and then specimens were machined to evaluate a wide range of material characteristics at both ambient and increased temperatures. Characterization experiments unearthed a novel material with mechanical properties comparable to CMCs but with fundamentally superior thermal stability. In addition, the study's shown scalability boosts the attractiveness of UHTCMCs in sectors like aerospace, where severe operating conditions prevent the use of conventional materials .

Gilli et al. (2021) [13] suggested that the evolution of the $(Zr, Ta)B_2$ solid solution's multi-scale microstructure was considered as a purpose of both time and high temperature . Hot persistent a combination of ZrB_2 and 15 volume percent $TaSi_2$, followed by annealing at 2100 degrees Celsius, yielded the final ceramics. TaC nano-needles precipitated inside the micron-sized boride grain matrix as a consequence of a supersaturated solid solution. Using phase stability diagrams, the optimal partial pressure settings inside the sintering chamber for the precipitation of metal or carbide nano-inclusions were identified. Different systems including various transition metals were produced utilizing this method to provide alternate preparations for in-situ nano-composites with amazing strength at ultra-high temperatures.

Ionescu et al. (2021) [14] discussed that the new domestic of resources known as ultra-high temperature ceramics (UHTCs) has the potential to provide mechanical stability and heat dissipation under extreme circumstances, such as chemically reactive plasma conditions and huge heat fluxes. The past several decades have seen much study and development in the areas of physical properties and processing of UHTCs. As a bonus, scientists are actively working to find synthetic entry routes to UHTCs and related materials with desirable properties like as high purity, changeable composition, nanoscale form, and improved sinterability. There has been a recent uptick in research on synthesis methods that use preceramic polymers as suitable precursors to UHTCs . These methods of synthesis are of significant interest for several uses, such as the creation of ultra-high temperature ceramic composites (UHT CMCs), additive manufacturing of UHTCs, etc. , since they permit the processing of UHTCs from the liquid phase. The physical properties and energetics of UHTCs are investigated in depth in the present review. UHTCs and related materials are also covered, as are several synthetic techniques including preceramic polymers to get these materials.

Orru et al. (2019) [15] discussed that the research delves into the importance of spark plasma sintering (SPS) technology in the production of ultra-high temperature ceramics for large-scale components (UHTCs). Very dense monophasic transition metal borides/carbides, binary/ternary composites, whiskers/fibers reinforced materials, high-entropy ceramics, and porous graded structures have been the focus of several studies, which have been published and studied. Particularly, a two-stage (nonreactive) technique is compared and contrasted, with the first phase being the production of UHTC powders using self-propagating high-temperature synthesis (SHS) and the second being consolidation via reactive sintering. Since the formation reactions of these ceramics are exceedingly exothermic, their synthesis processes evolve within the challenging-to-control combustion regime, and the latter method is generally considered more practical and adaptive for their production. Due to their high relative densities and other desirable features, SPS materials have great potential for use in industries like aerospace and solar power, where extreme circumstances are routine. The summary of the literature review is shown below in table 1:

Table 1. *summary of literature review*

Author	Methodology	Outcomes
Feilden et al. (2019) [11]	robocasting, an additive manufacturing method	A wide range of materials can be produced utilizing robocasting with Pluronic pastes, as shown by the successful printing of high-density HfB_2.
Sciti et al. (2021) [12]	UHTCMC	The study's shown scalability boosts the attractiveness of UHTCMCs in sectors like aerospace, where severe operating conditions prevent the use of conventional materials.
Gilli et al. (2021) [13]	UHTCMC	Transition metals were produced utilizing this method to provide alternate formulations for in-situ nano-composites with amazing strength at ultra-high temperatures.
Ionescu et al. (2021) [14]	Ultra-high temperature ceramics (UHTC)	The physical properties and energetics of UHTCs are investigated in depth in the present review. UHTCs and related materials are also covered, as are several synthetic techniques including preceramic polymers to get these materials.
Orru et al. (2019) [15]	UHTC	Due to their high relative densities and other desirable features, SPS materials have great potential for use in industries like aerospace and solar power, where extreme circumstances are routine.

3. Results and Discussion

Although UHTCs offer advantageous mechanical and thermal characteristics, their high working temperatures make them vulnerable to oxidation. At the high temperatures where UHTCs are most useful, the metal component oxidizes to a gas like CO2 or NO2, which would be rapidly lost. Boron, for instance, readily oxidizes to B2O3, which turns into a fluid at 490 °C and vaporizes very quickly above 1100 °C. Additionally, their fragility tends to make them poor manufacturing fabrics. Through the use of silicon carbide composites, fibers, and rare-earth hexaborides like lanthanum hexaboride, current research aims to increase their hardness and corrosion resistance.

It has been discovered that adding 30% mass silicon carbide to HfB2 and ZrB2 significantly increases their oxidative resistance due to the creation of a protecting glassy surface made of SiO2 at temperatures greater than 1000 °C. To ascertain the impact of SiC concentration on diboride oxidation, the oxidation scale thicknesses for pure HfB2, SiC, and HfB2 (20v %) SiC were examined as a result of temperature. Pure HfB2 has a smaller oxide scale than pure SiC at temperatures over 2100 K, and HfB2/20% SiC does have the best oxidation resistance. Increased oxidation resistance and enhanced mechanical qualities, such as impact toughness, are produced via extreme heat treatment.

To create thick, long-lasting materials, diboride-based UHTCs frequently need to be processed at high pressure and temperature. It is challenging to produce homogeneous densification in UHTCs due to their high melting temperatures and robust covalent bonds. Only at temperatures greater than 1800 °C, after grain boundary diffusion processes are activated, can densification occur. Sadly, manufacturing UHTCs at some of these temperatures yields materials having higher grain sizes and subpar mechanical characteristics, including lowered toughness and hardness. The surface oxide layer could be eliminated, the defect concentration can be raised, or additives like SiC can be utilized to generate a liquid phase just at processing temperature to accomplish densification at lower temperatures.

SiC can interact also with oxide on the surface layer to produce more energetic diboride surfaces by adding 5–30 vol% SiC has shown that UHTCs are more oxidation and densification resistant. Diboride UHTCs can have SiC incorporated as a powdered or a polymer. Since SiC develops at the crystalline structure when applied as a polymer, increasing measurements of microhardness (by around 24%), adding SiC as a polypropylene provides several advantages over adding SiC as a powder. When adopting this technique, less SiC must be added, which restricts the paths for oxygen to permeate into the substance and react, in addition to the method's better mechanical qualities. While adding additives like SiC can help UHTC materials become denser, doing so lowers the highest temperature during which UHTCs can function since these compounds cause the development of eutectic liquids. The working temperature of ZrB2 is reduced from 3245 °C to 2270 °C by the addition of SiC.

To withstand the stresses and temperatures encountered with leading automobile edges during atmospheric reentry and prolonged hypersonic flight, UHTCs, notably Hf as well as Zr-bound diboride, are now being developed. Hypersonic vehicles' surfaces are subjected to high-temperature, high-flow-rate oxidizing plasma as well as severe temperatures above 2500 °C. Because the bow amazement ahead of a blunt body shields the underpinning surface from the full heat force of both the oncoming plasma with such a thick layer of fairly dense and cool plasma, the configuration of interplanetary re-entry objects and hypersonic aerosol vehicles like ion thrusters have been constrained up to this point.

While sharp trailing edges greatly decrease drag, they also expose components of today's heat protection systems to far higher pressures and temperatures during reentry. In a leading edge, the relationship between temperature and radius of curvature is inversely proportional, meaning that during hypersonic flight, the temperature rises as the radius drops. The landings pass and flexibility of emerging reusable orbital space plane designs like the Reaction Technologies Skylon and Boeing X-33 are improved by the much greater lift-to-drag ratio of aircraft with "sharp" front edges.

Because of its refractory properties, corrosion resistance, thermal neutron cross-sections of 759 barns, and stoichiometric boron concentration, zirconium diboride is employed in several hot water reactor fuel assemblies. Since its two isotopes, 10B as well as 11B, both undergo neutron transmutation upon nuclear absorption and serve as sacrificial materials to safeguard other components that grow more radioactive when exposed to thermal neutrons, boron works as a "combustible" neutron absorber. Such facade components were used on this same uranium oxide solid fuel throughout Westinghouse AP-1000 nuclear reactors; even so, this same boron in ZrB2 should be enhanced in 11B so because gaseous helium managed to evolve by 10B strains of this same fuel pellet of UO2, creates a gap among both coating and fuel, and tends to increase the fuel's alignment temperature.

The secondary impact of boron's strong thermal neutron absorption is to bias the neutron spectrum toward higher energies, which causes the fuel pellet to retain more radioactivity 239Pu after a fuel cycle. A power density bulge is produced amid a nuclear reactor's fuel cycle by boron coatings in addition to the negative effects of incorporating neutron absorbers on a fuel pellet's surface. This is due to the superposition of 11B burning more quickly and 235U depletion. Researchers are looking towards ZrB2/Gd cermets, which would increase fuel lifespan by projecting three concurrent degradation curves, to help level off this bulge.

The exceptionally high melting temperatures of the transition-metal carbides, which are higher compared to those of the abovementioned resistive borides, have also been taken into consideration as UHTC substances of interest. Due to their extremely high hardness as well as elastic modulus, as well as the greatest melting temperatures of all substances, Ta and Hf's monocarbides are of considerable interest. Numerous monocarbides have a face-centered cubic structure that is similar to that of NaCl. As a result of the low-temperature "pasting" that takes place during oxidizing, which will be covered subsequently, the carbides aren't as frequently researched as the borides. However, the carbides have attracted a lot of interest for applications that need a quick increase to temperatures exceeding 2000°C.

It is not unexpected that the borides of such substances are likewise quite similar because Zr and Hf are known to have very similar chemical properties, with their major differences including density as well as nuclear capture cross-section. Both can be found in the hexagonal crystal formations of an AlB2 prototype, which alternate layers of Zr or Hf with coatings of B atoms in rings that resemble 2D graphite. These materials exhibit extremely high toughness and thermal stability because of the extremely high strength of the M-B and B-B bonds. The inherent thermal properties of the diborides are quite high, reaching copper at ambient temperature, with negligible drop-off up to 2500°C, unlike other extrinsic attributes, such as strength, which depend on processing and microstructures. Because of this, ZrB2 and HfB2 are extremely desirable for purposes where thermally stress response is a key consideration. Rocket motor nozzles are a prime illustration of this. In some applications, the interior surface temperature increase can reach 2000°C in much less than 0.15 seconds.

1. Conclusion

UHTCs are being researched as potential materials for thermal protection systems (TPS), coatings for items exposed to high temperature, and bulk materials with heating components because of their exceptional stability at temperatures above 2000 °C. UHTCs are essentially early transition metals borides, nitrides, oxides, and carbides, nitrides, oxides. Hafnium nitride (HfN), titanium carbide (TiC), thorium dioxide (ThO2), titanium nitride (TiN), zirconium nitride (ZrN), tantalum carbide (TaC) and their associated composites are other UHTCs under research for TPS applications. Current efforts have concentrated on heavy, initial transition metal borides including hafnium diboride (HfB2). Thus, the UHTC is now becoming one of the important materials in material science as well as metallurgy which can be used for high-temperature applications. Thus it was necessary to know the properties of such materials that are useful for industries.

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