A Review Paper on Analysis of Ultra-High Temperature Ceramic Using CAD Tools for Aerospace Applications

[1] Miss. Shweta Nandkishor Godulwar (ME Student), [2] Prof. A.M.Shende

*[1] Department of Mechanical Engineering, Jagadambha College of Engineering and Technology, Yavatmal
[2] Department of Mechanical Engineering, Jagadambha College of Engineering and Technology, Yavatmal

Abstract: Ceramic materials having melting points higher than 3000 °C and suitable for structural applications at above 2000°C are commonly known as Ultra-High Temperature Ceramics (UHTCs). Over the last couple of decades, there has been a growing interest for UHTCs in general, and for the transition metal di-borides in particular, due to the increasing demands in hypersonic aerospace vehicles, atmospheric re-entry vehicles and energy applications. However, problems pertaining to sintering, moderate fracture toughness and experimental challenges associated with reliably measuring the elevated temperature properties, as well as the properties that determine the performances at the actual service conditions, have limited their widespread applications. This paper comprehensively reviews the various routes/techniques, including the advanced ones, as adopted for the synthesis and densification of the di- borides. The effects of sinter-additives and reinforcements on the densification, microstructure and various properties, including elevated temperature properties have been discussed in critical terms. Due attention has been paid towards understanding the challenges associated with the experimental measurements of the high temperature properties under extreme environmental conditions and the very recently developed techniques for the same. Some of the existing and futuristic applications of transition metal di- borides have also been discussed. Finally, the review concludes with an outlook towards some of the outstanding issues.

Keywords: Ceramic materials having melting points, Ultra- High Temperature Ceramics, The effects of sinter-additives and reinforcements

1. INTRODUCTION

The space vehicles like rockets, hypersonic flights, reentry vehicles work at supersonic and hypersonic speeds (Mach number 6 or 7). At such high speeds leading and sharp edgesof space vehicles are subjected to very high aerodynamic heating than other blunt edges of the vehicle. During the reentry operation, they reach temperatures of 2000°C. Thus,to protect orbiter of the space shuttle, thermal protection system (TPS) is used. TPS of the orbiter of the space shuttleis designed to work effectively over an environment's spectrum typically for both aircraft and space shuttle. Whiledesigning TPS orbiter temperature must be maintained less than 177°C (350°F) [1]. Materials used for TPS should havehigh- temperature stability, high oxidation resistance, high corrosion resistance etc. Also, the TPS must perform acceptably in other environments, i.e., structural deflectionsinduced by aerodynamic loads, on-orbit cold soak, and natural environments, such as salt, fog, wind, and rain.Selection and location of the various TPS materials used for orbiter structure mainly depends on its inherent temperature capability. The location of materials on orbiter of spacecraft mainly depends on predicted maximum surface temperature and its reuse temperature. These requirements can be fulfilledby ultra-high temperature ceramics (UHTC). UHTCs are a new class of materials that have the potential foruse in extreme environments. UHTCs are the compounds having melting points greater than 2000°C. Generally, all UHTCs are binary compounds which contain boron, carbon, or nitrogen combine transition metals (TMs) such as Zr, Hf, Ti, Nb and Ta. The strong covalent bond between the TMs and B, C, or N causes high hardness, stiffness, and melting temperature [5]. Currently, structure materials used for high- temperature oxidizing environment limited to silicon carbideor Si_3N_4 based oxides materials and C/C composite. Also, materials used must withstand in high heat Flux with heavy mechanical stresses. These materials exhibit better oxidation resistance only up to 1600°C and their thermal cycling lifetimes are modest. Therefore, the development of materialsfor use in oxidizing and rapid heating environments at a temperature above 1600°C is of great engineeringsignificance. Hence to fulfil such high-temperature structural applications like hypersonic space vehicles, propulsion component, furnace elements and refractory crucibles etc. ultra-high-temperature ceramics (UHTCs) are better choices. Generally,these ceramic compounds are made of borides, carbides and nitrides such as ZrB_2, HfB_2, ZrC, HfC, TaC, HfN which are characterized by high melting points, high hardness, chemical inertness and relatively good resistance to oxidation in extreme environments, high thermal shock resistance [3,4]. But the only single-phase materials were not sufficient for high-temperature applications. Hence, many additives Nb, V,C, disilicate and silicon carbide were added to improve the resistance to oxidation in extreme environments. But UHTCshave high density compared to currently used materials. Hence in order to design TPS for maximum reuse and minimum weight, it is needed to go with some other UHTCs.Rapid advances in engineering design field lead to find out the alternate solution for conventional materials. Design engineers always looking for the material which gives better results than conventional materials in terms of weight, durability. From 1960 many of engineering applications in the world require high-temperature sustainability of materials. Most of the high-temperature field applications; SiC andSi_3N_4 are used as a primary high-temperature material. But this structural material does not withstand to recent temperature stability requirements. In recent scenario, a tremendous amount of interest is increased in an aerospace application, hypersonic concepts and weapons as well. To fulfil these high-temperature stability requirements there is need of new ultra-high temperature materials. Recent advance in TPS is needed for rockets, hypersonic flights, reentry vehicles to protect their orbiter from the extreme environment. While designing TPS orbiter temperature mustbe maintained at less than 177°C. To maintain orbiter temperature various materials are used TPS. In the modern era, space shuttle & hypersonic space vehicles require orbiter coatings that will ensure structures against temperature of more than 2000°C, enabling them to maintain compressive strength and

high oxidation resistance. As of now utilized TPS materials give high strength and low density but havingthe low compressive strength and they oxidize in air attemperatures more than 500°C. Hence it is necessary to identify material which will overcome these shortfalls and will be the prominent solution for TPS. It has been decided to identify such material composition, synthesize and characterize them to test their suitability in TPS as a coatingmaterial.
The objectives for achievement of the aim of dissertation work are as follows-

1. To select a suitable composition to develop an ultra-high temperature ceramic composite for aerospaceapplications.
2. To carry out structural and thermal analysis of proposed composite in view of aerospace applications like wing of the space shuttle.
3. To synthesize ultra-high temperature ceramic composite and evaluate its properties.

To compare proposed composite with conventional materials and check its suitability for aerospace applications.

2. LITERATURE REVIEW

The literature review includes the current thinking, findings and approaches adopted for a similar problem. Various researchers have presented their investigations on various materials used for TPS of space vehicles. Many researchers describe different types of UHTCs for TPS.There are more than 300 materials whose melting temperature above 2000°C like silicon carbide, refractory metals such as (Hf, Nb, Ir, Ta, W). These research papers from reputed journals are being referred, based on which literature gap is identified and a further statement of the problem is formulated for this research work.

2.1 Literature review

Donald M. Curry [1] has studied thermal protection system of the space shuttle with various TPS materials, theiroperating temperature range, their distribution on space shuttle orbit and properties of each material. It has been notedthat reinforced carbon-carbon**,** high- temperature reusable surface insulation tiles, low-temperature reusable surfaceinsulation tiles, fibrous refractory composite insulation givesa good thermal performance but need to improve some properties to avoid localized damage.

M. M. Opeka et al. [2] have investigated various materials which can be used at a temperature below 2000°C and above 2000°C. It has been noted that that low oxidation rate materials, which form pure scales of SiO_2, Al_2O_3, Cr_2O_3 was used at temperatures up to 1800°C due to disruptively high vapour pressures that occur at the interface of the basematerial.Whereas, ZrB_2 and HfB_2 based materials are used for temperature above 2000°C which provides good oxidation resistance due to the formation of multi-component oxide scale.

J.F. Justin et al. [3] studied various ultra-high temperature ceramics that can perform in oxidizing or corrosive atmospheres at temperatures in excess of 2000°C and sometimes over the course of a long working life. It is found that composite based on ZrB_2 and HfB_2 is the more attractive. It is summarized three composition ZrB_2-SiC, ZrB_2-SiC-$TaSi_2$ and HfB_2-SiC-$TaSi_2$ and found the addition of SiC causes improvement in resistance tooxidation, second allow densification by restricting grain growth of diboride and lowers the sintering temperature. Also found these materials have high hardness, high flexural stress, good machinability and high emissivity.

A. Jankowiak et al. [4] presented various ultra-high temperature ceramics for hypersonic flights, space shuttles and propulsion applications. Finds requirements of new materials which operate in oxidizing and corrosive atmospheres at temperatures higher than 2000°Cfor a long lifetime. ZrB_2-SiC, HfB_2-SiC and HfB_2-SiC-Y_2O_3 were studied on the basis of oxidizing and mechanical properties and compared with traditional SiC ceramic and finds HfB_2-SiC gives better properties compared to other composition.

William G. Fahrenholtz et al. [5] suggested various ultra-hightemperature ceramics from different families. It is presented synthesis, processing, densification, thermal properties, mechanical behaviors, and oxidation of ultra-high temperature ceramics. It has found that combination of metal-like and ceramic-like properties of UHTCs allows them to survive at extreme temperatures, heat fluxes, radiation level, mechanical load, chemical reactivities, and other conditions that are beyond the capacities of existing structural materials. The newapplications of UHTCs in the field of aerospace application, advanced nuclear fission reactors, high-temperature electrodes for metal refining, high power-density microelectronics, concentrated solar power, fusion energy systems and manyothers have been presented.

Pertti Auerkari [6]: has derived physical and mechanical properties of engineering alumina ceramic. Alumina has been divided into two groups; the first one is high alumina grades which contain 99% of Al_2O_3 and second one alumina grades inbetween 80% to 99% of Al_2O_3. It has been noted that first group have good mechanical and other propertiesbut have high density and high sintering temperature compare to the second group. The application of alumina ceramic according to a percentage as insulator and refractory has been presented.

Adebayo Y. et al. [7] have investigated various alumina ceramic samples for their hardness, fracture toughness and microstructural characteristics. Indentation technique has been applied for the evaluation of the fracture toughness of all the ceramic samples. SEM and XRD tests were used for microstructure analysis. It has found that fracture toughness decreases with increasing hardness and the fracture toughness and hardness values are higher for the 98% alumina samples but the differences between the lower alumina samplesare negligible.

M. V. Silva et al. [8] have studied three compositions of commercial alumina containing 92, 96, and 99.7% of Al_2O_3, and were investigated for ballistic ceramics. Compositions were characterized by Vickers hardnessmeasurements and four-point flexural bending strength. Thereliability of the obtained results was evaluated by Weibull statistics. It is found that compositions 92% of Al_2O_3 and 99% of Al_2O_3 showed comparable results with each other and higher Vickers hardness and bending strength than composition 96% of Al_2O_3. And from composition 92% of Al_2O_3 and 99% of Al_2O_3, composition 92% of Al_2O_3 is selected due to low porosity.

R Cao et al. [9] have investigated the effect of the addition of Si on the thermal and electrical properties. It is tested andanalyzed by varying the silicon content in Al-Si-Al_2O_3 composites. It is demonstrated that the coefficient of thermal expansion and thermal conductivity decreased as silicon content increased because silicon and Al_2O_3 disperseuniformly in Al matrix to suppress the high thermal expansion of Al to a large extent as well as the interfacial thermal resistance which results in a decline in thermal conductivity. The electrical resistivity increased when silicon content was increased because the low coefficient of thermal expansion particles of Si and Al_2O_3 severely damaged the continuityof the Al matrix which impeded the movement of an electron in the matrix.

Akin et al. [10] have shown the effect of the addition of TiO_2 on the properties of Al_2O_3- ZrO_2 composites. In this study Al_2O_3, Al_2O_3-ZrO_2 (90–10 vol%) and Al_2O_3-ZrO_2 with 5% by weight TiO_2 composites, were prepared by sparkplasma sintering (SPS) at temperatures of 1350°C, 1460°C and 1300 °C for 300 seconds under a pressure of 40 MPa, respectively. It was observed that addition of 5% by weight TiO_2 improved densification of Al_2O_3-ZrO_2 and decreased the sintering temperature of Al_2O_3-ZrO_2 composites from 1460°C to
1300°C. The presence of 10% by vol of ZrO_2-TiO_2 slightly increased the hardness of Al_2O_3 and suppresses the growth of alumina grains.

Lei Xu et al. [11] have studied the densification behaviour and mechanical properties of Al_2O_3-MgO and Al_2O_3-MgO-CaO of refractory brick. It is found that with the addition of CaO, the initial sintering temperature of Al_2O_3-MgO refractory was lowered from 1300°Cto 1100°C associated with the expansive formation of $CaAl_2$, and the compressive strengthwas also increased due to the formation of a bond linkage between $CaAl_2$ and aluminium- magnesium oxide. At high temperature, brick containing 4% CaO had poor sinterability with high porosity due to the $CaAl_2$ grains platelet formation, whereas brick containing 8% CaO content was well sintered with higher relative density but lower bulk density than Al_2O_3-MgO brick, indicating that the densification, as well as lightness of Al_2O_3-MgO refractory, was effectively promoted.

3.METHODOLOGY

The dissertation work is focused to carry out an analysis studyona newly developed ultra-high temperature ceramic material. This material is exposed to various loads and temperature conditions. The total proposed work divided in different phasesis as shown in fig. 2.1.

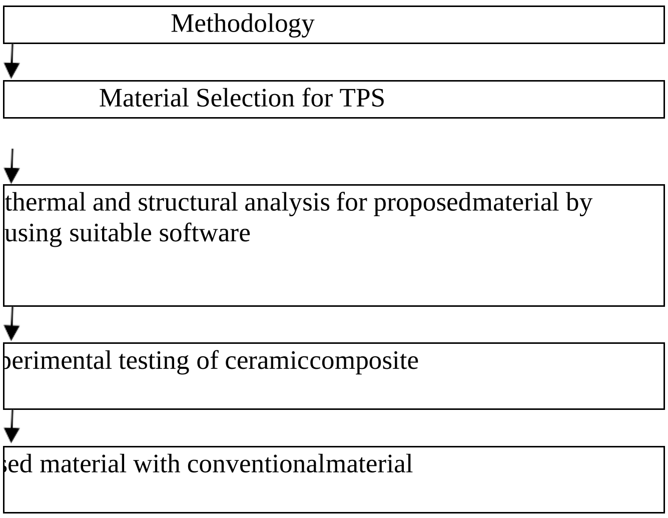

Fig. 2.1 Flowchart of the research plan

Phase I: Literature survey and selection of composition for proposed composite

In this phase, the literature regarding ultra-high temperature ceramic composites, nanocomposites, oxidation and corrosion resistant materials, ceramic materials, processing and fabrication techniques, experimental design and ANSYS software etc. will be studied.

Phase II: Structural analysis, Thermal analysis of the aerospaceapplication (Wing)

Preparation of wing model will be done according tospecifications. Loading conditionsand boundary constraints willbe applied to the model by using suitable software.

Structural and thermal analysis of composite wing will becarriedout.

Phase III: Synthesis of ceramic composite material and evaluation of properties

The Synthesis of composite according to the specifications required for testing will be done by using powder metallurgyprocess.

Various properties like density, young’s modulus, tensile strength, etc. of composite will be evaluated experimentally.

Phase IV: Comparison and suitability

Comparison of developed material with the conventional materials on the basis of mechanical properties will be done. Also, suitability of the developed material for aerospaceapplication will be checked.

Closure

This chapter gives information on various material used for thermal protection system (TPS). Also gives informationabout various ultra-high temperature ceramic composite, their properties and application in various fields.

CONCLUSION

Hypersonic, re-entry vehicles or propulsion applications provide some unique thermal structural challenges (sharp leading edges, air intake). To meet the requirements of thesecomponents, certain specific materials are mandatory (UHTC). UHTCs are a promising technology used in many high- temperature structural applications. In this dissertationwork, Al2O3-SiO2 was studied at 1247°C temperature and numerical analysis was carried out to finalize the composition among three different compositions. Simulated solutions at different nodes are validated with numericalsolutions that are fairly in good understanding and show the feasibility of the problem methodology.

REFERENCES

1. Donald M. Curry. “Space Shuttle Orbiter Thermal Protection System Design and Flight Experience.” NASA Technical Memorandum 104773 (1993): pp. 1-22.
2. M. M. OPEKA, I. G. TALMY, J. A. ZAYKOSKI.
“Oxidation-based materials selection for 2000◦C + hypersonic aerosurfaces: Theoretical considerations and historical experience.” JOURNAL OF MATERIALS SCIENCE, Vol. 39 (2004): pp. 5887 – 5904.
3. J.F. Justin, A. Jankowiak. “Ultra-High Temperature Ceramics: Densification, Properties and Thermal Stability.” Aerospace Lab (2011): pp.1-11.
4. A. Jankowiak, J.F. Justin. “Ultra-High Temperature Ceramics for aerospace applications.” ODAS (2014): pp.1-
5. William G. Fahrenholtz, Greg E. Hilmas. “Ultra- high temperature ceramics: Materials for extreme environments.” Scripta Materialia a letter journal SMM- 11330 (2016): pp.1-6. [6]. Pertti uerkari. “Mechanical and Physical Properties of Engineering Alumina Ceramic.” Espoo (1996): pp.1-26.
6. M. V. Silva, D. Stainer, H. A. Al-Qureshi, O. R. K. Montedo, D. Hotza. “Alumina- Based Ceramics for Armor Application: Mechanical Characterization and Ballistic Testing.” Journal of Ceramics (2014): pp.1-6.
7. Adebayo Y. Badmos, Douglas G. Ivey. “Characterizationof structural alumina ceramics used in ballistic armour andwear applications.” Journal of Materials Science Vol. 39 (2010): pp. 4995 – 5005.
8. R Cao, J X Jiang, C Wu, X S Jiang. “Effect of addition of Si on thermal and electrical properties of Al-Si-Al2O3 composites.” Materials Science and Engineering Vol. 213 (2017): pp. 1-9.
9. I. Akin, E. Yilmaz, O. Ormanci, F. Sahin, O. Yucel,
G. Goller. “Effect of TiO2 Addition on the Properties of Al2O3-ZrO2 Composites Prepared by Spark Plasma Sintering.” Bioceramics Development and Applications Vol. 1 (2011): pp. 1-5