Numerical Analysis of Ultra-High Temperature Ceramics for Aerospace Application

Waghmare Prashant Uttam1, Asst. Prof S. R. Patil

[1] *Department of Mechanical Engineering, , Maharashtra, India*

[2] *Department of Mechanical Engineering, , Maharashtra, India*

ABSTRACT

Aerodynamic drag and heating are the crucial in the thermal stability of hypersonic vehicles at various speeds. The latest developments in the design of wing structure of space shuttle demands an effective Thermal Protection System (TPS) meets the need of the space research technology. In this research a typical space shuttle wing with different Ultra High Temperature ceramic (UHTC) composite TPS materials like alumina(Al2O3) refectories (up to 48 %) with addition of Silica (SiO2), Titania (TiO2), Iron Oxide(Fe2O3), Lime (CaO) is going to analyzed and compared for its effective protection against transfer of heat in to the structure. A naval model is designed for from the concepts of wing and will analyzed with the commercial software. Typical quad 4 node elements will be adopted to perform coupled thermal and structural analysis in ANSYS software and the simulated results are validated with numerical solutions.

Keywords— Ultra High Temperature Ceramic, alumina refectories, coupled thermal and structural analysis, Thermal Protective system.

1. INTRODUCTION

In recent years space vehicles like rockets, reentry vehicles regardless their unique designs needed to control surface at hypersonic speed at low radius leading edge causes much greater aerodynamic heating. Hence for those of space shuttle due to aerodynamic heating they reach to temperature about 2000°C. Hence since few years projected needs material for thermal protection on hypersonic aerospace vehicle or atmospheric re-entry vehicles to withstands extreme operating condition, such as temperature above 2000°C in oxidant atmosphere. This leads great interest for Ultra High Temperature Ceramics (UHTCs). These ceramics compounds are generally borides, carbides and nitrides with high melting points [1,2]. Currently structure materials used in high temperature oxidizing environment limited to SiC or Si_3N_4 based oxide materials and C/C composite. Also materials for these areas must withstand strong heat flux with large mechanical stresses. These materials exhibit good oxidation resistance but only up to 1600°C, and their thermal cycling lifetimes are modest [3]. Therefore the development of structural materials for use in oxidizing and rapid heating environments at temperature above 1600°C is of great engineering importance. Hence rapid technological advances in engineering design field result in finding the alternate solution for these conventional materials. The design engineers brought to a point to finding the materials which are more reliable than conventional materials. Researchers and designers are constantly looking for the solutions to provide stronger and durable materials which will answer the needs of fellow engineers. In recent scenario tremendous amount of interest is increased in an aerospace application, hypersonic concepts and weapons as well. To fulfill these requirements there is need of new ultra-high temperature materials.

The thermal protection (TPS) for the Orbiter of space shuttle is designed to operate successfully over a spectrum of environments typical of both aircraft and spacecraft. While designing TPS orbiter temperature must be maintained at less than 177°C (350°F) [4]. In addition to withstanding the thermal environments, the TPS must also perform satisfactorily for other induced environments, i.e. structural deflections induced by aerodynamic loads, on-orbit cold soak, and natural environments, such as salt, fog, wind, and rain. Selection and location of the various thermal protection materials applied to the Orbiter structure are based primarily on the inherent temperature capability of the materials. The specific Orbiter locations for the materials are based on predicted peak surface temperature and the material reuse temperature.

Hence to fulfill such high temperature structural application we have Ultra High Temperature Ceramics (UHTCs). This family of ceramic compounds is made of borides, carbides and nitrides such as ZrB2, HfB2, ZrC, HfC, TaC, HfN which are characterized by high melting points, high hardness, chemical inertness and relatively good resistance to oxidation in severe environments. But the use of single phase materials was not sufficient for high-temperature structural applications. Thus, many additives such as Nb, V, C, disilicides and SiC were evaluated to improve the resistance to oxidation. But these UHTCs have high density compared to currently used materials. Hence in order to design TPS for maximum reuse and minimum weight we have to go with some other UHTCs.

In this research work a typical space shuttle wing with different Ultra High Temperature ceramic (UHTC)composite TPS materials like alumina refectories Al2O3 (up to 48%) with addition of Silica (SiO2), Titania (TiO2), Iron Oxide (Fe2O3), Lime (CaO) is going to analyzed for maximum temperature, total heat flux, deflection and equivalent von-Misses stresses, also compared for its effective protection against transfer of heat into the structure.

2. Materials and methods

Types of currently used materials for Thermal Protection System- Location of the various thermal protection materials applied to the Orbiter structure are based primarily on the inherent temperature capability of the materials. As due to aerodynamic heating temperature at different location of space shuttle are different. Hence various materials are used in Thermal Protection System (TPS). And its depend upon amount of required heat protection.

2.1 Reinforced Carbon-Carbon (RCC) –

RCC is a composite material consisting of carbon fiber reinforcement in a matrix of graphite. Carbon–carbon is well-suited to structural applications at high temperatures, where thermal shock resistance and a low coefficient of thermal expansion needed. It is used in the nose cap, the chin area between the nose cap and nose landing gear doors, the arrowhead aft of the nose landing gear door, and the wing leading edges. It is used where re-entry temperature exceeded 1260 °C (2300 °F).

2.2 High-temperature reusable surface insulation (HRSI) - It is made of coated LI Silica ceramics. HRSI tiles provided protection against temperature between 649 °C (1200°F) to 1,260 °C (2,300 °F). They were also used in areas on the upper forward fuselage, vertical stabilizer leading edge, elevon trailing edges, landing gear doors, orbiter underside.

2.3 Low-temperature reusable surface insulation (LRSI) - It is formerly used on the upper fuselage, but were mostly replaced by FIB. Used in temperature ranges roughly similar to FIB. It is used below 649 °C (1200°F). They are thinner than HRSI tiles and used where heat load are minimum compared to HRSI.

2.4 Flexible Insulation Blankets (FIB) - It is flexible blanket-like surface insulation. Used where re-entry temperature was below 649 °C (1200 °F). now a day it replaces LRSI due to its low density.

From above different types of materials for our study High-temperature reusable surface insulation (HRSI) is selected and it's properties are enlisted below –

Table 1. Properties of HRSI Tiles

Properties	**Value**	**Units**
Density	2195	Kg/m3
Tensile Strength	27.6	MPa
Compressive Strength	0.689	MPa
Modulus Of Elasticity	413	GPa
Thermal Conductivity	1.44	W/m k
Specific Heat	920	Joule/Kg k
Coeff. Of Thermal Expansion	1.08	(10-6/K)

New design material- The main ceramic materials used commercially in the development of refractoriness is Al2O3, B4C, SiC, and ceramic matrix composites (CMCs) such as Al2O3/ZrO2 system. Alumina Al2O3 provides the best cost-benefit ratio among advanced ceramics, featuring high modulus of elasticity, high refractoriness, high hardness, and relatively lower cost [5,6]. However, because of its low fracture toughness and low flexural strength its performance is lower when compared to SiC and B_4C. The properties of the alumina may be improved, either by introducing zirconia or by the manufacturing CMCs, which increase fracture toughness and flexural strength [7]. Here we develop CMCs with composition alumina refectories Al2O3 (48%) with addition of Silica SiO2 (43%), Titania TiO2 (4.0%), Iron Oxide Fe2O3 (3.5%), Lime CaO (0.5%). Properties of composition Al2O3 (48 %) + SiO2 (43 %) + Fe2O3 (3.5 %) + TiO2 (4.0 %) + CaO (0.5 %) are listed below-

Table 2. Properties of Composition

Properties	Value	Units
Density	2306.66	Kg/m3
Apparent Porosity	11.0	%
Cold Crushing Strength	12.41	MPa
Thermal Conductivity	4.2	W/m k
Coeff. Of Thermal Expansion	1.4	(10-6/K)
Poisson's Ratio	0.21	
Modulus Of Elasticity	268.89	GPa

Prepare 3D model and analysis of model under defined boundary conditions- As per the reference we will prepare 3D model of a wing of space shuttle using Solidworks. Basically, we are going to do two types of analysis on the model. First, we will do static structural analysis to understand Von misses stresses coming in the wing as well as maximum deformation. Second, we will do steady state thermal analysis to under maximum temperature coming in the wing. After the comparison of analysis result we will check suitability of selected composition with base material HRSI tiles.

3D modeling - The static structural and thermal analysis of ultra high temperature composite (UHTC) is carried on space shuttle half wing model employed detailed geometry of the half wing model. The Finite Element methodology was used for static structural and thermal analysis. Modeling is done in Solidworks 14.0 software with the following geometry dimensions-

Overall length of the Shuttle= 23.42 m Width of the Shuttle =9.05 m

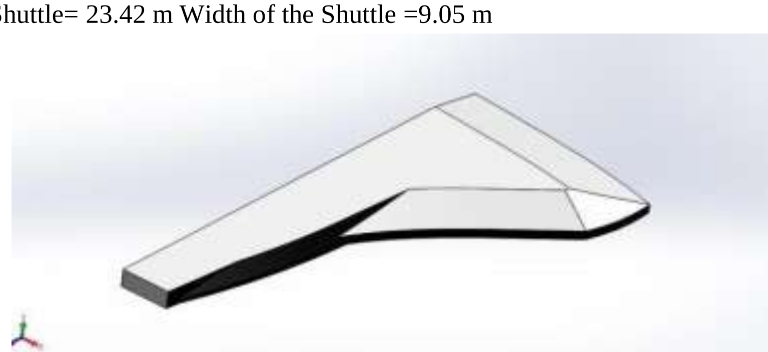


Fig. 1. CAD model of a Space Shuttle Wing

Meshing- After import the .iges model to Ansys Workbench 18.2. Materials are created in Ansys engineering data. Figure shows the mesh model of space shuttle wing model.

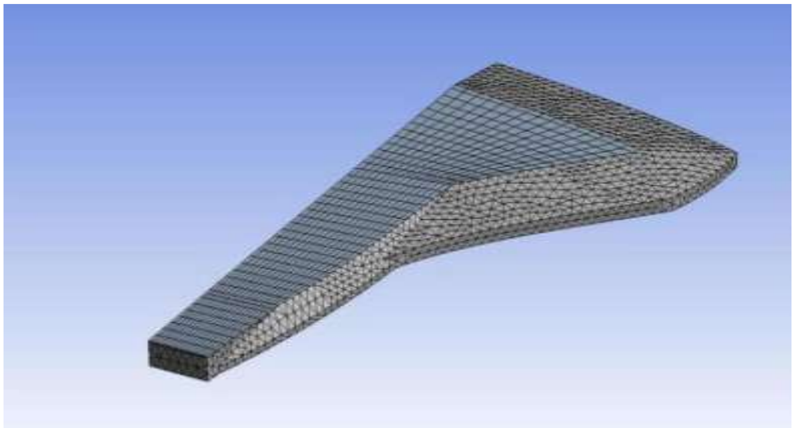


Fig. 2. Mesh model of a Space Shuttle Wing

For meshing following parameter is used:

Mesh Method-

Wing side panel: Hexahedron Mesh

Wing Edges and Side Surface: Tetrahedron Mesh

Boundary conditions –

In boundary conditions we give the input values for analysis. For thermal analysis maximum temperature of 1247° C is defined at lower side and edges of the wing and 648° C is at upper surface of the wing and convection is defined at all other surface of the wing.

For thermal and structural analysis temperature contour is important. For fix support wing side surface is selected.

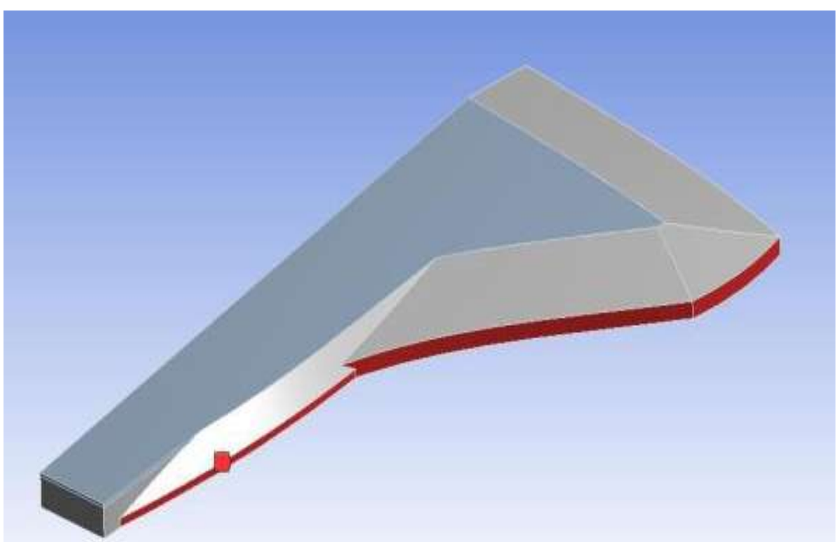


Fig. 3. Wing edges and bottom Surfaces of wing with 1247° C

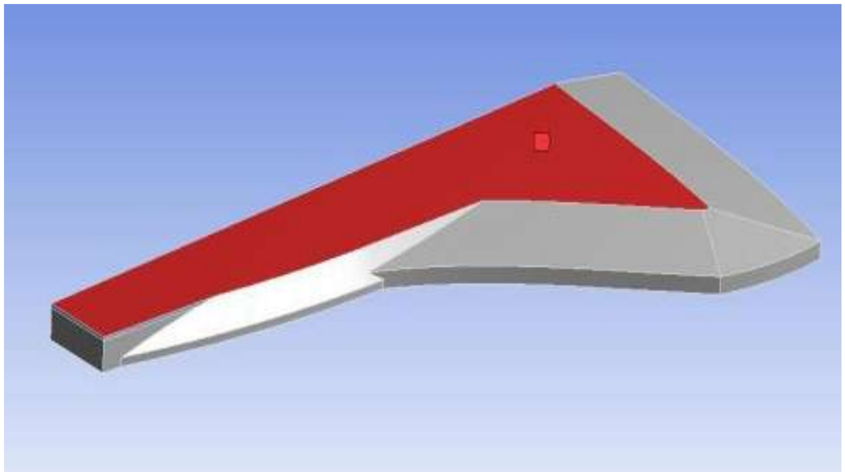


Fig. 4. Top Surfaces of wing with 648° C

3. Results

3.1 Analysis of Result for Current Material (HRSI)

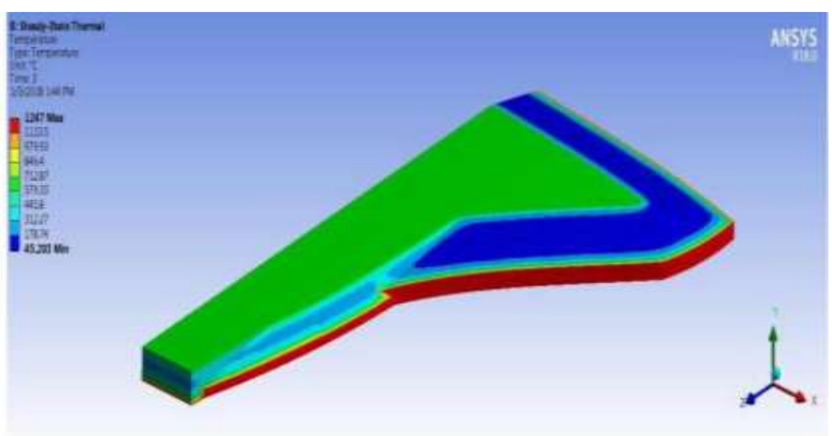


Fig. 5. Temperate distribution in wing body for current material (HRSI)

International Journal of Advance Research in Science and Engineering
Volume No.07, Special Issue No.03, April 2018
www.ijarse.com
IJARSE
ISSN: 2319-8354

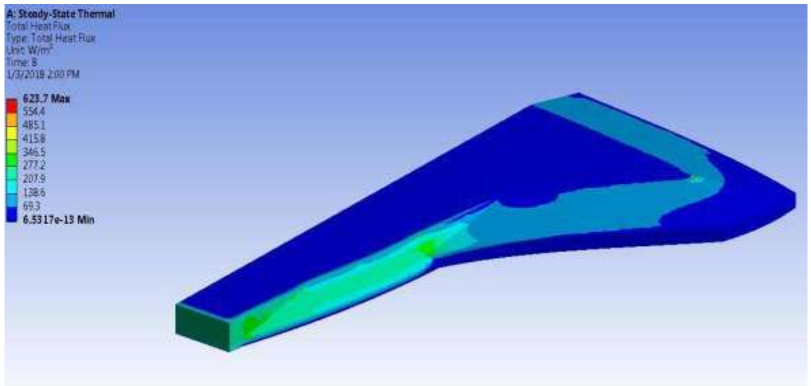


Fig. 6. Heat Flux distribution in wing body for current material (HRSI)

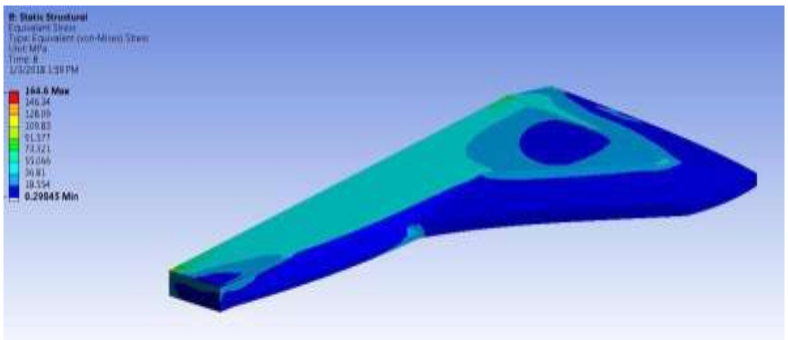


Fig. 7. Stresses in wing body for current material (HRSI).

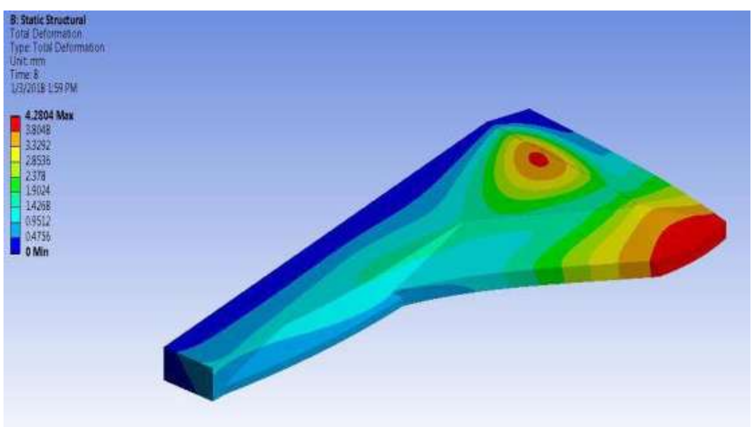


Fig. 8. Deformation in wing body for current material (HRSI)

3.2 Analysis of Result for selected composition

Al_2O_3 (48 %) + SiO_2 (43 %) + Fe_2O_3 (3.5 %) + TiO_2 (4.0 %) + CaO (0.5 %)

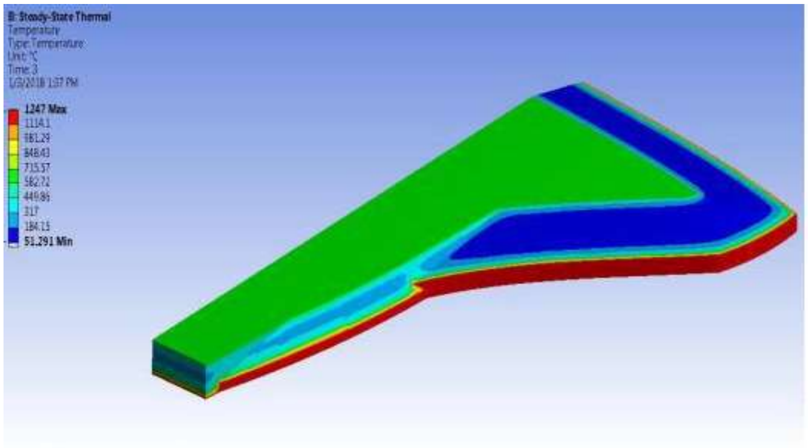


Fig. 9. Temperate distribution in wing body for selected composition.

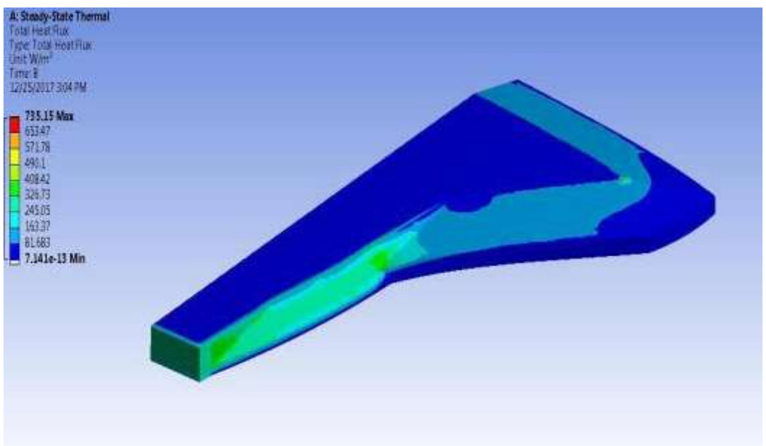
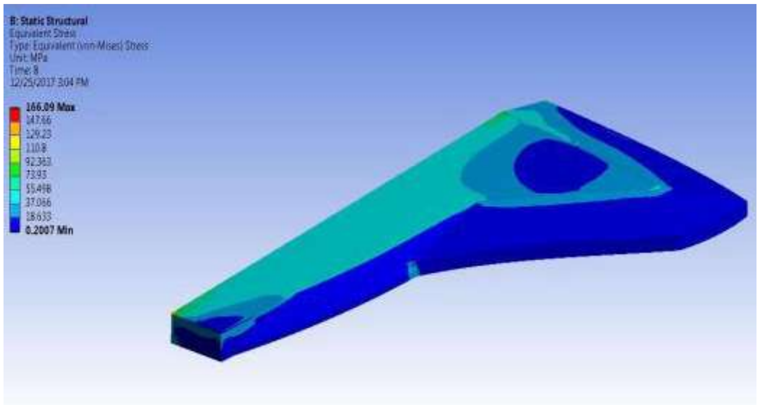


Fig. 10. Heat flux distribution in wing body for selected composition.



IJARSE
ISSN: 2319-8354

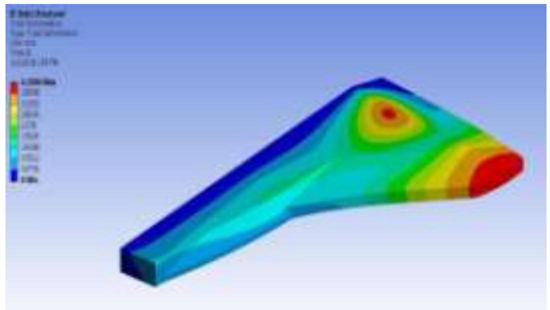


Fig. 11. Stresses in wing body for selected composition.

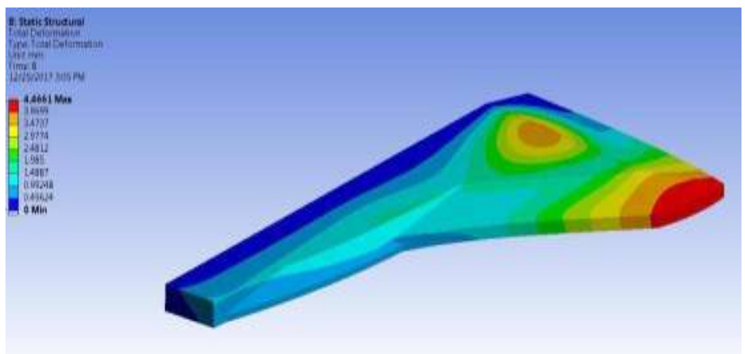


Fig. 12. Deformation in wing body for selected composition.

The results obtained from finite element analysis are tabulated below

Table 3. Equivalent Von-Mises Stresses

Sr. No.	**Material used for Analysis**	**Equivalent Von-Mises Stresses (MPa)**
1	Current Material (HRSI)	164.60
2	Selected Composition	166.09

Table 4. Deformation

Sr. No.	**Material used for Analysis**	**Deformation (mm)**
1	Current Material (HRSI)	4.28
2	Selected	4.46

IJARSE
ISSN: 2319-8354

	Composition	

Table 5. Residual Temperatures

Sr. No.	Material used for Analysis	Temperature (° C)
1	Current Material (HRSI)	45.20
2	Selected Composition	51.29

Table 6. Total Heat Flux

Sr. No.	Material used for Analysis	Total Heat Flux (W/m2)
1	Current Material (HRSI)	623.70
2	Selected Composition	735.15

4. Discussion

Following graphical representation shows the variation of the Equivalent von-Mises stresses induced in the wing body, total deformation coming in the wing body due to stresses, variation of the maximum stresses coming in the wing body, and counters of the total heat flux produced inside the wing body over the current material (HRSI) and selected composition.

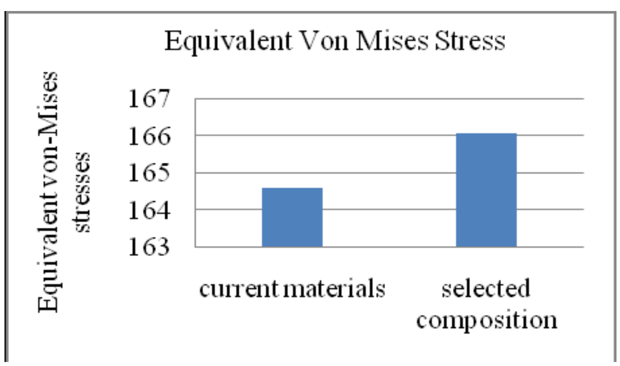


Fig. 13. Comparison of the Equivalent von-Miseses Stresses

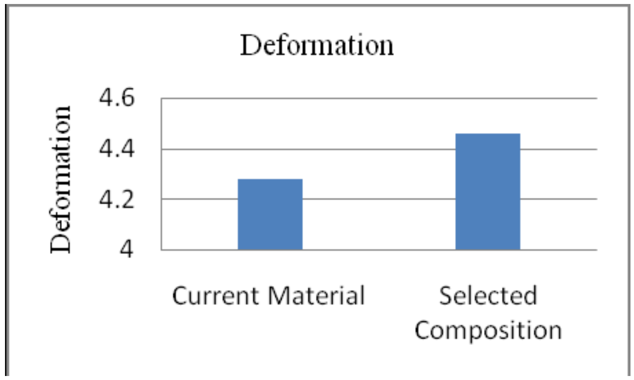


Fig. 14. Comparison of the Deformation

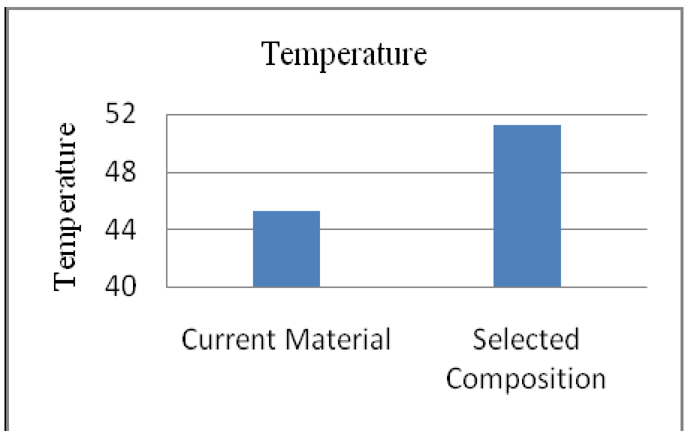


Fig. 15. Comparison of the Residual Temperature

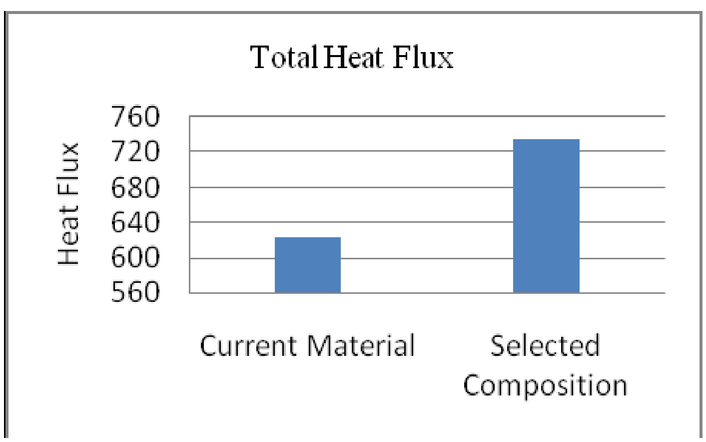


Fig. 16. Comparison of Total Heat Flux

From above graphs it is seen that there is not much variation in their values.

5. Conclusion

Hypersonic, atmosphere re-entry or propulsion applications provide some unique thermal structural challenges. To fulfill the requirements of these components, some specific materials are compulsory (UHTC). UHTCs are a promising technology for use in many high temperature structural applications. In this project, Al2O3-SiO2 were studied at 1248°C tempraure.

1. Simulated solutions at various nodes are validated with numerical solutions which are fairly in good understanding and show the feasibility of the problem methodology.
2. The stresses developed in selected composition 166.90 Mpa is slightly more than developed in current material 164.60 Mpa which are in safe region.
3. Cost of selected composition is 25% less than current material (HRSI).

Acknowledgment

I would like to express my deep sense of gratitude to my supervisor Prof. S. R. Patil for his inspiring & invaluable suggestions. I am deeply indebted to him for giving me a chance to study this subject & providing constant guidance throughout this work. I acknowledge with thanks,the assistance provided by the Department staff, Central library, staff &computer faculty. Finally, I would like to thanks to my colleagues and friends for directly and indirectly helping me for the same.

References

[1] William G. Fahrenholtz, Greg E. Hilmas, “Ultra-high temperature ceramics: Materials for extreme environments,” Scripta Materialia, October 2016.

[2] A. Jankowiak, J.F. Justin, “Ultra High Temperature Ceramics for aerospace applications,” ODAS, June 2014.

[3] J.F. Justin, A. Jankowiak, “Ultra High Temperature Ceramics : Densification, Properties and Thermal Stability.” AerospaceLab, pp. 1-11,
Aug 2015.

[4] Donald M. Curry, “Space Shuttle Orbiter Thermal Protection System Design And Flight Experience.” July 1993.

[5] Karen Davis, “Material Review: Alumina (Al2O3),” 2010.

[6] Pertti Auerkari, “Mechanical And Physical Properties Of Engineering Alumina Ceramic.” 1996.

[7] 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 ceramic, pp. 1-6, Jan 2014.

[8] Adebayo y. Badmos, douglas g. Ivey, “Characterization Of Structural Alumina Ceramicsused In Ballistic Armour And Wear Applications” Journal of Material Science, vol. 36, pp. 4995– 5005, 2001.