Thermal analysis of a variable cross-sectional Ti-6Al-4V alloy core with an insulating sandwich panel

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Abstract

Hypersonic aerospace vehicles subjected to an intense aerodynamic heating load, when it enters in a service environment with high speed of Mach 5 and over a long period of time. The thermal protection system is designed to maintain the sandwich structure of the vehicle within its tolerated temperature limit. Pyramidal lattice Ti-6Al-4V alloy core with an insulating sandwich panel is designed. Lattice core is considered not only as an insulating panel and also has an excellent strength to weight ratio. Current research work is focused on the optimization of temperature distribution by introducing multilayer composite material insulation in TPS. Variable core sandwich panel geometrical dimensions in the thickness are treated as a design variable and the main objective function is the total mass of the sandwich structure with the limitation of the intense thermal load on the sandwich test model. Multilayer composite insulation selection based on the thermal performance of the test model. To obtain the optimized thermal test model many assumptions and comparisons worked on variable cross-sectional cores, core material and multilayer composite insulating sandwich panel from the viewpoint of thermal insulation are carried out. The detailed transient thermal analysis and comparison specifies the advantages of the presented test model.

Keywords: Intense aerodynamic thermal load, multilayer insulation, pyramidal lattice core, transient thermal analysis, variable core.

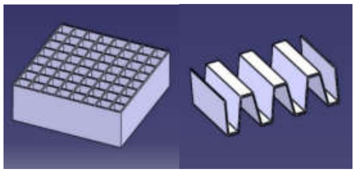
1. INTRODUCTION

Lightweight sandwich panels have a wide range of application in the aerospace industry.Sandwich construction is one of the valued structural design innovation. It consists of a low-density core with solid facing sheets. Sandwich panels are followed by different core topologies which are namely square comb core, corrugated core, and pyramidal lattice core are defined as the property of periodic lattice structure material. Intense thermal loads developed on the outer surface of the aircraft because of aerodynamic heating. However, the temperatures beyond the acceptable limit createa safety issue. Total heat fluxes developed on the panel can be normalized by thermal protection system named as pyramidal lattice core sandwich panel. TPS has a better thermal resistance and also protects the internal structures inside the aerospace vehicle from the intense thermal loads on the panel. Pyramidal lattice core has a less conducting contact surface. [1] Under the thermal environment condition, transient thermal analysis results show that the corrugated core is five times denser than heavier than the pyramidal lattice core sandwich panel. Maximum thermal stress developed in the pyramidal core is lesser than the conventional cores. Gongnan Xie. [2] Optimizing the sandwich structure accounting for the mass minimization of the mass of the panel with insulating thermal protection system. D.T.Queheillalt. [3] discussed the pyramidal structures which have been assembled by using 304 S.S tubes and face sheets. These are bonded with vacuum brazing approach. Stiffness and strengths are measured with analytical predictions depends upon the plastic yielding and also buckling effect identified at various nodes of the lattice core. Strength and buckling result in a very high energy absorption. Hadyn N.G. Wadley. [4] Investigated the diffusion bonding & temperature for the design fabrication of pyramidal lattice titanium alloy core panel. Introduced possible methodology for normalizing the stress impact and strength increment between the truss and face sheets. C.I.Hammeter. [5] Focused on innovation on photocuring of synthetic polymers are allowed for the fabrication of lattice structures with exact geometries. His studies address the strength and compressive deformation of a pyramidal lattice topology with emphasis on three independent variables. R.G. Rinaldi compared energy absorption by a factor of 3-5 on a mass-based in stochastic foams and pyramidal lattice. Evans. [6] focused on developing integrated thermal protection system to normalize heat fluxes over the panel and these structures have an excellent load bearing capability. Pyramidal lattice core is most suitable for multifunctional applications. Chen. [7] In thermal investigating structure heat sink subjected to a structural load, the lattice structure is tougher than the other conventional heat sink media. Deshpande. [8] Octet truss lattice structure is stiffer and stronger than the bent corrugated metal core at equal porosity level. Kim. [9] Describes the experimental study of the pressure loss and end wall thermal heat flow in a highly porous multifunctional lightweight sandwich structure exposed to forced convection. Liu. [10] Explains the multi-variable optimization procedure for the lightweight lattice core. He proposed the approach which involves objectives from the variable structural efficiency of the material at different working cases simultaneously. Kim. [11] Proposed two mutually perpendicular orientations for the geometrical measurements due to the inaccurate anisotropy of the pyramidal lattice core results. Pressure drop and heat transfer of the structural panel are analytically calculated. Zhu et al. [12] Studied on the comparison between titanium foam cores with a structural component with saffil insulation. The panel included with Saffil insulation favors of thin structure for high-temperature resistance. Bapanapalli. [13] Developed optimization procedure in order to implement an integrated thermal protection system with low mass occupancy and simplified core geometry of the corrugated core panel are the objective of the preliminary research work. Wadley et al. [14] define the relationship between friction flow loss and heat transfer and lattice topology are referred for the future developments. [15-19] Explains the nonlinear results of a presented model through a mathematical approach. Mismatch of thermal expansion coefficient of the core material and also discusses the effects of localized heating with temperature dependent property. Thermomechanical response with and without immovable supports. Previous research works focused on the structural strength and heat dissipation. In general sandwich panels are used in weight critical applications. Additionally, these panels have an ability to resists the heat flow. Low-density core enables the structural weight to a minimum. Thermal protection system includes the porous coreand solid metal facing. In the current research is discussed to develop a thermal efficient sandwich panel by conducting a transient thermal test model.

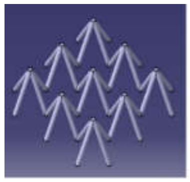
2. Design of a sandwich panel

2.1 *Size design of variable sandwich cores*

Figure 1 shows the variable core topologies for the sandwich structure. The structure is characterized as thermal protection system denoted by TPS. Variable core test model consists of three layers: a top solid facing sheet, internal sandwich core, and bottom solids facing sheet. The main objective is to design a TPS with less mass occupancy of the structure. Insulating sandwich panels are designed to increase heat transfer density without increasing overall its heat flow thickness. Lightweight panels built with highly porous core with low-density materials. Mechanical and thermal performance are considered while designing an insulating panel. A thermal protection system (TPS) is capable of thermal insulation as well as loadbearing aspect. The thermal investigation is continued on variable cores. Obtained results identify better core design test model.According to the working condition of the insulating panel top solid facing sheet is able to withstand a temperature is about 1200 K. surface emissivity and heat flux developed on the facing sheet. Assuming the higher temperature limit 1100 K. To overcome the higher temperature gradient, the material should be chosen to be with a higher Young's modulus. The toughness of the panel is the major factor of design due to debris potential impact in space. The material working temperature must be greater than 927 °C. Considering variable core topologies selection of core topology through thermal analysis performance. Bottom solid facing doesn’t exceed the temperature limit 450 K under the intense 1200 K heating load. Pyramidal lattice core obtains a better thermal performance than the conventional core and geometrical variables of a core geometry are shown below:



Squarecomb Corrugated core



Pyramidal lattice core

Figure.1 Variable Sandwich cores topologies

2.2 Material selection

Selection of material plays an important role in designing a thermal protection system. Lightweight sandwich structures opt for weight critical applications. Low density with high thermal resistivity materials is chosen while designing a thermally insulating panel. Titanium metal has a wide range of applications in aerospace industries. It performs an excellent mechanical thermal characteristic under the intense thermal loads. Pure Titanium and Ti-6Al-4V alloy also havesimilar properties. The thermal conductivity of Ti-6Al-4V is three times lesser than the Titanium metal. Alloy performs excellent thermal and mechanical strength than the pure metal. Material properties are listed in the table.

Material / Property	Titanium	Ti-6Al-4V	Aluminosilicate/ Nextel720	IMI	Saffil	Steel stainless
Thermal conductivity K W/m K	21	6.7	2.52	0.012 - 0.271	0.036 - 0.544	13.8
Density ρ kg/m³	4500	4430	2450	73	50	8055
Specific heat C J/kg k	522	533	950	839 - 1122	942 - 1340	480

Table 1. Material properties

2.3 Multi-layer composite insulation

Multi-layer composite insulation is introduced into the thermal protection system to provide superior thermal insulation to the space vehicles. This study chooses two different multilayer composite insulation cases. Insulating composite materials have a high working temperature suitable for the intense thermal working condition. Multi-layer composite case -1 & case- 2 test model insulating layers are shown as follows:

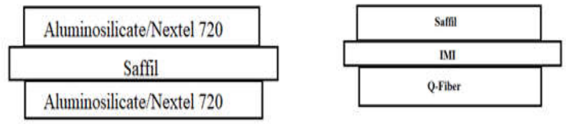


Fig.2 Case1 & Case2 multi-layer insulation test models

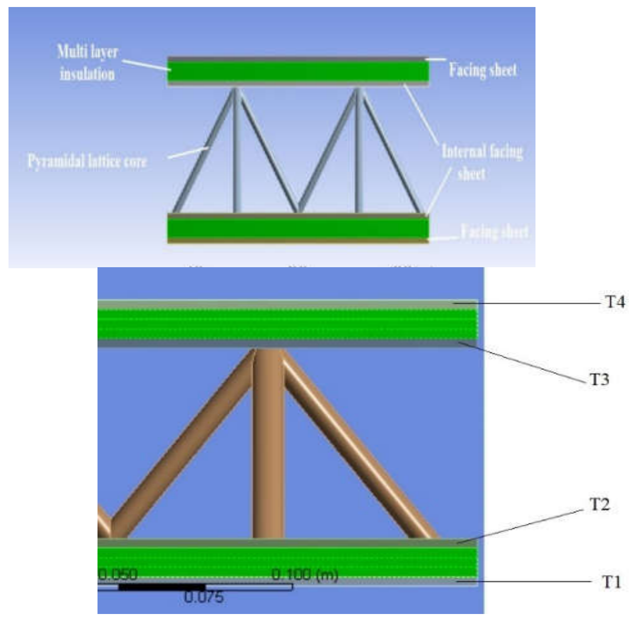


Fig.3 Design of a Ti-6Al-4V alloy pyramidal lattice core with insulating sandwich panel ITPS test model.

3.The transient thermal analysis model

The relative density of the pyramidal lattice is obtained by considering the volume occupied by each of the struts individually when neglecting volume overlap at the nodes.

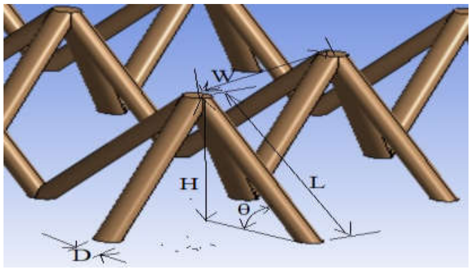


Fig.4 Unit pyramidal lattice geometry

$$\bar{\rho} = \left(\frac{D}{L}\right)^2 \frac{\pi}{2\sin\theta\cos^2\theta}$$

The exact formulation of volume overlap gives:

$$\bar{\rho}^* = \bar{\rho}\left[1 - \left(\frac{D}{L}\right)\frac{\left(1-\frac{1}{\pi}\sin^{-1}(x)\right)}{2\alpha\sin\theta\cos\theta}\right] \quad (1)$$

Thermal analysis assumptions:

1. The constant temperature at the outer surface of the insulating sandwich panel. T1=927°C+273= 1200K
2. One dimensional nonlinear thermal conduction problem. Considering heat flow along thethickness direction.
3. Initial temperature constant
4. Radiation and convective heat transfer are ignored.

Nonlinear heat conduction differential equation mathematical representation is as follow:

$$\frac{d}{dx}\left(K\,\frac{dT}{dx}\right)+\frac{d}{dy}\left(K\,\frac{dT}{dy}\right)+\frac{d}{dz}\left(K\,\frac{dT}{dz}\right)=\rho c.\frac{dT}{dt} \quad (2)$$

where density, thermal conductivity and specific heat of the insulating material is represented as ρ, K, C and T for temperature, t for time and x, y, z represents heat flow directions.

One dimensional differential equation (neglecting y, z direction)

$$\frac{d}{dx}\left(K\,\frac{dT}{dx}\right)= \rho c.\frac{dT}{dt} \quad (3)$$

Discretizing the equation (1), Finite element equation of conductive heat transfer is rewritten as follows:

$$[(C_1)\,(T)]\,[T^l] + [(K_1)\,(T)]\,[T] = [(Q)\,(T)] \quad (4)$$

Where K, C_1, and Q each variablestand for a matrix of conductivity, specific heat and heat flux of the node. T stands for nodal temperature and T^l are the derivative of the nodal temperature with respect to time. Each nodal nonlinear temperature can be obtained by using the Newton Raphson method.

Equation (3) subjected to thermal boundary conditions as follows:

$$T(x,0) = T_i = 295K \quad (5)$$

$$T(0,t) = T1(t) \quad (6)$$

$$T(L,t) = T4(t) \quad (7)$$

Where T_i stands for an initial temperature of the insulating panel, T1, T4 is the thermal load at top and bottom surface of the panel. Sandwich structure contacts should be within the permissible limit. L is the thickness of the panel.

4. Results and Discussion

Before simulating the transient thermal analysis of an insulating sandwich structure, selection of core topology and material selection is carried out analytically. Current research is focused on the thermal performance of a sandwich panel.

Generally, the sandwich panel consists of conventional type cores such as square comb, honeycomb structures, and corrugated cores. In this analysis, we introducing a pyramidal lattice core to improve the structural strength and decreasing the core weight. Selecting a core by its strength to weight ratio and considering of all its design specifications. Analytically design model is developed by using software CATIA V5R20 and conducting transient thermal analysis in ANSYS 15 software to investigate the thermal results on different types of sandwich cores. Comparing the temperature °C and total heat flux W/m2 distribution over a time period of 3000 sec on the bottom facing sheet. Conventional core max temperature distribution over a time 55% higher than the pyramidal core results, the max total heat flux is too high in pyramidal lattice when comparing with a square comb or conventional core. Corrugated core max temperature distribution over a time 50% higher than the pyramidal core results. Max total heat flux is too high in a pyramidal lattice when comparing with the corrugated core. Pyramidal lattice core reports greater total heat flux than the other type of conventional core. Because pyramidal lattice core has greater porosity than the conventional cores it also has a very less conducting path so heat flow over the lattice profile continuously by larger surface area of the TFS. Higher level heat flux can be normalized by modifying material which is having low thermal conductivity and introducing a thermal protection system to the sandwich panel.Thermal investigation of various cross-sectional cores through graphical representation is as follows:

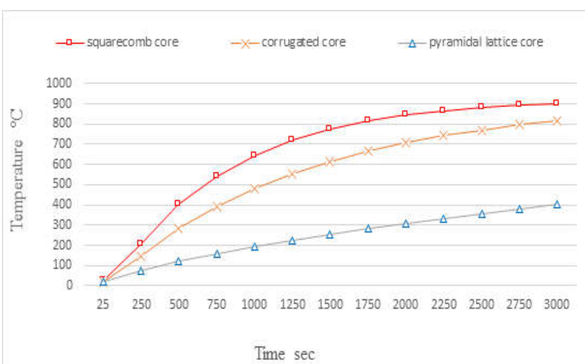


Figure.5 Max temperature distribution of a variable core

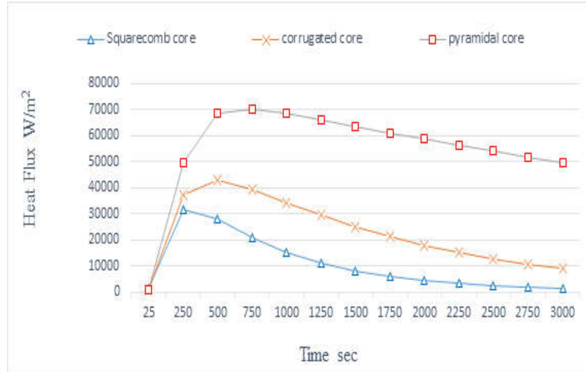


Figure.6 Max heat flux of a variable core

Material selection of a pyramidal lattice core with low thermal conductivity and low-density specification, most of the sandwich construction consists of low-density core material aluminium has a higher occupancy surface with less density, major drawback of this metal is higher thermal conductivity and low strength and low melting temperature it is not suitable for the thermal protection sandwich layer. Titanium metals have a very good thermal resistivity and low thermal conductivity with high strength material property. It has a wide range of application in the aerospace industry. Ti-6Al-4V alloy has a good thermal performance than the titanium it has less conductivity with the excellent mechanical strength to weight ratio. Titanium alloy has an impurity metal .impure metal has high strength when compared to the pure aluminum. The comparison is continued between the two metals which is titanium and Ti-6Al-4V alloy. Titanium analytical results show that temperature recorded on the bottom facing sheet is 36% higher than the Ti-6Al-4V alloy. Total heat flux recorded on the bottom facing sheet is 35% higher than the titanium because of its alloy composition.

Higher heat flux can be normalized by introducing integrated thermal protection system to the sandwich construction.Integrated thermal protection system provides excellent thermal insulation to the system when severe thermal loads affected on the panel.Thermal investigation of a pyramidal lattice core with titanium and Ti-6Al-4V alloy through graphical representation is as follows:

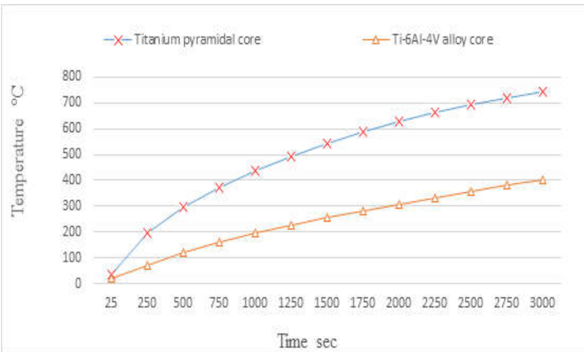


Figure.7 Titanium&Ti-6Al-4V alloy pyramidal lattice core max temperature distribution °C

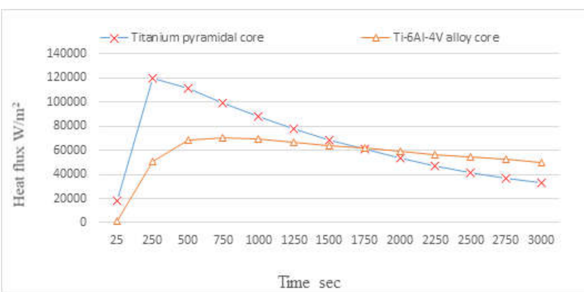


Figure.8 Titanium&Ti-6Al-4V alloy pyramidal lattice core max total heat flux W/m^2

The integrated thermal protection system is introduced in sandwich construction due to its intense thermal loads. Multi-layer composite insulation performs better thermal protection than the single layer thermal protection system known from the earlier researchers.

Test model	Layer type	Layer material	Thickness (mm)
Test model 1 (case-1)	Upper Layer	Aluminosilicate/Nextel720	2 mm
	Middle Layer	Saffil	4 mm
	Lower Layer	Aluminosilicate/Nextel720	2 mm
Test model 2 (case-1	Upper Layer	Aluminosilicate/Nextel720	2 mm
	Middle Layer	Saffil	2 mm
	Lower Layer	Aluminosilicate/Nextel720	2 mm
Test model 3 (case-2)	Upper Layer	Saffil	2mm
	Middle Layer	IMI	2mm
	Lower Layer	Q-fibre	2mm

Table 2. Thermal insulating multi-layer optimized test model Case-1 & Case-2

The multi-composite layer consists of different insulating materials. Current research followed by case-1 and case-2 multilayer insulations. Both insulation composite layer is used in the simulation over a period of time. Temperature results are tabulated. Without thermal protection system Ti-6Al-4V, alloy pyramidal lattice core reports max temperature on BFS is 403.6 °C. Providing thermal insulation to the system results shown that 4 times lesser temperatures result at T_4 surface of the sandwich test model.

Multilayer composite insulation case	Thickness (mm)	Time (sec)	Temperature T_{Max}			Total Heat Flux Q	
			T_2 (°C)	T_3 (°C)	T_4 (°C)	Q_{Min} (W/m^2)	Q_{Max} (W/m^2)
Case-1	6	500	626.64	281.26	93.033	0.31287	820.14
		1000	789.32	165.34	55.131	0.83184	1686.5
		1500	838.71	215.51	93.383	0.84382	1955
		2000	855.4	254.9	134.03	0.72525	1968.2
		2500	862.57	290.2	173.95	0.80315	1901.7
		3000	866.86	323.95	212.22	0.62614	1814.6
Case-1	8	500	406.07	64.196	24.084	0.15426	257.77
		1000	599.94	125.9	36.833	0.26188	643.54
		1500	697.37	177.49	60.29	0.44868	857.24
		2000	748.33	220.03	90.186	0.20097	942.72
		2500	776.44	256.54	123.04	0.24059	961.75
		3000	793.56	290.05	156.74	0.34076	949.03
Case-2	6	500	244.74	51.856	22.538	0.005687	105.87
		1000	388.48	107.77	26.851	0.008431	366.55
		1500	482.53	160.01	36.775	0.0144	597.29
		2000	546.82	205.79	51.876	0.0335	752.35
		2500	592.38	245.52	71.023	0.0286	843.43
		3000	626.64	281.26	93.033	0.081001	890.63

Table 3. Transient thermal analysis results of the Multi-layer insulating sandwich panel

Comparing both case-1 and case-2 insulating composites. Case-1 results shown that increasing multi-layer thickness thermal performance is superior. 8mm multi-layer insulation resists 55.46 °C than 6mm ITPS. Comparison between case-1 and case-2 integrated thermal protection system. Case-2 6mm ITPS has a better thermal performance than the case-1 8mm ITPS. Finally, the case-2 thermal protection system is selected for the Ti-6Al-4V pyramidal lattice core insulating sandwich panel through the transient thermal analysis. Thermal optimized model is designed with the combination of Ti-6Al-4V alloy core with multilayer insulating sandwich panel. Thermal investigation results identifies the thermal efficient insulating sandwich panel. Graphical representation is shown below:

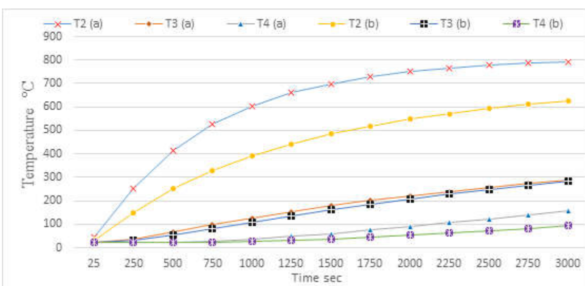


Figure.9 Comparison of case-1 & case-2 multi-layer insulation max temperature distribution °C

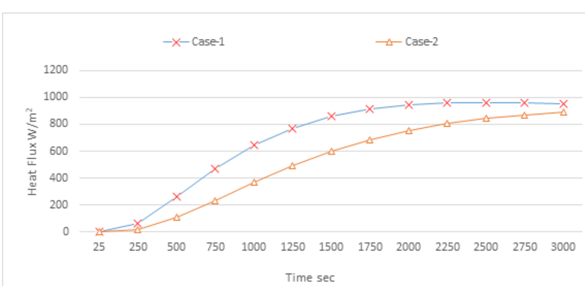
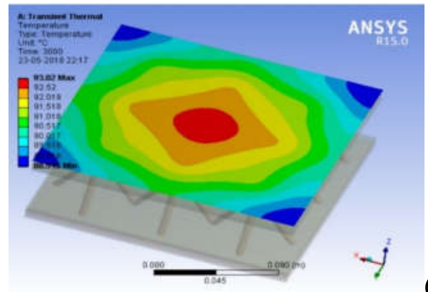
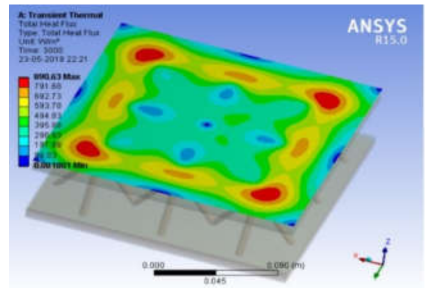


Figure.10 Comparison of case-1 & case-2 multi-layer insulation max total heat flux W/m^2

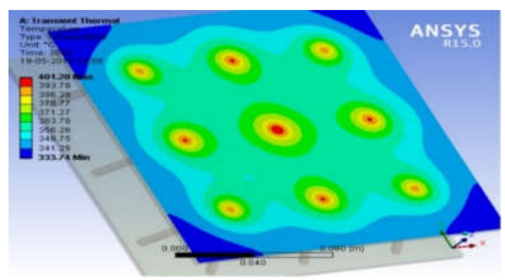


(a)

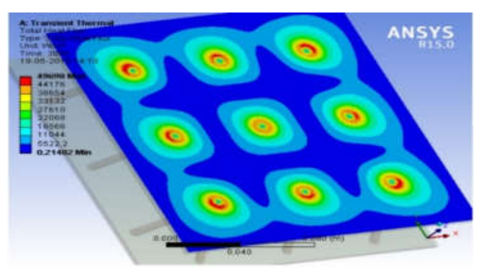


(b)

Figure.12 The temperature distribution (a) & Total heat flux (b) of a Ti-6Al-4V pyramidal lattice core with a Case-2 insulating sandwich panel



(a)



(b)

Fig.11 The temperature distribution (a) & Total heat flux (b) of

a Ti-6Al-4V pyramidal lattice core without multilayer insulation.

Conclusion

In this work, thermal optimization procedure accounting for the material mass minimization with lattice topology and minimizing thermal conductivity by material selection, thermal protection system addressed with a special emphasis on simplifying design, the material of the sandwich panel. Transient thermal analysis with several assumptions. Major work is done in the project is the selection of insulating core topology, insulating core material, and improving thermal performance by introducing multi-layer composite insulation.

Acknowledgment

This work was supported by Mechanical Engineering Department of Aditya Engineering College, Surampalem, Andhra Pradesh, India.

Nomenclature

C = Specific heat J/kgK

D = Diameter (mm)

K = Thermal conductivity (W/mK)

T = Temperature (°C)

T_i = initial temperature (°C)

$T_{(1, 2, 3, 4)}$ = Temperature of the contact surface (°C)

t = Time (s)

T^l = Nodal temperature derivative (°C)

K_l = Nodal thermal conductivity matrix (W/mK)

Q = Nodal heat flux (W/m^2)

Greek symbols

θ = Strut inclination angle (deg)

ρ = Density kg/m^3

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