Design and Analysis of Multi-layer Integrated Thermal Protection System based on Ceramic Matrix Composite and Titanium Alloy Lattice Sandwich

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Abstract. In order to satisfy the aerodynamic shape requirement of hypersonic vehicles, a curved multi-layer integrated thermal protection system (ITPS) is developed in this paper. The ITPS consists of a ceramic matrix composite layer, a lattice sandwich layer and a glass wool layer. The curved ITPS samples are fabricated. Then experimental test and numerical simulation are carried out respectively to evaluate the heating insulation effect of the ITPS samples. In addition, a series of numerical simulations are conducted to investigate the influences of lattice configuration and gradient layer layout on the heating insulation and load bearing capability of the ITPS.

1. Introduction
Thermal protection system (TPS) has been regarded as a key technique to protect hypersonic vehicles from overheating [1-4]. The early TPS was usually made of flexible materials with lightweight and high temperature resistance. Several kinds of metal-based TPS were studied as well [5-7]. However, the poor loads bearing capacity has limited the application of traditional TPS. In recent years, the integrated TPS (ITPS) was developed. The ITPS can simultaneously realize the thermal protection and loads bearing capacity [8-12]. As shown in figure 1, a typical ITPS usually has a multi-layer structure, including a heat resistant layer, a heat protection layer and a layer with double-functions of heat insulation and load bearing [13, 14].

Excellent mechanical properties and oxidative resistance under high temperature render the carbon fibre reinforced silicon carbide matrix composite (C/SiC) to be the promising material for the heat protection layer of ITPS [15-17]. However, C/SiC matrix composite has high thermal conductivity and low flexibility, so the inner parts of the multi-layer structure of ITPS must have low thermal conductivities and high mechanical performances. Motivated by this situation, lattice sandwich structures [18-20] have been applied in ITPS recently. It is found that the lattice sandwich structure can not only improve the compressive and bending strength of the TPS, but noticeably reduce the overall weight. Kai et al. [21-23] fabricated a C/SiC pyramidal core lattice sandwich panel and analysed heat transfer and compressive responses of the structure through numerical simulation. The areal density of the lattice sandwich panel is minimized as well. Zeng et al. [24] established the 3D heat transfer model of the gradient lattice structure under the different conditions. The numerical model was verified by high-temperature test.
To satisfy the aerodynamic shape requirement of hypersonic vehicles, the study of curved ITPS is necessary. However, there are few reports of the curved ITPS structure in the literature. Therefore, a curved multi-layer ITPS structure is proposed in this paper. The outer layer is a C/SiC composite panel, the bottom layer is a lattice sandwich filling with glass wool and a glass wool layer with excellent thermal insulation is located between them. The curved ITPS samples are fabricated. Then experimental test and numerical simulation are carried out respectively to evaluate the heating insulation effect of the ITPS samples. In addition, a series of numerical simulations are conducted to investigate the influences of lattice configuration and gradient layer layout on the heating insulation and load bearing capability of the ITPS.

![Figure 1. Illustration of the multi-layer structure of ITPS](image)

**Figure 1.** Illustration of the multi-layer structure of ITPS

2. Theoretical model

2.1. Titanium alloy lattice sandwich structure

Lattice sandwich structure is an ordered ultra-light porous material which consists of an upper panel, a lower panel and the lattice core. In the past years, the single-layer lattice sandwich structures were widely used in TPS, such as Kai Wei et al. [21]. In fact, with the same volume, the multi-layer lattice is expected to have a better thermal resistance than the single-layer lattice. This is because the diameter of rods inside the multi-layer lattice is smaller than the single-layer one. Hence, a curved double-layer lattice core structure is selected as the bottom layer of the ITPS in this study. The geometrical parameters of the unit cell of the curved lattice sandwich are shown in figure 2. The material of the double-layer lattice is Ti-6Al-4V titanium alloy. The strength of Ti-6Al-4V titanium alloy fabricated by 3D printing technology [25, 26] can reach 900 MPa, which satisfy well the load bearing requirements of the ITPS.

![Figure 2. The geometrical parameters of the unit cell of lattice sandwich structure](image)

**Figure 2.** The geometrical parameters of the unit cell of lattice sandwich structure

2.2. The curved multi-layer ITPS structure

The curved multi-layer ITPS structure established in this paper is shown in figure 3. The upper layer is C/SiC composite curved panel to survive the extreme heat flux from outside surroundings, the bottom lattice sandwich layer furtherly protected inside part from heating and compressive loadings, and the middle layer is glass wool for heat insulation. The three parts work together to prevent the structure from external high temperature heating and sustain the mechanical loads simultaneously.
3. Experimental test and numerical simulation

3.1. Experimental test
In this work, the curved ITPS samples are fabricated according to the three-dimensional model shown in figure 3. The fabricated sample is displayed in figure 4. The sample is heated for 900 seconds by a blowlamp, and the flame temperature of the blowlamp reaches about 800 °C. Several thermocouples are embedded inside the sample as T1-T9 in figure 4 and figure 5, which are then connected with a multi-channel digital display electronic thermometer to record the instant temperature during heating process. The whole multi-layer structure is connected by high-temperature ceramic bolts. During the test, the sample is surrounded by insulation materials and silicon carbide tiles to reduce the outside heat convection. After the structural temperature reaches a steady state, the data of instant temperature on each layer is recorded every 30 s.

3.2. Numerical simulation
In addition to the experimental test, the finite element method is used to simulate the thermal response of the curved ITPS sample. Finite element model of the curved multi-layer ITPS model is shown in figure 6. Uniform heat flux is injected on the outer C/SiC composite surface as 5000 W/m², the natural convection condition is exerted on the bottom surface of the titanium lattice sandwich as 5 W/(m²·°C), and the initial temperature of the whole structure is set as room temperature. To simulate the thermal response of the ITPS structure, a 900 seconds transient calculation is executed.
3.3. Results
The experimental and simulated results of the temperature-time variation on the hot and cold end of the titanium alloy lattice, T3 and T4, are presented in figure 7 and figure 8 respectively. It is seen that after 900s heating, the temperature of the hot end of the lattice reaches 300 ºC, while the temperature of the cold end is only 80 ºC. Experiment and simulation results both indicate that the proposed ITPS sample has an excellent thermal insulation performance.

Numerical simulation results are generally consistent with the experimental data. Simulation errors come from the simplification of the heating boundary. In the real test, the heat flow distributed on the heating surface is not uniform as simulation. Heat flux density of central field is much higher than the edge regions.

Figure 7. The instant temperature of the lattice hot end

Figure 8. The instant temperature of the lattice cold end

4. Parametric analysis
In this study, a parametric analysis is further carried out to investigate the influences of various parameters of the ITPS on the heat insulation and load bearing capability. Here, the number of lattice cells, the diameter of lattice rod and thicknesses of glass wool layer and lattice sandwich layer are considered.

4.1. Influence on heat insulation
Figure 9 shows the variation of the temperature difference between the upper and lower surface (∆T) with the number of lattice unit cells. It could be seen that the temperature difference ∆T is gradually reduced as the number of lattice cells increases. After the number of lattice cells exceeds 100, ∆T is reduced slowly and is expected to reach a steady value. Figure 10 shows the evolution of temperature difference ∆T with varied diameters of the lattice rods. As the diameter of the rod increases, the heat flux transferred along the lattice rod expands. Thus, the thermal insulation effect decreases and the temperature difference reduces. Similarly, it is found that after the diameter of lattice rod exceeds 1.8 mm, ∆T goes down slowly and is expected to reach a steady value.
Figures 11 and 12 display the variation of temperature difference $\Delta T$ with the thicknesses of lattice and glass wool layer, respectively. It can be seen that the temperature difference both increases with the increasing of lattice layer and glass wool layer thicknesses. However, the increasing is more pronounced in glass wool layer thicknesses.

4.2. Influence on load bearing

The load bearing capability is an important advantage of ITPS. In this section, influences of the number of lattice cells, the diameter of lattice rod and thicknesses of glass wool and lattice layer on the load capability of the curved ITPS are investigated through numerical method. Uniform pressure of 0.1 MPa is applied on the outer surface of C/SiC composite panel, the bottom surface of the titanium alloy lattice sandwich is fully fixed.

Figures 13 and 14 shows the variation of maximum stress and displacement within the ITPS with the number of lattice cells and the diameter of lattice rod, respectively. As the number of lattice cells or the diameter of lattice rod increases, stiffness of the ITPS structure has enhanced, maximum stress and displacement within the ITPS are found to be reduced effectively.
5. Conclusions
In this paper, a curved multi-layer ITPS based on C/SiC composite and titanium alloy lattice sandwich is proposed and fabricated. Both experimental test and numerical simulation are implemented to evaluate the heat insulation effect of the ITPS samples. The curved multi-layer ITPS shows an excellent heat insulation performance. After 900s heating of the blowlamp with 800 °C flame, the temperature of the cold end of ITPS is only 80 °C. Finally, a series of numerical simulations are carried out to investigate the influences of various parameters of the ITPS on the heat insulation and load bearing capability.

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