THERMAL-MECHANICAL BEHAVIOR OF SANDWICH PANELS WITH CLOSED-CELL FOAM CORE UNDER INTENSIVE LASER IRRADIATION

by

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Temperature field and thermal deformation of sandwich panels with closed-cell aluminum alloy foam core and heat-protective layer, which are subjected to Gaussian laser beam intensively irradiating, are investigated numerically. In transient heat analysis models, the influence of thermal conductivity, specific heat, and thickness of heat-protective layer on the temperature rise of the sandwich panels is calculated. In stress analysis models, a sequence coupled numerical method is utilized to simulate the thermal stress and deformation of sandwich panels induced by thermal expansion. Simulation results indicate that the temperature at center of sandwich panel increases firstly and then drops gradually with the increase of thermal conductivity of heat-protective layer after laser irradiation, and the critical thermal conductivity is obtained, while it decreases with the increase of specific heat and thickness of heat-protective layer. The thermal stress verifies the "Cyclo-hoop effect", i. e. radial stress is compression stress in "hot zone" and tension stress in "cold zone". The max thermal deformation of sandwich panels slightly increases with the increase of thickness of heat-protective layer for given specific heat and thermal conductivity.

Keywords: *sandwich panels, closed-cell foam, heat-protective layer, thermal-mechanical behavior*

Introduction

Cellular metal foams as novel engineering materials are of current academic and industrial interest due to their superior properties, such as high specific strength, high specific stiffness high energy absorption ability, *etc*. Sandwich structures with metal foam core are applied to space aircraft due to their high strength and light weight. With the faster increase of flight speed, its heat protection plays more and more great parts in ensuring flight safety of aircraft, especially supersonic speed space aircraft. Therefore, it is of importance to investigate the thermal deformation of sandwich structure subject to intensive heat. Usually, the surface of sandwich structure is covered by a thin insulating heat layer such as high-temperature ceramic and C/C composite materials to prevent its heat damage caused by temperature change [1, 2].

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In recent years, the thermal-mechanical behaviors of cellular metal foams and sandwich structures have been investigated. Lu *et al.* [3] and Zhao [4] have explored the heat transfer of open-cell metal foam as a compact heat exchangers using analytical model, and also made detailed research on the dependence of the apparent thermal conductivity of closed-cell metal foams on the relative density, irregularity, cell-wall non-uniformity and geometric imperfection. Calmidi and Mahajan [5] have reported an experimental and numerical study of forced convection in aluminum metal foams with lower relative density (0.03-0.11). Carmignani *et al.* [6] have simulated the laser welding process of thick plate using elastic-plastic finite element (FE) method, and given three dimensional stress distribution characteristic caused by molten pinhole. Martinez *et al.* [7] have considered the structures as the orthotropic panel by variables separation method and investigated the effect of the change of webs angle on stiffness and deflection of structure. Nevertheless, investigation on the thermal stress analysis of heat-protective sandwich panels with foamed metal core has been seldom published up to now.

The focus of this study is the dependence of the temperature rise and thermal stress of sandwich panels on the thickness, specific heat, and thermal conductivity of heat-protective layer. First, FE models of sandwich panel with heat-protective layer under intense laser beam are built. Following the numerical solution of temperature field and thermal stress, the detailed analysis of simulation results are provided. Finally, some significant conclusions are drawn.

Finite element models of sandwich panels with heat-protect layer

Sandwich panels consist of core layer, top, and bottom panels. Heat-protect layer is covered on the surface of top panel for protecting sandwich panels from intensive heat. Given symmetry of sandwich panels with heat-protect layer in geometry structure and thermal load, a quarter of FE models were established, as shown in fig. 1. Close-cell aluminum foams core with given cell shape irregularity (0.8) has been constructed based on 3-D Voronoi structure by Li *et al.* in published literature [8], and its length in x-, y-, and z-direction is 0.04 m, 0.04 m, and 0.02 m, respectively. Closed-cell aluminum foams are 5052 aluminum alloy. Top and bottom panels are 2024 aluminum alloy plate with the same thickness of 0.0005 m. Heat-protect layer is high temperature resistant ceramic with four varied thickness of 0.0005 m, 0.001 m, 0.0015 m and 0.002 m. In fig. 1, 0.005 m radius quadrant of heat-protect layer center is the laser irradiation area.

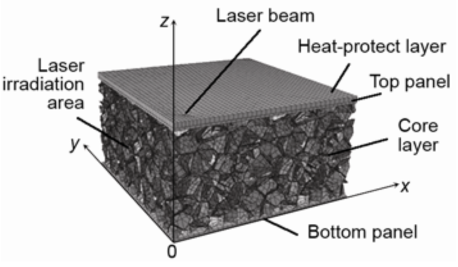

Figure 1. A quarter of FE models of sandwich panels with heat-protective layer

In FE analysis, four assumptions are made: (1) Continuous laser beam exerted on the sandwich follows Gaussian distribution, which is expressed as in Cartesian co-ordinate system:

$$I = I_0 \exp\left(-2\frac{x^2+y^2}{a_0^2}\right) \tag{1}$$

where I_0 is the central laser intensity, a_0 – the laser spot radius where laser intensity is $1/e^2$ of central laser one. Here, $I_0 = 1.2\cdot10^7$ W/m and a_0 is 0.005 m. (2) All materials are isotropic, and their temperature-dependent thermal-mechanical parameters are listed in tab. 1. (3) Compared with heat power from laser irradiation, convection, and irradiation power between the

Table 1. Thermal-mechanical parameters of each part of sandwich panel with heat-protective layer

Parameters parts	Density [kgm^{-3}]	Specific heat [Jkg^{-1}K^{-1}]	Thermal conductivity [Wm^{-1}K^{-1}]	Poisson ratio	Elastic modulus [MPa]	Expansion coefficient [10e-6 K^{-1}]			Yield strength [MPa]			
Heat protection layer	4000	850	7.79	0.24	310e3	10						
Top and bottom panels	2680	875	190	0.33	72.1e3	100 °C	200 °C	300 °C	20 °C	100 °C	200 °C	300 °C
						22.9	23.8	24.7	75.8	55.1	45	31.1
Core layer	2700	900	137	0.34	69e3	100 °C	200 °C	300 °C	20 °C	100 °C	200 °C	300 °C
						23.8	24.8	25.7	260	224	179	150

structure and ambient are negligible. (4) Thermal-mechanical sequential coupling method is used to solve structural temperature field and stress field.

Considering that laser power is partially absorbed, an absorption coefficient is assigned 0.3. Time span of laser irradiation is 1 s, and the initial ambient temperature is set as 20 °C.

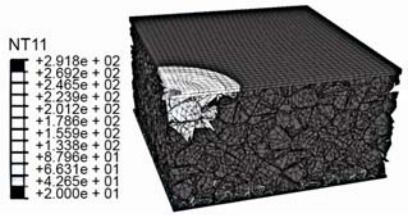

Figure 2. Temperature distribution of sandwich panels with heat-protective layer after laser irradiation

Results and discussion

Temperature field of sandwich panels

Figure 2 presents the temperature distribution of heat-protective sandwich panels after laser irradiation. The change in temperature far from laser irradiation area is negligible. Here, the area with higher temperature rise is called "hot zone", while one with nearly zero temperature rise is called "cold zone". Temperature is highest in the laser center, which is 292 °C. The emphasis below is placed on the effect of thermal conductivity, specific heat, and thickness of heat-protective layer on the temperature rise of sandwich panels' center.

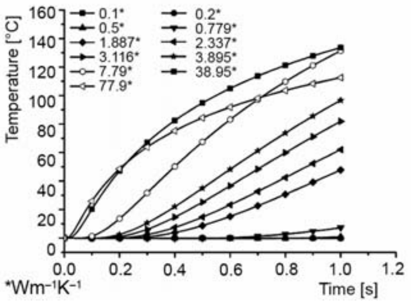

Figure 3. Variation of temperature rise in the center of sandwich panels with different thermal conductivity

Effect of thermal conductivity

Keeping the constant heat specific (C = 850 J/kgK) and thickness (t = 0.0015 m) of heat-protective layer, fig. 3 illustrates the temperature rise variation of sandwich panels' center with different thermal conductivity (λ) ranging from 0.1W/mK to 77.9 W/mK. The temperature rise is not obvious for these thermal conductivity such as 0.1 W/mK, 0.2 W/mK, 0.5 W/mK, and 0.779 W/mK while it is apparent that the temperature rise grows with the increase of thermal conductivity ranging from 1.887 W/mK to 7.79 W/mK even though there is definite time-delay. The temperature rise drops for higher thermal conductivity like 38.95 W/mK and 77.9 W/mK when laser irradiation ends. It can be concluded that too large or too small thermal conductivity of heat-protective layer would reduce the temperature rise, and 7.79 W/mK is the critical value.

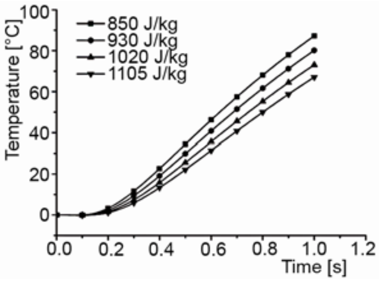

Figure 4. Variation of temperature rise in the center of sandwich panels with different heat specific

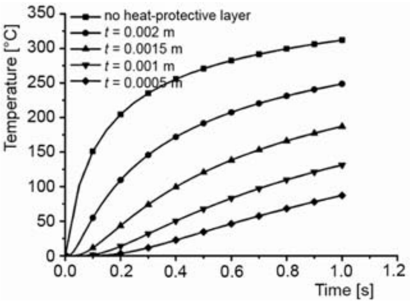

Figure 5. Temperature rise variation in the center of sandwich panels with varied thickness

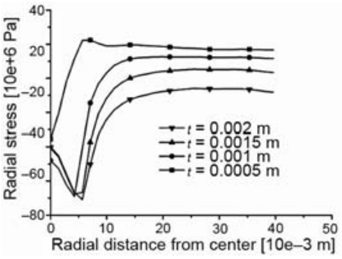

Figure 6. Radial stress variation of sandwich panels with radial distance

Effect of specific heat

Keeping λ = 7.79 W/mK and t = 0.0015 m of heat-protective layer, fig. 4 depicts the variation of temperature rise of sandwich panels' center with different specific heat ranging from 850 J/kgK to 1105 J/kgK. The temperature rise decreases with the increase of the specific heat during the laser irradiation, and the temperature rise drops from 87 °C to 67 °C after 1 s duration of laser irradiation. Increasing the same temperature rise, larger specific heat leads to more heat quantity absorbed by thermal-protective layer. Then less heat quantity is transmitted to sandwich panels, which lowers its temperature rise.

Effect of the thickness of thermal-protective layer

Keeping λ = 7.79 W/mK and C = 850 J/kgK of heat-protective layer, fig. 5 shows the variation of temperature rise of sandwich panels' center with different thickness. The temperature rise decreases with the increase of the thickness during the laser irradiation, and the temperature rise drops from 248 °C to 87 °C after 1 s duration of laser irradiation. In the special case without heat-protective layer, the temperature rise rapidly reaches 312 °C within 1 s but 87 °C for sandwich panels with heat-protective layer of 2 mm thickness within the same time. Laser irradiation of 0.045 s makes the temperature rise of sandwich panels without heat-protective layer to arrive at 87 °C. Therefore, protective layer has strong heat protection effect on sandwich panels.

Thermal stress and deformation of sandwich panels

In thermal stress analysis, temperature-dependent thermal expansion coefficient and yield strength of face panels and core layer (tab. 1) are employed to analyze the influence of the combined action of thermal expansion and thermal softening on thermal stress. In "hot zone", structure expands due to high temperature rise, while structure expands little due to nearly invariable temperature change in "cold zone". As a consequence, mismatching structure expansion results in radial compression stress in "hot zone", and radial tension stress in "cold zone". This is called "Cyclo-hoop effect". Figure 6 demonstrates variation of radial stress of sandwich panels with varied thickness of heat-protective layer. It can be seen that thermal stress is compression stress in "hot zone", and tension stress in "cold zone". All maximum stresses are lower than local yield strength of sandwich panels, so the structures do not failure within laser intensity given in the present study. The maximum deformation of sandwich panels reduces with the increase of thickness of heat-protective layer.

Conclusions

Thermal-mechanical coupling FE models of closed-cell aluminum foam core sandwich panels with heat-protective layer are developed to calculate the temperature field and thermal stress field of sandwich panels subject to intensive laser irradiation. The effects of thermal conductivity, specific heat and thickness of heat-protective layer on the temperature and stress distributions are investigated in details. The following conclusions are drawn.

Thermal conductivity of heat-protective layer has a dominating effect on the temperature field of sandwich panels and a critical thermal conductivity exists. When thermal conductivity is less than the critical value, the temperature rise increases with the increase of thermal conductivity. If not, the temperature rise decreases with the increase of thermal conductivity. The temperature rise of sandwich panels decreases with the increase of specific heat and thickness of heat-protective layer. The thermal stress distribution satisfies “Cyclo-hoop effect”, *i. e.* laser beam divides sandwich panels into two zones – “hot zone” and “cold zone”, where radial stress is of different state and the former is compression stress, while the latter is tension stress. The thermal deformation slightly reduces with the increase of thickness of heat-protective layer.

Research results provide scientific foundation for design of heat protection system of supersonic aircraft.

Acknowledgments

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