ON EFFECTIVE THERMAL CONDUCTIVITY OF SUPER ALLOY HONEYCOMB CORE IN SANDWICH STRUCTURES

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1 General Introduction

The Honeycomb core sandwich structures are widely used in aerospace applications due to their high specific strength and specific stiffness, good thermal insulation and vibration absorption capabilities, etc. A typical sandwich panel consists of three layers: two thin and stiff face sheets and a lightweight core (Fig.1). In many cases, heat transfer analysis is necessary for the design of sandwich structures. Due to the discontinuity of honeycomb cores, heat transfer modes in sandwich structures usually include heat conduction, heat radiation and heat convection and are quite complex. Modeling a detailed sandwich structure in thermal analysis is very difficult, extremely costly and sometimes even impossible in real engineering applications. It is commonly expected that a discontinuous honeycomb core can be replaced as a continuum with effective macroscopic thermal parameters, such as thermal conductivity and specific thermal capacity. This paper mainly focuses on the experimental and numerical methods to determine the macroscopic effective thermal conductivities of honeycomb cores.

2 Experimental Methods

The effective thermal conductivities of honeycomb sandwich structure specimen at different temperatures were measured using static test method. As shown in Fig.2, in the test, the specimen was placed on a heating plate, surrounded by zirconia fiber insulations; upper face of the specimen was exposed in air. The heat dissipated from the upper face was in two forms: thermal radiation and thermal convection. According to Fourier's Law, the heat flux along the thickness direction is:

$$q = -\lambda \frac{dT}{dx} \qquad (1)$$

q is the heat flux along the thickness direction, λ is the effective thermal conductivity of the specimen, dT/dx is the temperature gradient in the thickness direction. While the thermal equilibrium is achieved, q equals to the total heat flux dissipated from the outer face, i.e. the summation of thermal radiation flux and thermal convection flux.

The radiation heat flux can be obtained according to Stefan-Boltzmann's Law:

$$q_r = \varepsilon\sigma(T_1^4 - T_a^4) \qquad (2)$$

ε is the emissivity of the specimen upper face, σ is Stefan-Boltzmann constant, T_a is the ambient temperature.

The thermal convection between the specimen upper face and the ambient air can be regarded as natural convection problem in infinite space, as can be computed according to the experimental correlation formula for natural convection in infinite space. The simplified equations are adopted to calculate the heat transfer of natural convection in infinite space [1]:

$$N_u = C(Gr\,\mathrm{Pr})^n \qquad (3)$$

$$Gr = \frac{g\alpha\Delta t l^3}{\upsilon^2} \qquad (4)$$

N_u is the Nusselt number. Gr is the Grashof number, α is the volume expansion coefficient, Δt is the temperature difference between upper face and environment, υ is the kinematic viscosity coefficient under reference temperature, l is the reference length, g is the gravity acceleration.

For the heated isothermal horizontal surface facing upward, the experimental correlations which has been used extensively for the Nusselt number can be given as [1]:

$$\begin{cases} N_u = 0.54(Gr\,\mathrm{Pr})^{1/4}, 10^4 \le Gr\,\mathrm{Pr} \le 10^7 \\ N_u = 0.15(Gr\,\mathrm{Pr})^{1/3}, 10^7 \le Gr\,\mathrm{Pr} \le 10^{11} \end{cases} \quad (5)$$

$$h = N_u \frac{\lambda_f}{l} \quad (6)$$

l is the characteristic length, λ_f is the thermal conductivity of fluid at reference temperature, h is the thermal transfer coefficient for thermal convective heat transfer.

According to Newton's Law of Cooling, the convective heat flux can be given as follows:

$$q_c = h(T_1 - T_a) \quad (7)$$

Thus, the total heat flux dissipated from the upper surface to environment can be calculated by summing Eq.2 and Eq.7. With the temperatures of the both sides of the specimen be obtained, the total thermal conductivity of the sandwich structure can be derived from Eq.1; moreover, the conductivity of honeycomb core itself can be derived using thermal resistance analysis method.

Total thermal resistance of the honeycomb sandwich is:

$$R = \frac{T_2 - T_1}{q_o} \quad (8)$$

The upper face sheet, honeycomb core and lower face sheet of the sandwich structure can be treated as series connection for heat transfer. According to the principle of superimposition of thermal resistance in series, total thermal resistance of the sandwich structure equals to summation of the resistance of the three parts:

$$R = \frac{t_1}{\lambda_m} + \frac{t_c}{\lambda_c} + \frac{t_2}{\lambda_m} \quad (9)$$

t_1, t_2, t_c are the thicknesses of the upper face sheet, honeycomb core and lower face sheet respectively, λ_m is the thermal conductivity of the face sheets, is the effective thermal conductivity of the honeycomb core itself.

The experimental system consists of high temperature heater, thyristor control system, PSI multi-channel temperature scanning valve and data acquisition computer, as shown in Fig.3, high-velocity thermo couples were utilized to measure the surface temperatures of the both sides of the specimen. The honeycomb core sandwich structure specimen was made of super alloy Hastelloy X, its dimensions are illustrated in Fig.4. A standard specimen of same surface condition with the specimen upper surface was manufactured to measure its emissivity, the result is 0.54; the inner surface of the core cavity undergoes sufficient oxidization, its emissivity is 0.85 [2].

3 Theoretical Model

Complex thermal transfer modes exist in the honeycomb core cavity when it is heated, including heat conduction of cell foils, conduction and convection of gas, thermal radiation between different surfaces.

The Swann and Pittman semi-empirical model has been utilized as a standard in aerospace industry to predict the effective thermal conductivity of honeycomb core panels [3,4]. Swann and Pittman analyzed the combined heat transfer problem of honeycomb sandwich structure using finite difference method, developed a semi-empirical model for computing radiation heat transfer in the core cavity. Moreover, Swann and Pittman developed an parallel thermal network model to compute the effective thermal conductivity of the honeycomb sandwich structure [5]:

$$k_e = k_f \frac{\Delta A}{A} + k_g \left(1 - \frac{\Delta A}{A}\right) + k_r \quad (10)$$

Where k_e is the effective thermal conductivity, it is a function of honeycomb core geometries and material thermal properties; k_f , k_g and k_r are the thermal conductivities contributed by the constitutive foil material, the gas in the core cavity and the radiation respectively; $\Delta A / A$ is the ratio of the cross-section area of solid core to the entire honeycomb core.

The thermal conductivity of gas can be obtained from:

$$k_g = \frac{k_g^*}{1 + 2\left(\frac{2-\alpha}{\alpha}\right)\left(\frac{2\gamma}{\gamma+1}\right)\left(\frac{1}{P_r}\right)\left(\frac{\lambda}{L_c}\right)} \quad (11)$$

k_g^* is the thermal conductivity of air, α is the accommodation factor, γ is the specific heat ratio of air, P_r is the Prandtl number, L_c is the core height, λ is the mean molecule free path, which can be obtained through:

$$\lambda = \frac{K_B T}{\sqrt{2}\pi d_g^2 P} \tag{12}$$

K_B is the Boltzmann constant, T is the temperature, d_g is the molecule collision diameter of air, P is the pressure.

$$k_r = 4\xi\sigma T_{avg}^3 L_c \tag{13}$$

T_{avg} is the average temperature of the honeycomb core structure, σ is the Stefan-Boltzmann constant, ξ can be obtained through:

$$\xi = 0.664(\eta + 0.3)^{(-0.69)}\, \varepsilon^{1.63(\eta+1)^{(-0.89)}} \tag{14}$$

ε is the uniform emissivity of cavity surfaces， d is the incircle diameter， η is the ratio of core height to d .

4 Finite Element Analysis

Honeycomb core sandwich structures are regular and periodic structures, the material properties of entire structure could be represented by the material properties of representative unit cell generally [5]. Finite element thermal analysis model was constructed using a representative unit of honeycomb core sandwich structure as shown in Fig.5. Only the solid heat conduction through sidewall foils and radiation among surfaces of the cavity were considered, the air in the unit cell cavity was neglected because its contribution to heat transfer is very small, and the model would be simplified obviously.

Radiation heat transfer was computed using the Aux12 radiation matrix method in ANSYS, which was used to calculate the form factors between the radiation surfaces. The radiation matrix was introduced to the thermal analysis model as a super element. The face sheets are meshed with 8 nodes solid element, the sidewalls are meshed with 4 nodes shell element, for the thickness of sidewall foil is very thin compared to the core height and cell side length.

Fixed temperature boundaries (T_u and T_l) are applied on the upper face sheet and lower face sheet respectively, subsequently conduct the nonlinear steady-state thermal analysis. For steady-state heat transfer, heat flow through each parallel cross section of the unit cell should be equal. As the nonlinear thermal analysis has been done, the total heat flow(Φ) through the cross section of the unit cell can be obtained by extracting the summation of the reaction heat flow at each node on the outer surface of the upper face sheet.

The heat flux through the cross-section can be computed through:

$$q = \frac{\Phi}{A} \tag{15}$$

Where A is the cross section area. According to Fourier's Law:

$$\lambda = \frac{qH}{T_u - T_l} \tag{16}$$

5 Results and Discussion

As shown in Fig.6, the predicted results from the finite element model and semi-empirical model agree well with the experimental results. A study to examine the effects of different geometrical variation on the effective thermal conductivities of honeycomb cores was performed based on the semi-empirical model.

The variations of cavity surface emissivity and the normalized geometrical parameters were discussed respectively. The results can be seen from Fig.7 to Fig.10. As the cavity surface emissivity increases with the other parameters unchanged, the total thermal conductivity of honeycomb core increases not obviously while the temperature is below 200℃; when the temperature is above 200℃, the emissivity makes an more important contribution to the growth of honeycomb core conductivities as the temperature grows up. Similarly, when change one normalized geometrical parameters respectively, the other parameters were kept unchanged. The effective thermal conductivities of honeycomb core raise monotonously as l/d , d/l and t/d increase.

6 Conclusion

A static thermal experiment was conducted, based on which the macroscopic effective thermal conductivities of honeycomb core varying with different temperatures were obtained using thermal resistance analysis method, in combination with Stefan-Boltzmann's law and experimental correlation formula for natural convection in infinite space. Finite element analysis model was constructed, and the Swan-Pittman semi-empirical model was also used to predict the effective thermal conductivity of honeycomb cores. Comparison was made between the experimental results and the predicted results, good conformity was observed. Based on the semi-empirical model, a parametric study was performed, several useful curves were obtained, which can be a reference for the design of honeycomb cores.

Table 1 Geometries of the sandwich specimen(mm)

Face sheet thickness	Core height	Foil thickness	Incircle diameter
0.2	7	0.1	5

Table 2 Thermal conductivities of Hastelloy X alloy material

Temperature(℃)	21	93	200	593	704	816	927
Thermal conductivity(W/mK)	9.1	11.0	14.1	20.8	22.9	25.1	27.2

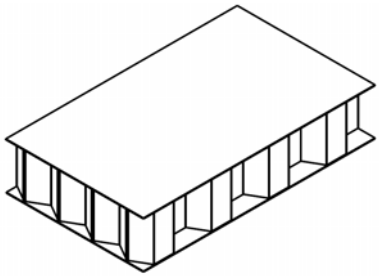

Fig.1. Typical honeycomb sandwich structure

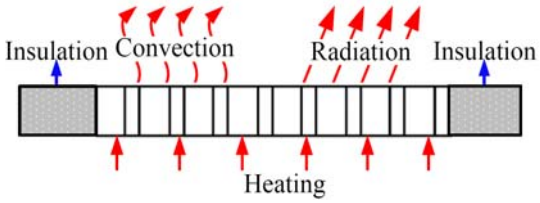

Fig.2. Heat transfer modes of the specimen

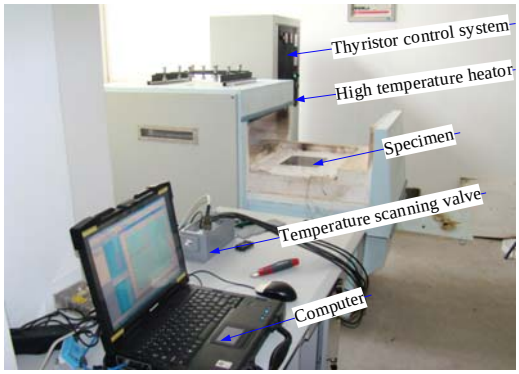

Fig.3. Photo of the test system

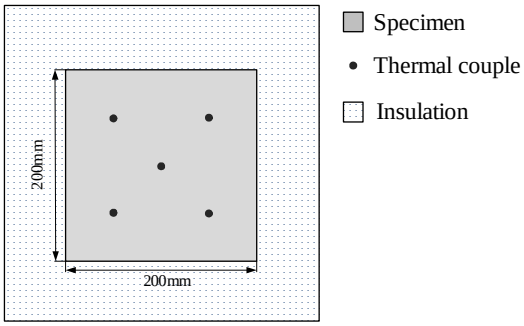

Fig.4. Sketch for specimen

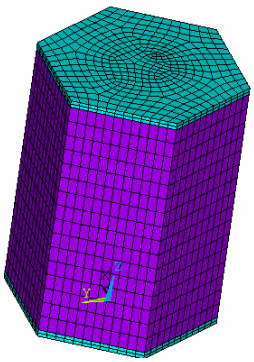

Fig.5. Finite element thermal analysis model

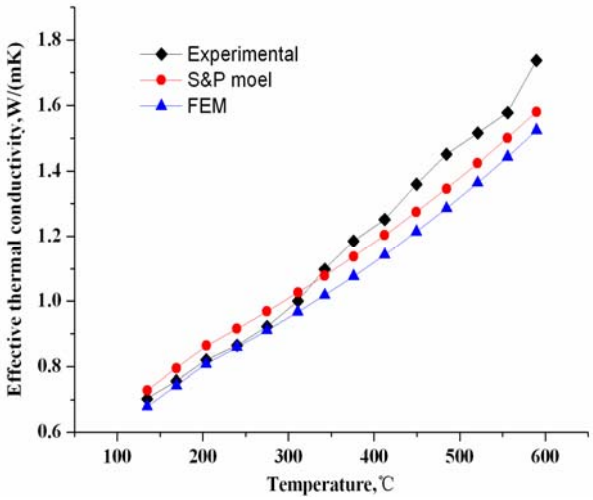

Fig.6. Comparison between the predicted and the experimental results

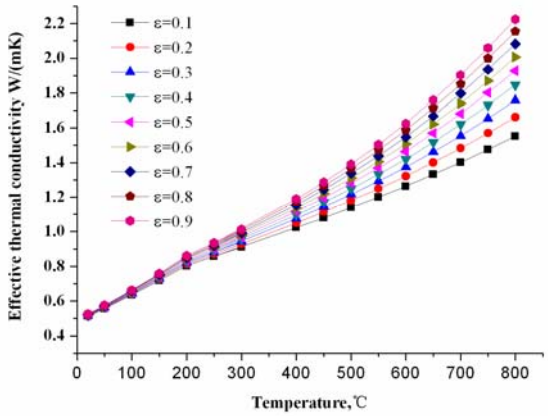

Fig.7. Effects of the cavity surface emissivity on effective thermal conductivities of the core

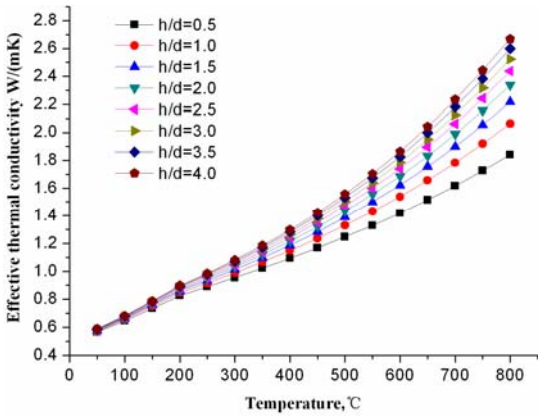

Fig.8. Effects of the parameter h/d on effective thermal conductivities of the core

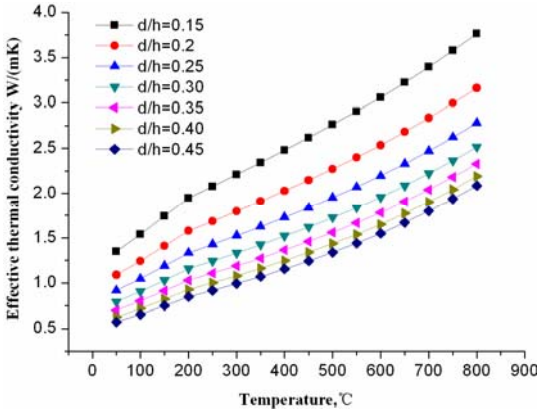

Fig.9. Effects of the parameter d/h on effective thermal conductivities of the core

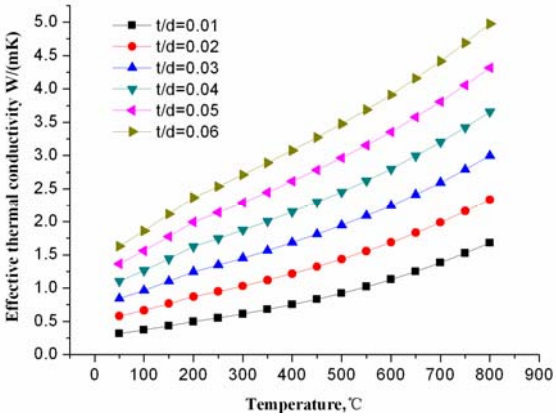

Fig.10. Effects of the parameter t/d on effective thermal conductivities of the core

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