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Thermal and mechanical properties of a multifunctional composite square honeycomb sandwich structure

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ABSTRACT

A multifunctional composite square honeycomb sandwich structure (MCHSS) is developed which provides both high thermal conductivity and adequate mechanical property for a thermal management system. The out-of-plane thermal conductivity of MCHSS is improved by a simple method of coating highly oriented graphite film (HOGF), and investigated both theoretically and experimentally. There are two most efficient methods to further enhance the out-of-plane thermal conductivity of MCHSS: one is to increase the HOGF volume content, and the other, to decrease the interface thermal resistance. The maximum improvement is up to approximately 26 times for the measured out-of-plane thermal conductivity as compared with the traditional composite sandwich structures. Results indicate that, except for high specific thermal conductivity for thermal management, MCHSS also possess adequate mechanical properties for structural applications. Thus, MCHSS can be considered as a promising candidate for multifunctional structure material in the high-end heat dissipation field.

1. Introduction

Periodic lattice materials are considered as the most promising multifunctional structure materials in the 21st century, and put forward by Ashby, Evans, Fleck, Gibson, Hutchinson and Wadley, owing to their excellent mechanical properties (specific stiffness and specific strength) and multifunctional application potentials [1–5]. Carbon fiber reinforced plastic (CFRP) composite sandwich structures are more remarkable for building ultra-lightweight multifunctional structures, especially for spacecraft. Recently, a variety of composite lattice cores have been fabricated and their performance evaluated [6–13]. The experimental results have been added to the modified Ashby material property chart [14] as shown in Fig. 1. It can be obviously seen that composite square honeycomb sandwich panels [11] have significantly higher compressive and shear modulus than the other sandwich panels, on an equal mass basis. For core densities more than 100 kg/m^3, composite square honeycomb sandwich panels [11] have superior out-of-plane compressive strength than most known materials. Only when the core densities are less than 100 kg/m^3, pyramidal truss core sandwich panels [6] exhibit greater out-of-plane compressive strengths. Moreover, square honeycomb structures overcome the drawback of hexagonal honeycomb structures and show a high in-plane stretching strength (at least for loadings along the directions of the cell walls).

However, owing to vast inner space and low thermal conductivity of composite cores, composite sandwich structures show very low thermal conductivity, which limits its application in the high-end heat dissipation fields such as satellite. Therefore, a multifunctional composite sandwich structure, possessing both the superior mechanical properties and high thermal conductivity, is urgently needed in these fields.

In this paper, MCHSS is devised and fabricated by the CFRP composite laminate coating HOGF [15,16]. Efforts are underway to determine the out-of-plane thermal conductivity of MCHSS and to assess its out-of-plane compressive and shear properties, both theoretically and experimentally. Moreover, the detailed analysis is conducted to reveal the main factors that affect the out-of-plane thermal conductivity.

2. Experimental

2.1. Materials and fabrication

The plain woven Toray T300-3 k carbon fiber epoxy prepreg with 45% resin content (a density of 1.45 g/cm^3, Liso Composite Material Technology Co. Ltd., China) is used to fabricate the square honeycomb core due to its high specific stiffness and strength. HOGF (the density 2.1 g/cm^3, in-plane thermal conductivity is up to 1500 W/mK) with a thickness 20 μm is from Tanyuan Science and Technology Co., Ltd., China. The aluminum alloy (thermal conductivity of 208 W/mK) is used as the facesheet with a thickness of 0.25 mm.

In this paper, multifunctional composite square honeycomb structures are fabricated by a slotting and assembling procedure as follow.

(i) Orthogonal symmetric composite prepregs are laid up on a base plate and then placed in a compressive molding for curing and

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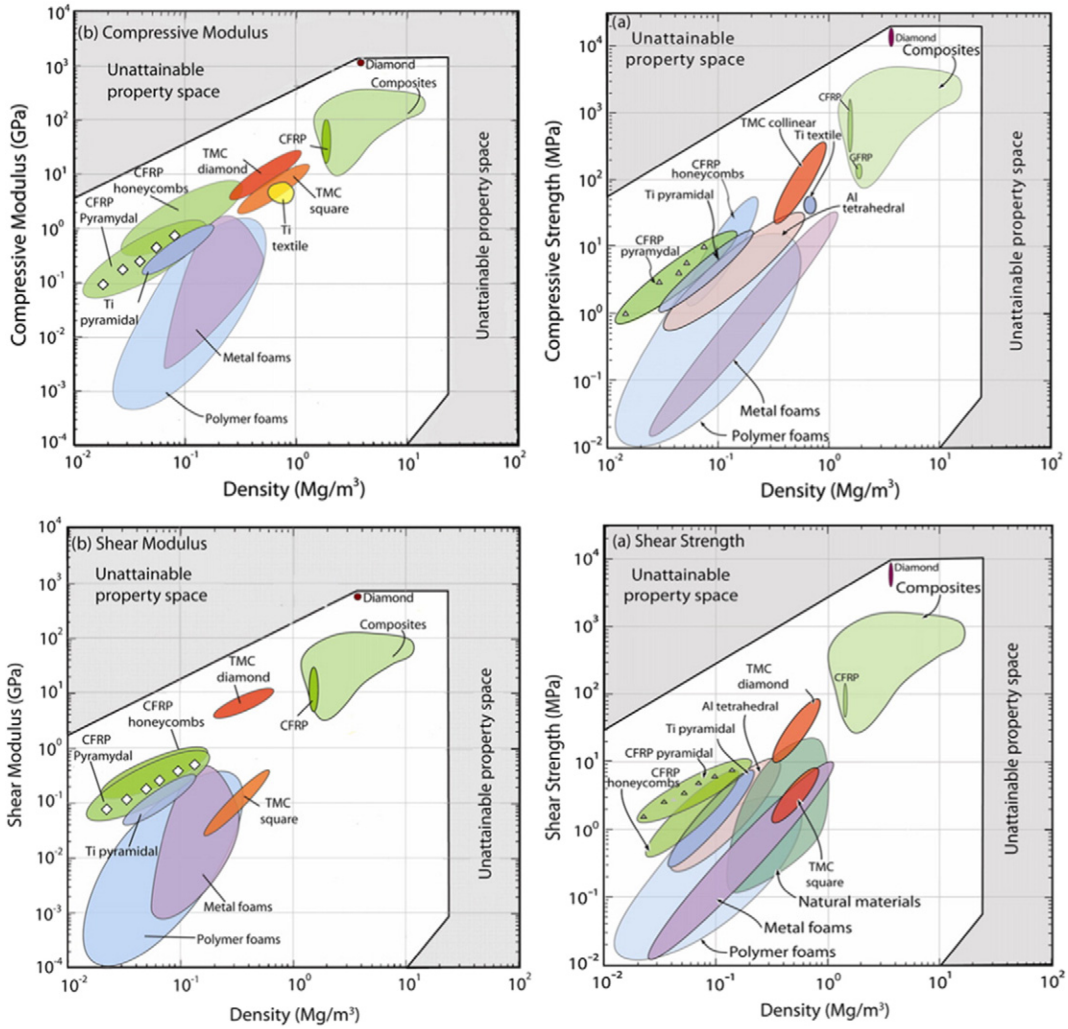

Fig. 1. Modified Ashby material strength versus density map for engineering materials [9].

heated at 3 °C/min up to 80 °C, held for 30 min, then heated at 3 °C/min to 130 °C, for 120 min at 1.0 MPa before furnace naturally cooling to ambient temperature.

(ii) Square honeycomb wall straps with the cross-slots are cut from the composite laminates by using the diamond wire cutting machining into long strips of height $H = 3l$ and length $L = 6l + 2\Delta l$, where Δl is a small overhang length set at 2.0 mm, see Fig. 3A. Cross-slots are of spacing l and of width $d = c + 2t + e$, where e is a clearance of 0.1 mm to provide a sufficiently tight fit during honeycomb assembly.

(iii) After the surface grease is cleared, the rich resin layer of composite surfaces is gradually removed by the fine sandpaper, and then HOGF is adhered to the surface of square honeycomb wall straps.

(iv) The modified honeycomb wall straps are slot-fitted and assembled to build the honeycomb core topology. The sandwich panels are fabricated by bonding the composite core to facesheets with a high strength adhesive (J272-A, shear strength of 48 MPa, thermal conductivity of 0.3 W/mK) or a high thermal conductivity adhesive (J-TC, thermal conductivity of 2.5 W/mK).

2.2. Measurements

2.2.1. Thermal conductivity

Three different standard techniques measuring the effective thermal conductivity of typical honeycomb core panels are the guarded hot plate (ASTM C117), the heat flow meter (ASTM C518) and the transient radiant step heating method (ASTM E1461), respectively. The measured effective thermal conductivities of the sandwich panel using the standard steady-state techniques of the guarded hot plate and heat flow meter are significantly higher than the reported radiant step heating data and are determined to be inaccurate [17]. Therefore, the flash method is used to measure the effective out-of-plane thermal conductivity of MCHSS. With the measurement of the thermal diffusivity, heat capacity and density of the specimen, the thermal conductivity of MCHSS is calculated by the following equation:

$$k = \alpha \rho C_p \tag{1}$$

where k is the effective thermal conductivity (W/m K), α is the effective thermal diffusivity (m^2/s), ρ is the effective density (kg/m^3); C_p is the effective specific heat (J/kg K). The effective specific heat C_p is given by:

$$C_p = \sum C_i m_i \Big/ \sum m_i \tag{2}$$

According to Ref. [18,19], the out-of-plane thermal diffusivity α is as follows:

$$\alpha = \frac{0.1388 \times d^2}{t_{1/2}} \tag{3}$$