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Further considerations on anisotropic thermal efficiency of symmetric composites

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A R T I C L E I N F O

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The paper investigates the anisotropic thermal efficiency of symmetric composites made of two components, matrix and fiber reinforcement. The anisotropic degree of the composite is the ratio between the effective thermal conductivity in the direction parallel to the fiber reinforcement, and that in the perpendicular direction. The potential anisotropy of the materials is the ratio between the thermal conductivity of the fiber to that of the matrix. The anisotropic thermal efficiency is the ratio between the anisotropy degree of the composite, and the potential anisotropy of the two materials. The theoretical model solves the heat conduction equation under the two thermal assumptions of parallel isotherms and parallel heat fluxes, and without any empirical constant nor analogy with other phenomena, evaluating the anisotropic thermal efficiency of the symmetric composite. The variation of the anisotropic thermal efficiency is investigated versus the potential anisotropy of the materials and the ratio between fiber and matrix thicknesses. The anisotropic thermal efficiency has a maximum versus the ratio between fiber and matrix thicknesses, and decreases with the increase of the potential anisotropy, reaching a minimum, which is only dependent on the geometrical configuration of the symmetric composite.

1. Introduction

Thermal anisotropy of a composite can be an important property for several applications, e.g. poly-functional materials under complex, sometimes extreme operating conditions.

Gu and Tao [1] studied a periodic composite with contact resistance on the inclusion surface. The study was made for composite materials containing a simple cubic array of spherical inclusions. Solutions were derived by applying the generalized Rayleigh identity. On the surface of the inclusions a discontinuity of the temperature was suggested and the conclusion of the work was that the contact resistance can change the effective thermal conductivity dramatically. Havis et al. [2] used the finite difference method to simulate the thermal behavior of fiber reinforced composites, where the fiber thermal conductivity is an order of magnitude greater than the matrix one. An experimental investigation on cylinder samples from 0 °C up to 90 °C was carried out to test the model at different configurations of the fiber. The agreement between numerical and experimental results was good, especially in the samples where the angle of the fiber with the cylinder axis was large. James and Harrison [3] evaluated the effective thermal conductivity of composites, made of two materials, simulating numerically the microscopic structure of the composite for different orientations of the anisotropic materials and evaluating the effect of the sample geometry on the heat flow and on the temperature. Shim et al. [4] investigated the thermal behavior of carbon fiber-reinforced composites with different fiber cross-section, with the results that the thermal conductivity was greatly depending on the type of cross-section of the reinforcement fiber and orientation.

Skorokhod [5] studied a multi-layered composites, made of ceramic and metallic sheets. An angular dependence of the effective thermal conductivity on the anisotropic layered composite was described to depend on the angle between the direction of the temperature gradient and the layer direction. Felske [6] studied the effective thermal conductivity of mixtures containing composite spheres randomly distributes in a continuous medium. Contact resistance was taken into account at the interface between the spheres and the continuous phase obtaining an exact analytical solution. For the case of syntactic foams, it was found that the dimensionless effective thermal conductivity depends on the volumetric fraction of the particles and that the thermal conductivity of the continuum could be increased or decreased by adding hollow spheres.

To understand the heat transfer in carbon-fiber/epoxy natural-gas tanks, Tian and Cole [7] presented an experimental

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Nomenclature

Latin

a	matrix thickness
ATE	anisotropic thermal efficiency
b	fiber thickness
k	thermal conductivity
PIL	parallel isothermal lines assumption
PFL	parallel heat flux lines assumption
s	generic thickness
s_1, s_3	matrix thickness
s_2	fiber thickness
T	temperature

Greek

δ	potential anisotropy
ξ	anisotropy degree
ρ	composite density
ϕ	reinforcement volume fraction
χ	anisotropic efficiency

Subscript

f	fiber
m	matrix
lim	limit value

and theoretical work to evaluate the thermal conductivity of these materials. An impedance analysis model was employed to convert the phase and amplitude of the voltage to those of the temperature response, founding the best frequency range for estimating the thermal conductivity along the x and y directions and obtaining a two-dimensional anisotropic model for the simultaneous fitting of in-plane and through-thickness thermal conductivities. Ma and Chang [8] presented an analytical exact solution for the heat conduction in anisotropic multi-layered media, analyzing the steady-state temperature and the heat fluxes with anisotropic properties, and subjected to prescribed temperature on the surfaces. Le Quang et al. [9] developed approximation schemes for estimating the effective thermal conductivity or resistivity of composites made with several phases and imperfect interfaces. The interface could be either highly conducting or resistive, the constituent phases could be anisotropic and the closed-form expressions for the effective thermal conductivity or resistivity tensor of anisotropic multiphase composites have been derived.

Leclerc et al. [10] proposed an efficient numerical model for taking into account the influence of the micro-structure on the thermal conductivity of heterogeneous media. Anisotropic configurations were proposed for controlling the orientation of the contact angles in order to direct the heat flux, taking benefit of the wall effects. Agrawal and Satapathy [11] developed a mathematical model to determine the effective thermal conductivity of polymer composites filled with two conductive materials, aluminum nitride and aluminum oxide and two insulation natural fibers, pine wood dust and rice husk. The authors found that the presence of two dissimilar particulate fillers contribute to modify the thermal conductivity value of such hybrid filler composites. The experimental measurement of the thermal conductivity of different sets of composites validated the proposed model.

A heat shield, made of composite materials, was studied, theoretically and numerically, during thermal degradation in [12], with the aim of evaluating the effective thermal conductivity of an ablative composite material in the state of virgin material and during three paths of degradation. The composite material undergoing ablation, with formation of void pores or char and void pores, and ablation for a re-entry mission at high Mach number was studied in [13].

In [14] the effective thermal conductivity and diffusivity of a multilayer composite was evaluated in the two directions (x and y), theoretically and numerically, as a function of the reinforcement volume fraction. The matrix of the composite was silica and the second component could be asbestos, or steel or copper. The theoretical results were evaluated by the solution of the heat conduction equation, while the numerical analysis was carried out with a second order finite-difference non-iterative steady-state explicit scheme. The comparison between theoretical and numerical results was very good. The maximum anisotropy degree was obtained when the reinforcement volume fraction was 50%. A multilayer material made of two plane slabs has been investigated theoretically in [15]. The composite material, made of two homogeneous and isotropic materials, was thermally anisotropic and could be used to drive heat towards colder regions. This phenomenon is very useful when a device, such as a spacecraft, must be thermally protected. A composite material composed of a ceramic matrix and a fiber, made of steel or copper or asbestos, has been investigated in [16] during the consumption of the composite and numerical simulations of heat conduction have been compared favorably with the theoretical predictions. The anisotropy degree of the composite has been investigated for the three composites during the degradation process and the thermal efficiency of the anisotropic symmetric composite has been introduced.

In the present paper the authors extends the theoretical study of [16] evaluating first of all the thermal conductivity in the direction parallel to the fiber reinforcement, and that in the perpendicular direction and then the thermal anisotropy of the composite. The anisotropic thermal efficiency is investigated by varying the ratio between fiber and matrix thicknesses, and the potential anisotropy of the materials. The theoretical model allows evaluating the anisotropic efficiency of the composite under the two thermal assumptions of parallel isotherms and parallel heat fluxes.

2. Theoretical models

The effective thermal conductivity of the symmetric composite is calculated by the solution of the Fourier heat conduction equation without the need of any similitude with other phenomena, e.g. electric or electromagnetic, nor ad-hoc assumptions or empirical constants, and applied to an elementary cell representing the multiphase material, under the two thermal assumptions of parallel isothermal lines (*PIL*), and parallel heat flux lines (*PFL*).

The theoretical approach of solving the Fourier equation under a thermal assumption has been proposed originally for a cubic elementary cell, representing a two-phase media for the two thermal assumptions, *PIL*, and *PFL*, in [17], unsaturated frozen soils [17] and bricks [18] for the thermal assumption *PIL*, extended to two-phase media for the thermal assumption *PFL* in [19]. Then, the model has been extended to three-phase soils at moderately high temperatures [20,21], verified experimentally for two-phase [22] and two and three-phase water/olivine media [23], applied to particulate materials in extraterrestrial conditions and to foams at low density [24], to Mars soil analogues [25,26], to frozen meats with low and high fat contents [27], employed to detect a dry frozen boundary inside Martian regolith [28].

The same theoretical approach of solving the Fourier equation under the thermal assumption of parallel heat flux lines, *PFL*, has been applied to a cubic elementary cell containing a