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Numerical prediction of effective thermal conductivities of 3D four-directional braided composites

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ABSTRACT

The temperature distribution in a representative volume element of three-dimensional and four-directional braided composites is studied with appropriate boundary conditions by the finite element method (FEM) to predict the effective thermal conductivity of the composite. Models with elliptical, circular and hexagonal cross-section of braiding yarns are considered. The model is validated by experiments based on hot disk thermal constant analyzer. The influences of fiber volume fraction V_f, and interior braiding angle γ, on heat transfer of the composite are studied with V_f equal to 0.40, 0.50 and 0.58, and γ from 15° to 50°. The results show that for the composite studied increasing fiber volume fraction results in higher thermal conductivity in both axial and transverse direction, while a larger interior braiding angle leads to higher transverse thermal conductivities but lower axial ones.

1. Introduction

Braided composites made from braided fabrics as reinforcing phase in appropriate matrix are widely used in aerospace engineering, automobile industries and other related fields because of their low weight and high strength. In the widely used materials with reinforcing fiber, such as the braided composites, carbon fiber exhibits relatively serious anisotropy between axial and transverse thermal conductivities, which provides a big challenge in predicting their thermal conductivity. Many researches [1,2] have been conducted on this subject both experimentally and numerically. The study of braided composites can be conducted at three scales: micro-, meso- and macro-scale, which correspond to fibers, braiding yarns and braided composites, respectively (see Fig. 1). In order to calculate the thermal conductivity of braided composites, the thermal conductivity of braiding yarns which can be considered as unidirectional fiber reinforced composites has to be obtained first. The classic rule of thermal conductivity for mixtures can be used to calculate the axial thermal conductivity of braiding yarns, while the transverse thermal conductivity needs other measures like analytic method [3] and numerical simulation [4,5]. For the macro-scale, the braided composite is often represented by a unit cell, the so called representative volume element (RVE) and often studied by FEM. In this paper the concept of RVE is adopted, and the thermal conductivity of braiding yarns and braided composites are studied by FEM.

Compared with two-dimensional composites, three-dimensional braided composites have excellent out-of-plane mechanical performance and thus study on their characteristics becomes a hot research topic. 3D four-directional braided composite is a kind of very popular braided composites, and its geometric construction and complexity attract a lot of research effort. At macro scale the braided composite preform can be divided into three regions: interior, surface and corners. The term "preform" refers to the framework formulated by fiber bundles in braiding processing and the braided composite is formed by filling the matrix into the empty space of the preform. Wu [6] established three-unit-cell models based on the microstructures of each regions and the proposed interior unit cell accounts for the largest volume fraction and contains 8 yarns. This interior unit cell model has been widely employed by other researchers [7,8] to study mechanical performance of the composite. According to the movement of braiding yarns during the braiding process an interior unit cell model containing 12 yarns was built up by Chen et al. [9]. This interior unit cell has also been used to predict mechanical properties of composites [10], or referred to by other researchers to establish their own unit cell [11]. It was also found by Chen et al. [9] that the surface unit cell contains three yarns comprised by a straight line and a segment of helix while the corner unit cell has two helical yarns.

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Nomenclature

A	braiding yarn's cross section area
a_1	length of unit cell A
a_2	length of unit cell B
C_p	specific heat of composite
C_{pm}	specific heat of matrix
C_{pf}	specific heat of fibers
d_f	diameter of fibers
h	height of unit cells
m_f	mass of fibers in composite
M	mass of composite
n_f	number of fibers in one braiding yarn
$q_x,\ q_y,\ q_z$	heat flux in $x,\ y,\ z$ direction
T	temperature
$T_x,\ T_y,\ T_z$	temperature gradient in $x,\ y,\ z$ direction
V_f	fiber volume fraction of composite
V_{fy}	fiber volume fraction of braiding yarns
V_y	yarn volume fraction of unit cells
γ	interior braiding angle
λ_{fa}	axial thermal conductivity of fibers
λ_{ft}	transverse thermal conductivity of fibers
λ_m	thermal conductivity of matrix
$\lambda_{xx},\ \lambda_{yy},\ \lambda_{zz}$	thermal conductivity in $x,\ y,\ z$ direction
λ_{ya}	axial thermal conductivity of braiding yarns
λ_{yt}	transverse thermal conductivity of braiding yarns

Apart from the orientation and distribution of braiding yarns which need to be incorporated in the construction of the topological structure of braided preforms, factors like shape of braiding yarns cross-section and porosities of braided composites should be taken into account for an accurate numerical simulation. The cross-section of braiding yarns may influence predicted performance of the composite, and thus has to be carefully treated. In the previous studies it has been assumed to be ellipse [9,12], hexagon [13,14] and octagon [15], while it was not identified which one was the best among these cross-section. From numerical simulation point of view, the polygon cross section is convenient to be meshed but its straight line boundary does not resemble the curved boundary in reality.

Another important factor which affects composite performance is the porosity. Porosities in ceramic matrix composites were classified and quantified by Del et al. [16]. For weave composites the influence of porosity on heat transfer was taken into account in the numerical study of Farooqi and Sheik [17], the effective thermal conductivities of composites with different porosities were calculated and the numerical results had good agreement with experimental ones. If the composite matrix is carbon or silicon carbide, the braided composites may contain lots of manufacturing pores. However, to the authors' knowledge, the study of the effects of porosity on the three-dimensional braided composites is very limited so far.

The effective thermal conductivity of 3D four-directional braided composites has been predicted in [11,18–20]. Most of the researchers [19,20] claimed that their models are reliable based on the comparison with the experimental transverse thermal conductivity obtained in [18]. In authors' experiences, the lack of direct comparison of numerical and corresponding thermal experimental results of different three dimensional braided composites leaves some uncertainty about the reliability of the numerical results. In addition, in the above references the boundary conditions are to some degree improper and will be discussed later. From the above brief review it is obvious that more efforts should be made on the study of heat transfer characteristics of 3D four-directional braided composites.

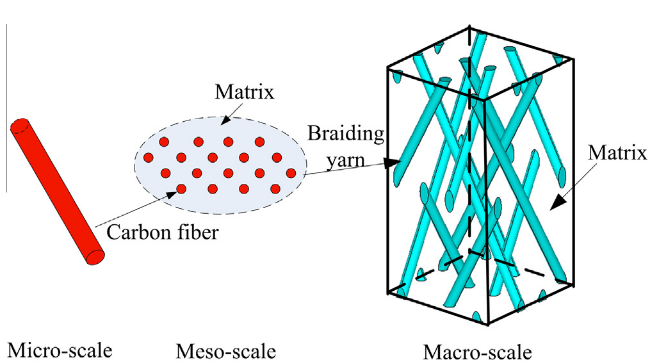

Fig. 1. Three scales of braided composites.

In the present paper, the heat transfer characteristics of 3D four-directional braided composite are studied at both meso-scale (for braiding yarns) and macro-scale (for composites) with appropriate boundary conditions. Different shapes of braiding yarns' cross-section are considered. The model is validated by experimental results.

2. Numerical model

2.1. Topological model

As Li et al. indicated in [21,22] the effective properties of composites can be analyzed by unit cell and a model of a complete structure is not needed. As a matter of fact most researches of 3D four-directional braided composites are based on unit cells method [9,19,20]. The unit cell can be established according to the movement of braiding yarns during the braiding process. For the details of the braiding process Refs. [9,13] can be consulted.

The 3D topological structure of unit cell is shown in Fig. 2 [9], where z is the braiding direction, h the braiding pitch length, γ the interior braiding angle and a the length of the unit cell boundaries. If the wedge shaped yarn segments along the edges of the unit cell (the shortest yarns in figures) are considered, the unit cell contains 20 yarns as shown in Fig. 2. The axes of all yarns are straight and do not intersect each other. One can see in the figures that braiding yarns in interior region of 3D four-directional braided composites can be classified into four groups, denoted by I, II, III, and IV, respectively, by their directions. As shown in Fig. 2, type I and II yarns are parallel to y–z plane, while type III and IV yarns are parallel to x–z plane. In every group, there are 5 yarns including 1 long yarn, 2 short yarns and 2 segments which located around an edge of the unit cell.

As indicated above the cross-section shape of braiding yarns should be carefully treated during the establishment of the unit cell model. In this paper the analysis is mainly based on the elliptical yarn model. The related geometric factors can be determined as follows:

The corresponding yarn volume fraction of the unit cell when yarns contact with each other [9]: