International Journal of Heat and Mass Transfer 85 (2015) 897–903

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Role of in-plane stacking sequence on transverse effective thermal conductivity of unidirectional composite laminates

Hang Yu [a,b], Dirk Heider [a,c], Suresh Advani [a,b,*]

[a] Center for Composite Materials, University of Delaware, Newark, United States
[b] Department of Mechanical Engineering, University of Delaware, Newark, United States
[c] Department of Electrical and Computer Engineering, University of Delaware, Newark, United States

ARTICLE INFO

Article history:
Received 24 September 2014
Received in revised form 30 January 2015
Accepted 1 February 2015
Available online 5 March 2015

Keywords:
Laminated composite
Angle-ply
Through-thickness thermal conductivity
Finite element

ABSTRACT

Laminated polymer matrix carbon fiber composites have poor thermal conductivity in through thickness direction as all the conductive fibers are within the plane. One can increase the through thickness thermal conductivity by introducing conductive fibers in that direction or by modifying the form, direction and architecture of the fiber network. In this paper we conduct a parametric study using finite element analysis to investigate the relation between the local fiber architecture and its effective through-thickness thermal conductivity. The role of the fiber tow orientation, volume fraction and stacking sequence is explored. Unidirectional laminates containing fiber tows aligned in the same direction for all laminae exhibit higher through thickness thermal conductivity than the stacking sequence with other orientations. A conductive coating surface layer enhances the thermal conductivity of laminates independent of fiber orientation configuration. A geometric scalar parameter is proposed to correlate laminate through-thickness thermal conductivity with fiber tow stacking sequence. The influence of different boundary condition types on the through-thickness thermal conductivity is also assessed.

1. Introduction

Fiber-reinforced laminated composites continue to replace metals in structural applications. However structural applications that require rapid heat transfer across the thickness direction need to have a higher thermal conductivity in the thickness direction. The polymer composite thermal conductivity is usually at least one to two orders of magnitude lower than metals which preclude their use in such thermal applications. Although the unidirectional laminates have already been investigated for their longitudinal and transverse thermal performance [1–4], the influence of stacking sequence in determining the through thickness thermal conductivity have not been addressed for non-woven composite structures [5]. This paper will explore laminated heterogeneous systems and study the dependence of the in-plane fiber volume fraction and fiber tow angle-ply sequence on the through-thickness thermal conductivity. Previous studies [6–8] did not explore in detail the effect of in-plane fiber tow orientation on transverse thermal properties. In this numerical study, the role of various microstructural arrangements and fiber tow contact points that influence the transverse thermal conductivity are characterized and their influence on effective transverse thermal conductivity of laminated composites is quantified.

2. Finite element modeling

To predict the effective through thickness (transverse) thermal conductivity of non-woven laminate structures, a numerical parametric study is conducted to investigate the effect of material and geometric parameters such as fiber tow orientation, volume fraction and stacking sequence. The study is conducted in a unit cell domain which represents the materials and the architecture of the laminate which is either square or circular in shape [9,10]. The boundaries of the in-plane direction are insulated to avoid in-plane temperature gradient and constant temperature is specified across the top and bottom surfaces of the unit cell. In this study, each layer has a thickness of one fiber tow which is 3 mm. Effective transverse thermal conductivity across the layers is calculated using Fourier's law as follows,

$$q = -k_{eff}A(T_1 - T_2)/L, \quad (1)$$

in which q is the calculated heat transfer rate over the entire surface area (A) across the unit cell thickness L; and T_1 and T_2 are the

* Corresponding author at: Department of Mechanical Engineering, University of Delaware, Newark, United States.

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.02.003
0017-9310/

temperatures imposed as boundary conditions on the top and the bottom surface of the unit cell respectively. Eq. (1) allows one to calculate the effective through-thickness thermal conductivity k_{eff} of the composite.

Numerical models are developed using the finite element based ANSYS software [11] in which specialized macros have been scripted using Mechanical APDL to create the unit cell. The element type is eight noded 3-D brick element used to create the unit cell mesh as shown in Fig. 1. The cylindrical shape model is utilized as it allows one to maintain the same fiber volume fraction for any rotation of the plies. Some fiber tows look distorted as the top/end surfaces of the fiber tow cylinder intersects with the side surface the cylindrical cell, which has 983,676 elements and 192,376 nodes. In the finite element model, a nonconductive resin matrix skin layer is introduced on the top and bottom of the cell as for most composites, a resin rich layer exists on the top and bottom surfaces. This also helps to avoid the numerical singularity when integrating q over the surfaces caused by large differences in the thermal conductivity of resin and fibers.

Without loss of generality, a set of cylindrical models with multiple fiber tow layers and two surface skin layers were created to study the effect of fiber tow orientation and the stacking sequence in the laminate on the effective thermal conductivity of the composite in the thickness direction.

3. Stacking sequence study

Many laminates are constructed by stacking unidirectional plies on top of each other. Most reported models do not consider the angle of the stacking sequence to influence the through-thickness conductivity. However in reality the heat transfer paths can change based on the ply stacking sequence which influences the through-thickness thermal conductivity. In this section, the effect of the fiber orientation and the order of stacking the plies in a laminate on through-thickness thermal conductivity are investigated. It is assumed here that all fiber tows are straight without exhibiting continuously varying curvilinear tow paths [12].

All laminated composite structures are composed of multiple layers, which are bonded in specific stacking sequence for desired mechanical properties. In this study, we focus on the stacking sequence influence on the through-thickness thermal conductivity, starting from a specified ply orientation to systematic increment in ply orientation from one layer to the next to understand the role of the geometric arrangement of the oriented lamina in the laminate.

3.1. Specified ply orientation sequence

It is known that the k_{eff} asymptotically approaches a plateau as k_f/k_m increases, where k_f is the fiber tow thermal conductivity and k_m is the matrix thermal conductivity. Unidirectional fiber laminates [13] are created by placing all lamina with aligned fibers parallel to each other. Cross-ply laminates are formed by rotating adjacent lamina by a specified angle. Unidirectional laminates exhibit higher k_{eff} compared to other cross-ply arrangements. In unidirectional laminates the 0/0 fiber tow layers have the adjacent conductive fiber tows in contact along the entire fiber tow axis direction, while angled fiber layers have fewer contacts due to the cross geometric feature.

To understand and correlate the role of the stacking sequence with arbitrary orientation, a study is conducted in which the adjacent ply is rotated by 5° in succession to evaluate its effect on through thickness conductivity.

3.2. Effect of angle increment on stacking sequence

In this section, we focus on investigating the effective through-thickness thermal conductivity due to variation in the sequencing angle of adjacent layers. The goal is to understand how the in-plane fiber tow rotation affects the out-of-plane thermal properties and the mechanism that accounts for the resulting trend as a function of different increment angles from one ply to the next during the formation of the laminate.

3.2.1. Number of layers for numerical convergence

As we apply a thin matrix skin layer on the top and the bottom surface (10% of the laminate thickness), a series of finite element models were meshed to determine the number of layers necessary to ensure that the calculated conductivity does not change with the number of layers. Results in Fig. 2 show that 24 to 36 layers are required if the thermal conductivity of the skin layer is the same as that of the matrix layer. One dimensional analysis has been used to find the effective through thickness conductivity by subtracting the resistance introduced due to the surface layer as follows:

$$\frac{k_c}{k_m} = \frac{L_c}{\frac{L_t}{\frac{k_t}{k_m}} - \frac{2L_l}{\frac{k_l}{k_m}}} \tag{2}$$

In Eq. (2), L_c, L_t, L_l represent laminate thickness, total thickness of laminate with skin and skin layer thickness respectively; k_c, k_t, k_l represent their thermal conductivities, respectively. In the calculation, k_t the total thermal conductivity including the skin layer is obtained through finite element analysis, k_l is the conductivity of the skin layer with thickness L_l, which is equal to 1/10 of the thickness of each layer and k_c is the effective through-thickness thermal conductivity of the laminates after subtracting the contribution of the surface matrix layer resistance.

This becomes computationally very expensive as the ratio of the fiber to matrix thermal conductivity increases. One way to address

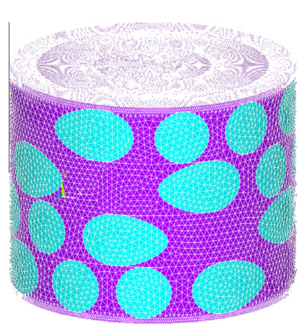

Fig. 1. An example finite element mesh of a cylindrical laminated model with four fiber tow layers with different in plane orientations.

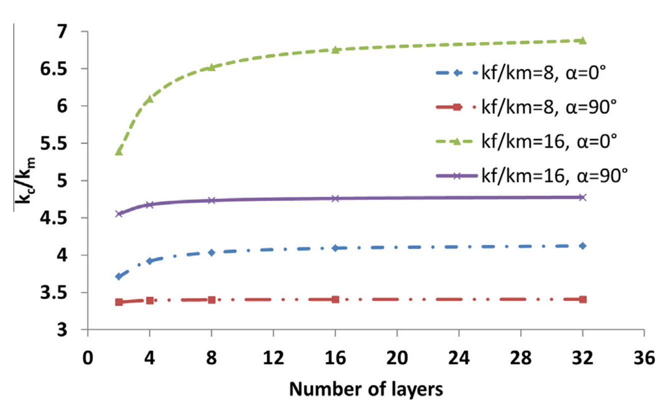

Fig. 2. Convergence of effective through-thickness thermal conductivity with the number of layers for different k_f/k_m ratios and stacking sequence.