USING FINITE ELEMENT MODELING TO ANALYZE THERMAL DIFFUSIVITY MEASUREMENTS ON UNIDIRECTIONAL CARBON FIBER-EPOXY COMPOSITES

Rebecca M. Alway-Cooper[1], *Merlin Theodore*[2,3], *David P. Anderson*[2,4], *Amod A. Ogale*[1]

[1]Clemson University Chem. Engr. Dept. and CAEFF, 127
Earle Hall, Clemson, SC 29634
[2]AFRL/RXBC, 2941 Hobson Way, WPAFB, OH 45433
[3]Universal Technology Corporation, Dayton, OH
[4]University of Dayton Research Institute, Dayton, OH

Introduction

The accurate determination of carbon fiber thermal transport properties have always been a challenging task, largely due to the high thermal conductivity, small size and often brittle nature of these materials. The difficulty in performing these sorts of measurements is evidenced by the significant number of proposed techniques that have appeared in the literature over the years [1-5.] Beyond the challenge of dealing with micron sized fibers, many of these techniques require specialized equipment and have trouble with measurements on very high thermal conductivity fibers.

Our ongoing research focuses on the use of a common bulk unsteady-state heat transport technique, laser flash analysis (LFA) [6], to obtain thermal diffusivity values for uniaxial carbon fiber-epoxy composites from which fiber conductivity can be determined. Composite theory states that the thermal conductivity of individual fiber (k_f) and matrix (k_m) components should be related to that of the composites (k_c) by volume weight rule-of-mixtures (Eq. 1).

$$k_c = k_f v_f + k_m v_m \qquad (1)$$

If this relation holds true for unsteady measurements, fiber properties could be back calculated from measured composite values. It has been proposed by Lee and others that the laser flash theory can be applied directly to unidirectional fiber reinforced composites [7]. On the other hand, Alam et al. observed that the unsteady state nature of the technique caused complex heat flow patterns through polymer filled graphite foam, which violate the 1-D heat conduction requirements of the LFA method. However, using a finite element model (FEM) they were able to better interpret experimental results, and obtain acceptable values for the thermal conductivity of their graphite foams [8].

More recently, we've reported finite element results which suggest that for a composite containing high conductivity fibers (k ~ 1000 W/m*K), at low volume fractions (v% < 40%), rule-of-mixtures could not accurately describe heat flow through a 1 mm thick sample [9]. Here we further our analysis by exploring the effects of sample thickness on model results.

Model Development

PDEFlex software (version 6.09) was used to develop a finite element model (FEM) of the unsteady state heat flow through a unidirectional carbon fiber-epoxy composite, which takes place during laser flash analysis. In order to simplified computations, a 2-D axisymmetric model of a single fiber surrounded by a resin matrix was created, with the axis of symmetry corresponding to that of the fiber. Composite samples of 1 mm and 2 mm in thickness (L) were modeled. A fiber radius of 5 μm was used throughout. Fiber volume fraction was varied by changing the thickness of the resin layer in the radial direction. For each fiber type, three different fiber volume fractions (10, 20, 60%) were modeled. A 5 μm graphite spray layer was then added to the top and bottom surfaces of the composite mesh in order to simulate the graphite spray applied to experimental samples.

Fiber thermal conductivity values of 10, 100 and 1000 W/m*K were modeled. Fiber heat capacity and density were held constant at 1 J/g*K and 2 g/cm^3 throughout. Resin matrix thermal conductivity, heat capacity and density were specified to be 0.1 W/m*K, 2 J/g*K, 1 g/cm^3, and graphite spray properties were 1 W/m*K, 1 J/g*K, 0.3 g/cm^3.

The 2-D, cylindrical form of the unsteady state heat transfer equation was solved using adiabatic boundary conditions after initialization ($t > 0$). The initial condition was an exponential decay whose shape was such that at $t = 0$ most of thermal energy resides in the lower graphite spray layer, which corresponds well with experimental conditions.

Results & Discussion

Fig. 1a summarizes the composite thermal diffusivity values predicted from the FEM, as a function of the programmed fiber thermal conductivity at 10% fiber volume for both 1 mm and 2 mm thick samples. Also plotted is the line representing the rule-of-mixtures relationship (Eq. 1). For the modeled composites containing a fiber specified to have a conductivity of either 10 or 100 W/m*K, FEM results for both sample lengths predict similar composite diffusivity values. Additionally, these diffusivity values also correspond well with the rule-of-mixtures relationship. However, for the highest conductivity fiber, the FEM predicted composite diffusivity for the 1 mm sample is almost twice that of the 2 mm sample. The FEM predicted value for the 2 mm sample is only slightly higher than that specified by rule-of-mixtures.

Furthermore, as the fiber volume fraction is increased to 20%, the difference between the FEM predicted composite diffusivity values for the 1 and 2 mm samples decreases, but is still apparent for the highest conductivity fiber (Fig. 1b). No difference is apparent between the 2 mm FEM sample and rule-of-mixtures. Finally, at 60% fiber volume fraction all three predictions (1 mm FEM, 2 mm FEM, and rule-of-mixture) are identical.

These results suggest that the transient heat flow imposed by LFA conditions through these types of uniaxial fiber composites is not simply in the fiber direction, as would correspond to rule-of-mixtures, but also has transverse comments. Additionally, the complexity of this two dimensional conduction is affected by sample geometry, fiber thermal conductivity and fiber volume fraction. Thicker samples, lower fiber conductivity and higher fiber volume fraction causes the sample to act more like a homogenous material. Conversely, a thinner sample with a higher fiber conductivity and lower fiber volume fraction results in a significant amount of transverse heat flow.

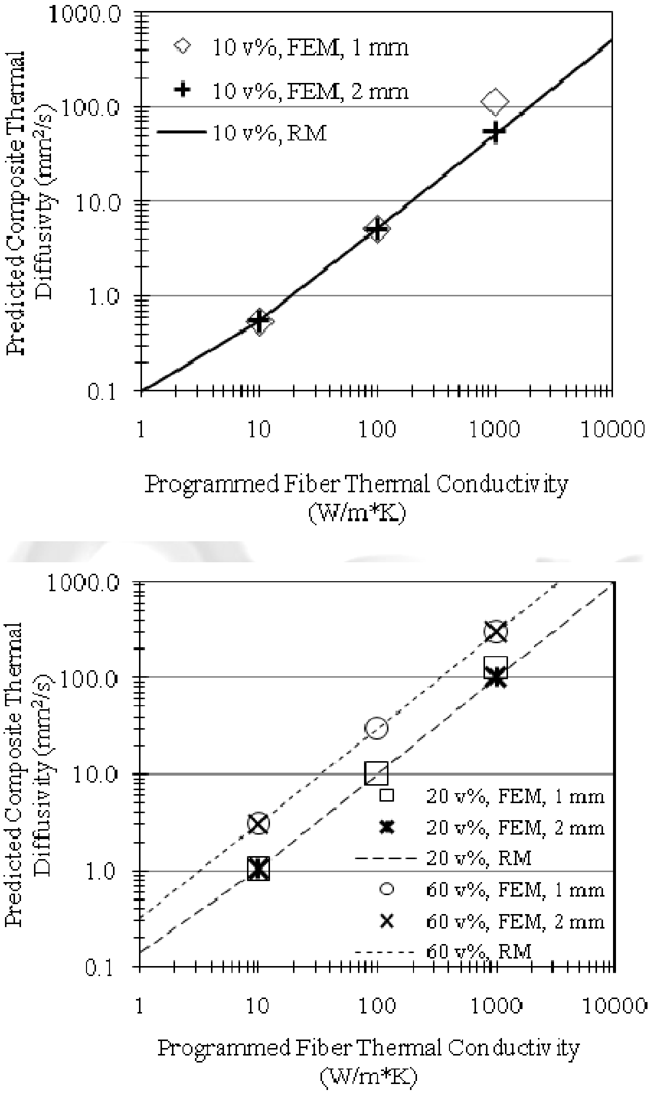

Fig. 1 Composite diffusivity versus fiber thermal conductivity versus as predicted using finite element model and volume added rule-of-mixtures for 1 and 2 mm long samples at 10, 20 and 60% fiber volume fraction.

Conclusions

A finite element modeling was used to explore the unsteady state heat transfer which occurs in uniaxial carbon fiber-epoxy composites during thermal diffusivity measurements using the LFA method. Specifically, the effect of sample thickness on the relationship between fiber thermal conductivity and composite diffusivity was explored. For composites containing fibers of low or moderate axial conductivity, simple additive rule-of-mixtures accurately describes how composite thermal properties are related to that of its individual comments regardless of sample length.

As the axial conductivity of the fibers increases, a strong preferential heat flow through the fiber, in combination with the transient nature of the LFA technique, causes the composite to exhibit an apparent thermal diffusivity which is higher than that predicted by simple additive rule-of-mixtures for thinner samples. As sample length increases, composite thermal diffusivity predicted by the FEM and by rule-of-mixtures become nearly equivalent.

Future work will focus on quantifying the affects of broken fibers on predicted fiber and composite thermal properties using the LFA method.

Acknowledgments. The authors gratefully acknowledge funding for this work by the US Air Force via contract numbers FA8650-05-D-5052 and F33615-00-D5006. Additional thanks are extended to Dr. Karla Strong (AFRL project monitor) for her help on this project.

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