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Model-based characterization and enhancement of the through-thickness thermal conductivity of polymer composites using infrared camera

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

[a] Department of Mechanical Engineering, University of Delaware, Newark, DE 19716, USA
[b] Center for Composite Materials, University of Delaware, Newark, DE 19716, USA
[c] Department of Electrical and Computer Engineering, University of Delaware, Newark, DE 19716, USA

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ABSTRACT

Improved out-of-plane thermal conductivity of fiber reinforced polymer (FRP) composite materials will enable light weight structures to integrate efficient thermal management. Heat extraction through its relative thin thickness direction can be improved by placing highly conducting material strategically and sparingly across the thickness. This paper combines an infrared camera temperature measurement system with a finite element method to investigate the natural convection influence on the effective thermal conductivity of such heterogeneous materials. Measurements of reference samples were conducted to validate the methodology. Effective conductivity of a PTFE matrix with embedded copper rods was characterized with one of its boundaries exposed to natural convection and the results were contrasted with the condition under which the specimen is placed between two conducting bars. Our method was extended to characterize the effective thermal conductivity of a heterogeneous 3D woven fabric structure embedded within a polymer matrix. A conductive coating layer was introduced and quantified to demonstrate the heat transfer enhancement.

1. Introduction

Composite materials are extensively used in many applications to replace traditional materials due to their light weight, corrosion resistance and superior mechanical properties. However, the low through-thickness thermal conductivity of composite materials prevents their use in thermal applications where heat needs to be extracted efficiently. Such systems and applications include light weight heat exchangers, electronics packaging materials, hydraulic pump enclosures, electro-magnetic interference enclosures, etc. Polymer composites are usually very thin in the thickness direction, which implies the best way to extract heat from a composite enclosure is through its thickness direction. This can be accomplished by increasing its out-of-plane thermal conductivity.

In terms of through-thickness thermal conductivity measurement methods, many studies have been performed to determine the thermal conductivity of various materials which include both steady state methods and transient approaches [1–18]. Most experimentalists have been characterizing the thermal conductivity using a constant temperature gradient approach in which the two faces of the sample are held at uniform but different temperatures (T_1 and T_2) and the effective heat flux (q) flowing across the sample of thickness L is measured. Using Fourier's law of heat conduction one can express the relationship between the heat flux and the temperature gradient as follows:

$$q'' = -k(T_1 - T_2)/L, \tag{1}$$

which allows one to numerically, analytically or experimentally calculate its effective thermal conductivity (k) in the thickness direction. Hind and Robitaille [1] used the device of Hukseflux THISYST and THASYS to measure the in-plane and out-of-plane thermal conductivity of carbon/epoxy laminates. Liang and Li [2] measured the thermal conductivity of polypropylene composites using a guarded hot plate thermal conductivity instrument at steady state. The transient plane source (TPS) method is also widely used [3–6]. Two possible elements: one resembling a hot disk and the other one a hot square are embodied in TPS methods by Gustafsson [4,5], Bohac [6] and Solorzano et al. [7]. Fan et al. [3] developed a fractal model and an improved transient

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* Corresponding author. Department of Mechanical Engineering, University of Delaware, Newark, DE 19716, USA
E-mail address: advani@udel.edu (S. Advani).

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measurement technique to measure the thermal property of wood. Assaf et al. [8] developed and characterized a mold to measure the transverse thermal conductivity of glass/PE composites. Sweeting and Liu [9] optimized a vacuum cavity design to measure the in-plane and out-of-plane thermal conductivity of fiber composites. Similarly, Marotta and Fletcher [10] also utilized the vacuum chamber to reduce convection and radiation shield to minimize radiation effect, where the uncertainty was assessed with the method of Kline and McClintock [11]. Kiani et al. [12] used a guarded hot plate technique to measure the out-of-plane thermal conductivity by symmetry configuration. James et al. [13] performed similar steady state tests with symmetric bars rather than placing the heater in the middle. Kappagantula and Pantoya [14] adopted the laser flash analysis to characterize the thermal properties of Aluminum/PTFE nanocomposites. Albouchi et al. [15] and Krause et al. [16] introduced infrared camera and optimized the experimental design with the crenel heating excitation to measure the thermal conductivity of granular media and porous dust aggregates, respectively. Khandelwal and Mench [17] performed direct measurement of thermal conductivity and contact resistance of thin films in fuel cell by a steady state approach. Sparrow et al. [18] recently developed low-cost and easy-to-use novel technique to measure thermal conductivity of both high and low conducting solid media using constant temperature fluid heat source and for low conducting material using a heat flux meter without a guard heating.

Almost all reported characterization methods are designed for statistically homogeneous materials, or they ignore the sample surface heterogeneity which causes surface temperature variation. Some of the methods based on steady state approach calculate the heat flux value by measuring the temperatures with thermocouples at few selected points with the assumption that the entire surface is isothermal which is not valid for a surface that contains more than one material with large difference in thermal conductivity. Use of transient methods to measure thermal conductivity relies on etching or depositing a thin wire or metal foil (for example, Nickel) heat source on the sample surface; the disadvantage is that the sample is not able to maintain its original shape completely after the etching or deposition which could change the heat input and maybe difficult to calculate from the deformed shape. The challenge for characterizing the heat transfer across a heterogeneous surface is how to gather and analyze the temperature information on the surface, address the complexity of the data reduction and to quantify the heat transport across its surface.

Numerically, constant temperature boundary conditions at the two faces of the composite sample can be imposed and the heat flux can be calculated. However, for heterogeneous samples it is impossible to experimentally maintain a uniform surface temperature when the conductivities of the constituent materials within a composite are significantly different. In this paper, we will introduce a modification of a steady-state guarded hot plate technique in which the inhomogeneous surface temperatures are measured by employing an infrared camera. The new steady state based measurement technique overcomes the drawback of monitoring limited number of spatial points with thermocouples or thermistors. Use of finite element models for heterogeneous materials with constant heat flux boundary condition on one surface and natural convection on the exposed surface will provide the temperature distribution on the exposed surface which can be compared with the IR camera measurements. This allows one to characterize the thermal conductivity of composite samples exposed to natural heat convection environments. This technique is compared to standard measurement techniques in which the sample is in direct contact with conducting bars. Both approaches are quantified to explore the effect of boundary conditions on the thermal performance of composites. This is contrasted by introducing a conductive coating layer on the heterogeneous sample surface (exposed to convection or in direct contact with a conducting rod) to reduce temperature gradients and quantify its enhancement in heat transfer.

2. Experimental setup and methodology

A set-up that couples high-resolution infrared camera with brass conducting bars is employed to measure the temperature field on one of the surfaces of the heterogeneous sample. The results are integrated with a finite element computational modeling methodology to characterize the heat transfer across the sample thickness. The schematic of the experimental setup is shown in Fig. 1. In this configuration, an insulated long circular cross section of standard brass bar (diameter 50.8 mm and length 190 mm) is placed on a horizontal table, with a resistance heater as the heat source. The measurement cell is insulated with foam and shielded by a guard pipe to minimize the side radiation. The cylindrical specimen attached to the brass bar has one of its surfaces exposed to the infrared camera from the company FLIR Systems, Inc., which is mounted so that it can record the temperature profile of the exposed sample surface.

2.1. Design and instrumentation

The horizontal implementation is chosen to prevent asymmetric temperature distribution due to natural convection on the surface due to the influence of gravity. The infrared camera employed is equipped with InSb detector, 640 × 512 resolution, $-20\,^\circ\mathrm{C}$ to $350\,^\circ\mathrm{C}$ temperature range, ±2% accuracy for real-time data acquisition. The infrared camera is calibrated and can record the entire surface temperature profile until steady state is reached. This allows one to quantify the variation in the temperature on the surface which is important for heterogeneous composite samples with surfaces containing very sparse distribution of conducting fibers embedded perpendicular to the surface.

2.2. Surface emissivity calibration

A thin layer of thermal grease is applied on the surface facing the camera to ensure uniform emissivity on the surface for measurement accuracy. To characterize the grease emissivity, a cylindrical brass specimen is covered with thermal grease and is heated from $20\,^\circ\mathrm{C}$ to $70\,^\circ\mathrm{C}$. The temperature at the center is recorded by both a thermistor and the infrared camera at an emissivity default setting of 1.00. For the duration of the heating, we use the thermistor reading as the reference temperature and also record the corresponding IR image. The procedure is repeated as the sample is cooled from $70\,^\circ\mathrm{C}$ back to the room temperature. To verify that the emissivity of grease is independent of the sample material, a heterogeneous material surface of copper-PTFE sample was also coated with grease and grease emissivity was characterized as a function of temperature. For both materials, the grease surface emissivity with temperature showed the same variation. Fig. 2(left) shows the linear relation between infrared camera readings and the thermocouple readings from which one can extract the emissivity of the thermal grease as a function of temperature. This allows us to independently characterize the temperature of the surface. Also, the temperature dependence of grease emissivity is indirectly accounted for in the calibration. Fig. 2(right) shows the emissivity as a function of temperature, which can be described by a third order polynomial.

Based on the emissivity calibration, the temperature field of the entire surface of the sample facing the camera can be determined. To calculate the thermal conductivity at steady state, we need to