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Prediction of interfacial thermal resistance of carbon fiber in one dimensional fiber-reinforced composites using laser flash analysis

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ABSTRACT

Laser flash analysis (LFA) is a sophisticated method to access the thermal diffusivity of homogeneous planar samples with very little effort. LFA measurement on fiber-reinforced composites, however, often generates inconsistent results due to violation of homogeneous assumptions. We propose a computational method to reduce this inconsistency. The method compares the radiometer signals of one dimensional carbon fiber-reinforced composite from LFA measurement and the finite element simulation results to predict the interfacial thermal resistance and the axial thermal conductivity of carbon fiber. The thermal conductivities of the composite under different environmental temperature are obtained. Agreement between the simulation signal curves and the experiment signal curves is within 5% error during the main temperature rise. The method extends the functionality of LFA to measuring thermal conductivity of complex composite with known microscopic structure, and provides a way to estimate microscopic parameters and to evaluate macroscopic and microscopic effect of different preparation methods.

1. Introduction

Carbon fibers and its reinforced composites are widely used today due to their high mechanical strength, low weight, high flexibility and high thermal conductivity [1,2]. However, in practical applications, the properties of fiber-reinforced composites vary greatly, depending on their constituent materials, physical properties of fiber structure, the morphological structure of composites, and fiber volume fractions. Knowing the accurate composite material properties is important to their development, integration and application. Considering carbon fiber composites, there are established standards and procedures for the measurement of various mechanical properties. However, the same does not apply to the measurement of thermal conductivity of composites and carbon fiber, and the interface thermal resistance across the composite. Typically, the radial dimension of the small fibers ranges from 1 to 30 μm, but yet the heterogeneity effects are still evident, rendering the homogeneous assumption incorrect and affecting various property measurement. Nowadays, there is no universal method which can simultaneously test the thermal conductivity and interface contact resistance of carbon fiber [3–7].

Zhang et al. [3,5,8] proposed a T-shaped method to test the thermal conductivity of a single carbon fibers suspending over a thin platinum hot wire. But the result is influenced by the contact thermal resistance to the hot wire and the uncertainty related to the geometry. Moon et al. [6] used a steady-state DC thermal bridge method to predict the thermal conductivity of carbon nanotube fiber. However, the results are significantly influenced by the value of electrical heating and electrical-thermal sensing, and also influenced by the contact thermal resistance between the sample and heat sink. The thermal conductivity of the composite is influenced by the conductivity of filler and matrix, and the interface conductance between them. Nan et al. [7,9–16] have studied the interface effect on the thermal conductivity of composite. The experimental prediction of the interface thermal resistance across the matrix and the reinforced materials is not their main focus.

Laser flash analysis (LFA) is a popular tool to measure thermal conductivity of engineering materials. Parker et al. [17] in 1961 proposed and successfully developed a laser pulse technology to measure thermal conductivity. The measurement technique is widely used due to the short testing period, wide temperature range of testing, and only a small testing sample is required. LFA is a quick and sophisticated method to access the thermal

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diffusivity of common homogeneous planar samples, but its application to heterogeneous composites may be limited due to this homogeneous theoretical assumption. Although models for specific composite structures exist, there is no general heterogeneous composite model for the temperature rise phenomena on the radiating surface. Homogeneous model is often employed as an approximation, which can be highly inaccurate for some composite materials with complex internal structure.

To avoid this problem, we remove this assumption by employing computational tools to calculate the detail thermal transports inside composites and then compare the results with experimental signal taken from LFA. Finite element method (FEA) is widely used to calculate the thermal conductivity of heterogeneous materials [18,19]. It is capable of incorporating different structural and interfacial factors into the computation. The direct computation of the modeled material structures avoids the difficulty of homogeneous material assumptions in analytical modeling. The method extends the functionality of LFA to measuring thermal conductivity of complex composite with known microscopic structure. Thru direct simulation of the structure, the new analysis method provides a way to estimate microscopic parameters of the composite. It also helps to provide macroscopic and microscopic information for quantitative evaluation of different preparation methods for composite materials.

We employed the ANSYS FEA package to model the LFA procedure of one-dimensional (1D) fiber-reinforced composites, and then compare the temperature rise signal of experimental measurement with the simulation result. The interface thermal resistance R and the carbon fiber axial thermal conductivity λ_{cfz} were then predicted.

2. The principle of LFA measurement of thermal diffusion coefficient α

This study used the Netzsch LFA447 Nanoflash for measurement. The laser is generated by laser pumping a Xenon gas flashtube and specialized optics to produce a homogeneous heat pulse on the front end of the sample. The radiation at the sample's rear surface is received by a liquid-nitrogen-cooled InSb infrared detector. As shown in Fig. 1, an intensive laser light pulse is absorbed in the front surface of an otherwise thermally insulated specimen a few millimeters thick, and the resulting areal-average temperature history of the rear surface is measured by the radiometer. The thermal diffusivity is determined by the characteristic shape of the rising temperature curve at the rear surface according to the theoretical solution [17].

Equations for the temperature distribution are used within a thin slab of material which has received a short pulse of energy on one surface. The theory has several important assumptions, including energy loss at the surfaces (by radiation or convection) is negligible, the specimen is homogenous in properties, and there is no significant unintended radiation energy leak in the system (e.g. laser flash-thru the specimen). The internal heat conduction equation of the sample is,

$$\frac{\partial T}{\partial t} - \alpha\nabla^2 T = 0. \tag{1}$$

The system is initially in the trivial thermal state with constant temperature, i.e. $T = T_0$. The boundary conditions are:

$$\begin{cases} q(z=0) = q_0 \\ q(z=L) = 0 \end{cases}, \quad 0 < t < t_0 \tag{2}$$

$$\begin{cases} q(z=0) = 0 \\ q(z=L) = 0 \end{cases}, \quad t > t_0 \tag{3}$$

L is thickness of the sample, and α is the thermal diffusivity. The value of α is determined by an experimental measurement of the half-rise time $t_{0.5}$ which is the time the temperature of rear surface reached one-half of the maximum value during the process.

$$\alpha \approx 0.1388 \frac{L^2}{t_{0.5}} \tag{4}$$

Eq. (4) depends on the homogenous assumption on the material. Without Eq. (4) for heterogeneous composite samples, the LFA analysis procedure is of limited use, and requires more elaborated theory on specific composites or calls for the assistance of computational methods.

3. 1D carbon-fiber reinforced materials

The samples were prepared in the laboratory of Wuhan University of Science and Technology. The carbon fibers of the samples were prepared by a melt-spinning method using mesophase pitch as the raw material, and highly oriented ribbon-shaped graphite fibers with high thermal conductivity were obtained through pre-oxidation, carbonization and graphitization. The 1D carbon fiber reinforced composite materials were prepared by hot press-

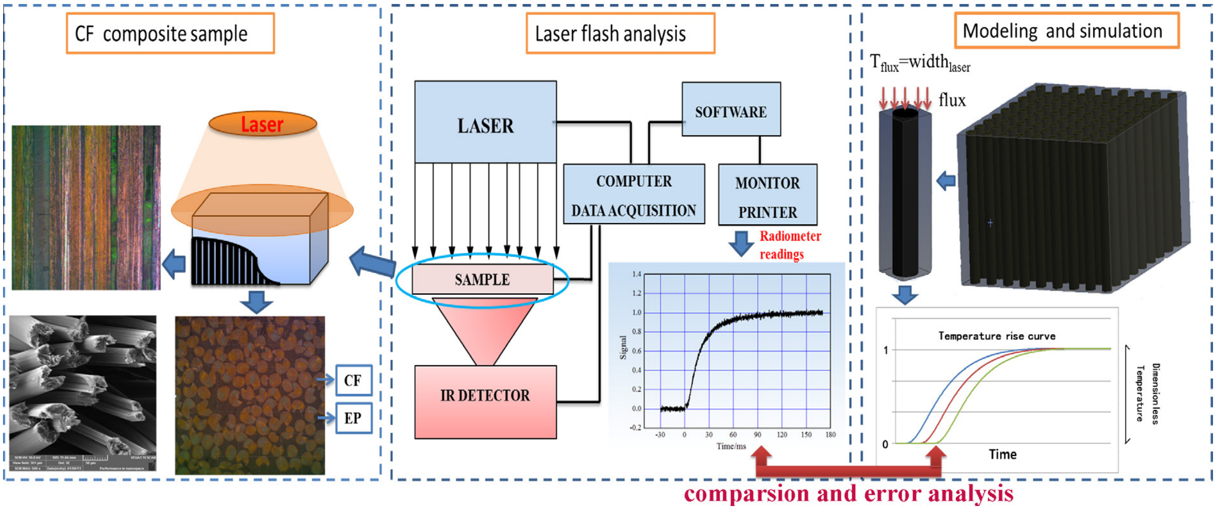

Fig. 1. The principle of LFA measurement.