USING THE FLASH METHOD AND STEP-HEATIG METHOD FOR MEASUREMENT OF THE THERMAL DIFFUSIVITY OF FIBROUS COMPOSITES

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Abstract

The effective thermal diffusivity of copper–steel fibers composites was measured at the room temperature by the flash method and the step-heating method. Both methods were tested on copper and steel samples of various thicknesses. The transversal and longitudinal effective thermal conductivities were evaluated from a single flash experiment.

Key words: flash method, step-heating method, composite, effective thermal diffusivity, effective thermal conductivity

1. Introduction

The steady-state thermal conductivity and the transient thermal diffusivity are important parameters involved in manufacturing of composite materials. During the analysis of composite materials it is desirable to approximate the heterogeneous material as a homogeneous having “effective” properties, thus allow for substantial simplification of the simulation process. This “homogenization” is well established for the steady state heat conduction in composite materials, and considerable progress has been made in relating the effective steady-state thermal conductivity of the composite to the thermal conductivities of the individual components.

On the other hand, the thermal diffusivity, strictly speaking, is not a characteristic property of composite materials since the thermal conduction equation in which the thermal diffusivity appears as a transient characteristic constant applies only to homogeneous materials. Therefore, it is necessary to evaluate the conditions under which the composite may be treated as homogeneous. This has to be done for every material independently, although some common criteria could be applied. Despite the mentioned problems diffusivity techniques have been successfully applied to various composite materials.

Among the theoretical means of estimating the transient diffusivity of composites, the simplest one is the "static" diffusivity approximation. This approximation treats the composite material as a homogeneous medium with "static" thermal diffusivity a_s, the definition of which is based on the effective thermal conductivity k_e and the effective volumetric specific heat $(\rho\, c_p)_e$:

$$a_s = \frac{k}{(\rho c_p)_e} \quad (1)$$

This "static" thermal diffusivity is often compared to "effective" thermal diffusivity which is the result of a transient experiment. When the agreement between those two characteristics is good, it is believed that the concept of "static" diffusivity can be used. If not, one has to resort to a fully numerical solution.

If the "static" thermal diffusivity is calculated, the knowledge of the effective thermal conductivity is required. For unidirectional fibers in an isotropic matrix the longitudinal and transversal thermal conductivity is derived. It is easily shown that the longitudinal effective thermal conductivity can be expressed by simple rule of mixture for any cylindrical fibrous geometry[1]. For the transversal thermal conductivity, the two dimensional Hashin-Shtrikman bounds (λ^+, λ^-) set the interval within which the values of the effective thermal conductivity should lay:

$$\lambda^+ = \lambda_2 + \frac{f_1}{\frac{1}{\lambda_2 - \lambda_1} + \frac{f_2}{2\lambda_2}} \quad (2)$$

$$\lambda^- = \lambda_1 + \frac{f_2}{\frac{1}{\lambda_2 - \lambda_1} + \frac{f_1}{2\lambda_1}} \quad (3)$$

Among all existing experimental methods of determining the thermal diffusivity of composite materials, the most popular one is the flash method of Parker *et al.* [2]. The method has been extended to measurement of effective thermal diffusivities of laminates, particulate and fiber-reinforced composites [3,4].

The present work deals with the evaluation of the use of the flash method and step-heating method for determination the effective thermal diffusivity of unidirectional copper-steel fibers composite with the fiber volume fraction about 40%.

2. Experiment

In the flash method the front face of a sample is irradiated by a short burst of light from a flash lamp or laser. From the recorded rear face temperature history the thermal diffusivity can be obtained. A modification of the method, step-heating method, differs in using a constant source of light instead of a pulse. It is advantageous for measurement of thicker samples where a high energy pulse, necessary for supplying enough energy, can cause some unpredictable damages at the irradiated surface of the sample. In our apparatus it is used when the flash lamp dissipates an insufficient amount of energy to obtain the response with favorable signal to noise ratio.

In this work the thermal diffusivity was measured by the apparatus depicted in Fig.1. It consists of a flash lamp or halogen lamp as a heat source, thermocouple as a detector (chromel-constantan of diameter 75 μm, intrinsically attached to the rear face of the sample), preamplifier, amplifier, A/D converter and personal computer, which controls the experiments. A shutter was placed beneath the halogen lamp when step-heating measurements were performed.

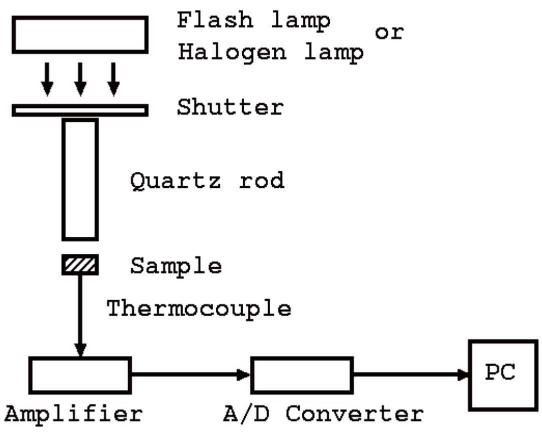

Fig.1 The experimental setup.

In order to test the apparatus, stainless steel and copper samples of diameter 12mm and 10mm, resp and thicknesses from 1.67mm to 10mm were measured. The measured composite samples were of cylindrical shape with diameter 12mm and thickness 4.8mm, 5.92mm and 12mm. The material consists of ellipsoidal unidirectional steel fibers and copper matrix. The steel fibers, with semi axes 0.6mm and 0.4mm, lay along the longitudinal axis of the sample. The fiber volume fraction is about 40%.

The radially symmetric arrangement of the fibers allowed us to evaluate the longitudinal and radial effective thermal diffusivity of the composite simultaneously from a single experiment as was suggested by Donaldson and Taylor [5]. Thus, two types of the flash and step-heating experiment were performed. First, the entire front face was irradiated and 1D model for isotropic material was used to evaluate the longitudinal effective thermal diffusivity. Then, only a part of the front face was irradiated which caused radial heat flow and the used 2D anisotropic model gave both, longitudinal and transverse effective thermal diffusivity. Unlike in Donaldson model, only one temperature sensor placed in the center of the sample was used [6]. The reason was that the used data reduction method was very sensitive to the position of temperature sensor if it was placed radially aside from the irradiated part of the sample.

3. Experimental results and discussion.

3.1 Data reduction

The thermal diffusivity was calculated using the data reduction software which can fit the measured data to various models (1D, 2D, isotropic, anisotropic, heat losses, no heat losses, finite pulse time duration) and their combinations. For every particular data set, the model which described the experiment more realistically was chosen. The results of the test sets of copper and stainless steel confirmed that it is very reasonable to use both methods to enlarge the interval of possible thicknesses of measured samples. The measured thermal diffusivity values are summarized in . It is clear that for thin samples the flash method is more suitable since the step-heating method is not able to provide enough energy for such a short time (about tens to hundreds of milliseconds for the mentioned samples). The same reason prefers the step-heating method for thicker samples.

Table 1 Measured longitudinal (a_l) and transverse (a_r)effective thermal diffusivity for different irradiation diameters *R*.

	Step	***Flash***				
	R=100%	***R=100%***	***R=50%***		***R=66%***	
l [mm]	a_l [m^2/s]	a_l [m^2/s]	a_l [m^2/s]	a_r [m^2/s]	a_l [m^2/s]	a_r [m^2/s]
12.0	6.88×10^{-5}	7.45×10^{-5}				
5.92	6.41×10^{-5}	6.41×10^{-5}	6.46×10^{-5}	4.99×10^{-5}		
4.87	9.80×10^{-5}	9.86×10^{-5}	9.32×10^{-5}	4.65×10^{-5}	9.89×10^{-5}	4.56×10^{-5}

The copper-steel fibers composite of thickness 12 mm and 5.92 mm were measured only with full irradiation adopting just 1D model because the corresponding sensitivity analysis showed that for these sample thicknesses it was not possible to obtain the transverse and longitudinal thermal diffusivities simultaneously. The flash data for 12 mm thick sample were obtained from a very noisy signal, thus the step-heating data are more relevant for this sample length. The sensitivity analysis for the 4.87 mm thick sample was satisfactory, so both diffusivities were evaluated.

Fig. 2. shows a typical response of the flash experiment for the 4.78 mm sample with partial irradiation. The response curve demonstrates that radial heat flow occurs visibly and the corresponding sensitivity analysis confirms the possibility of simultaneous determination of the transverse and longitudinal thermal diffusivities (Fig. 3).

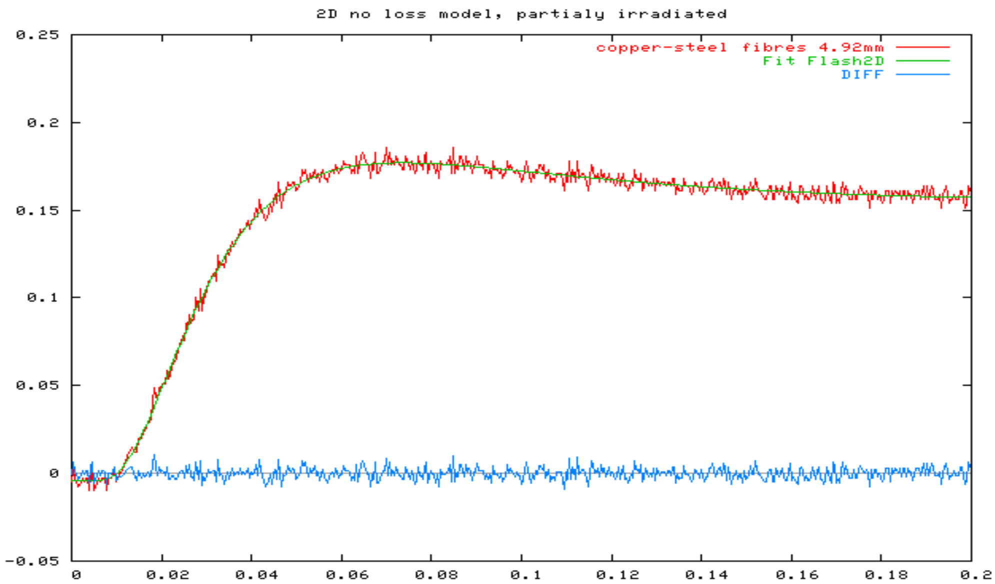

Fig. 2 Response of a partially irradiated composite sample fitted to the 2D model.

3.2 Comparison with the theoretical predictions.

The values of the measured effective thermal diffusivities were compared to the "static" thermal diffusivities which were calculated from Eq. (1). The effective volumetric specific heat was calculated from the relation

$$(\rho c_p)_{ef} = \rho_{Cu}\, c_{p-Cu}\, f_{Cu} + \rho_f\, c_{p-f}\, f_f \qquad (4)$$

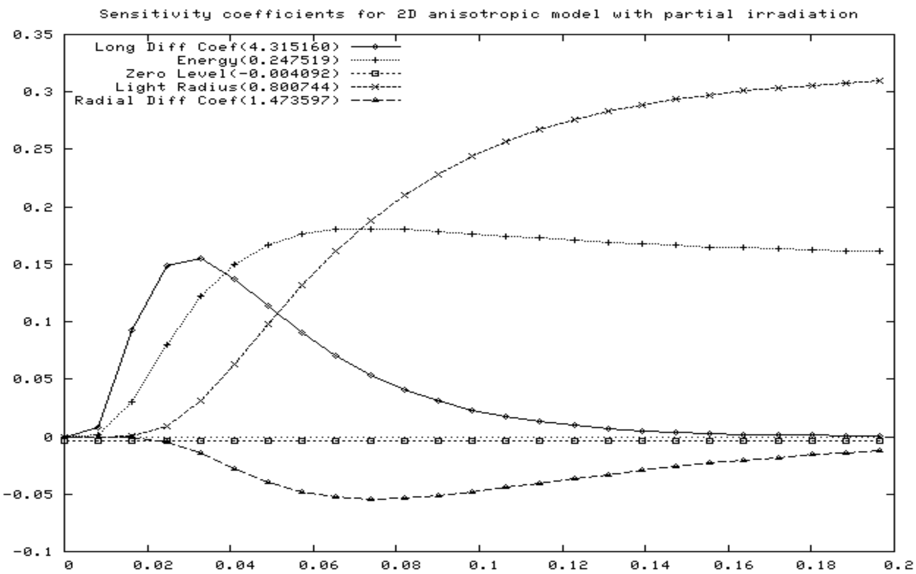

Fig. 3 Sensitivity coefficients for the response presented in Fig. 2.

where subscript "Cu" denotes copper matrix and "f" steel fibers. The longitudinal effective thermal conductivity was calculated from the rule of mixture. For the transversal case, the corresponding upper and lower bounds of the effective thermal conductivity were calculated using the two dimensional Hashin and Shtrinkman relations (Eq. 2 and 3). The values of thermal conductivity, specific heat and density of the constituent phases were taken from literature. The calculated "static" longitudinal thermal diffusivity $a_{sl} = 7.31 \times 10^{-5}$ m^2/s. This value is closer to the values of effective thermal diffusivity of the 12mm sample, and differs from the values of the other two samples. The calculated transversal "static " thermal diffusivity should be within the interval $2.477 \times 10^{-5} - 5.192 \times 10^{-5}$ [m^2/s]. This is in agreement with the measured effective transverse thermal diffusivity of the 4.87 mm sample.

The discrepancies in the longitudinal effective thermal diffusivities may be explained by insufficient homogeneity in the direction of the fibers. The copper matrix has high thermal conductivity and diffusivity values, while the steel fibers have relatively low values compared to those of the copper matrix. Thus the copper matrix acts as preferred path for heat transfer. When such composites are subjected to an instantaneous heat pulse on one surface, the temperature wave is not planar. The results of thermal diffusivity methods and the applicability of the concept of diffusivity for such materials legitimately can be questioned. However, for all three samples the rear face temperature response curves measured in the flash diffusivity experiments followed the theoretical curve very closely, so we assumed the experiment could be valid. If a disagreement occurs, one has to turn to a full numerical solution which is our next task.

4. Conclusion

The effective thermal diffusivity of copper-steel fibers unidirectional composite was measured by the flash method and step-heating method. Such composite is anisotropic and both longitudinal and transversal effective thermal diffusivities were evaluated. The measured effective values were compared to the theoretical "static" values. Quite a good agreement was achieved for the transverse effective thermal diffusivity while the longitudinal effective thermal diffusivity differs considerably. This was explained as a lack of homogeneity. A fully numerical solution of the thermal model taking into account thermal resistance between phases could yield more satisfactory results.

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