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Thermal Diffusivity Measurement of Polyamide Mesh by Temperature Wave Analysis[1]

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The thermal diffusivity α of a polyamide mesh having plane wave structure was determined by a temperature wave analysis method developed in our laboratory. The measured thermal diffusivity of the polyamide mesh represents the combined result for the polyamide fiber part and the open space of the mesh. The polyamide mesh was measured in air and liquid paraffin conditions. Its effective thermal diffusivity was obtained as a function of the volume content of the surrounding material. A unit-cell model was applied to the polyamide mesh structure and shows good correspondence with the experimental results.

KEY WORDS: effective thermal diffusivity; plane wave structure; polyamide mesh; temperature wave analysis; unit-cell model.

1. INTRODUCTION

The thermophysical properties of composite materials are important for the design of functional materials and for heat control in processing. Only recently have measurements methods been developed for the thermal diffusivity α and thermal conductivity λ. However, because of the difficulty in measuring these important thermophysical properties over a wide temperature range using conventional methods, such as the hot-wire, laser-flash, and ac calorimetry techniques, there have been few studies of the thermal transport phenomena for composite materials based on detailed experimental data.

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A new thermal diffusivity method has been developed in our laboratory for polymer thin films over wide temperature ranges from the solid to the melt states. This method, the temperature wave analysis (TWA) method, has been applied for measurements on polymers [1–5]. In addition, we have shown that this method can be used to measure the thermal diffusivity of paper, which is a porous material composed of cellulose fiber and air [6]. The main advantages of this technique are as follows: (1) a small temperature gradient across a small part of the sample; (2) a short measurement period; (3) high temperature resolution; and (4) no pretreatment.

Because the composite material has an irregular structure, the structure has been estimated with an empirical method. In case of cloth or mesh-type material, the structure shows repetition structure and is easily expressed as a numerical equation. In other words, theses type of materials are very useful for the numerical analysis of a thermal transport phenomenon.

In this study, the effective thermal diffusivity of polyamide mesh with different open spaces was measured by the TWA method. The measurements were carried out in air or liquid paraffin conditions. The measured results are compared with calculated values by using various thermal conductivity models.

2. EXPERIMENTAL

2.1. Sample

The mesh-type material used in this study is polyamide mesh (Nytal, produced by Schweiz. Scidengazefabrik AG Thal). All meshes have the same structure, a plane wave structure for which length- and breadth-direction fibers cross each other. The width of open space, the diameter of the fiber, and the ratio of open space in the meshes are given in Table I. The volume content of open space used in this measurement was calculated from the ratio of open space to the fiber part of the mesh.

Table I. Characteristics of Polyamide Mesh

Width of mesh (μm)	Fiber diameter (μm)	Volume of open space (%)
5	86	5
20	34	37
30	30	50
37	30	55

2.2. Measurement

Figure 1 shows the TWA sample cell for mesh-type material. A small sample specimen (1 cm × 1 cm) was inserted between two slide glasses on which a thin gold layer was sputtered on a surface area of $1 \times 4\,\text{mm}^2$. Copper lead wire was attached to each gold layer. To increase the thermal contact of the gold-sputtered layer and the mesh, the sample cell was maintained under slight pressure, which did not affect the thickness.

The thermal diffusivity was measured in air or liquid paraffin conditions at atmospheric pressure. The gold layers attached on the front and rear surfaces of the specimens were used for a heater and a sensor detecting the temperature wave, respectively. The electrical resistance of the gold layers was controlled at approximately 50 Ω.

The temperature wave was generated by a function generator, NF Type 1915, on a gold layer heater. The temperature wave was diffused across the sample in the thickness direction. The variation of the temperature at the rear surface was detected as a change of electrical resistance. This resistance change was converted into the variation of the voltage and amplified using an NF Type 5610 lock-in amplifier. All instruments were controlled by a personal computer. The reproducibility of the measurements was confirmed by repeated measurements with several specimens.

The relationship between the temperature wave frequency of the measurement and the phase shift of the signal, which was analyzed by a lock-in amplifier at the rear surface, is expressed by [3, 4]

$$\varDelta\theta = -\sqrt{\frac{\pi f}{\alpha}}\,d - \beta \tag{1}$$

where $\varDelta\theta$ is the phase shift, α is the thermal diffusivity, f is the frequency of temperature modification, d is the sample thickness, and β is an instrument constant.

In Eq. (1), the relationship between the square root of f and the phase delay of the signal $\varDelta\theta$ at the rear surface is linear, and the thermal

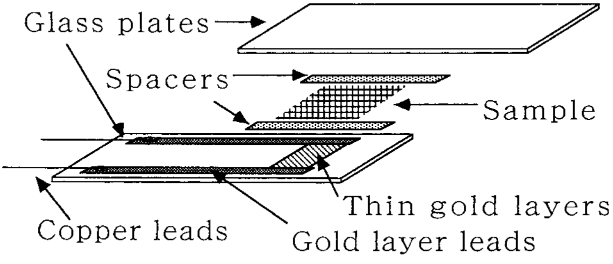

Fig. 1. Schematic diagram of the sample cell.

diffusivity α can be obtained from the slope of the plot of $f^{1/2}$ versus $\Delta\theta$ when the thickness of the sample film is known. Since this method is based on a phase delay measurement, the influence of backing material such as the glass plate can be neglected.

3. RESULTS AND DISCUSSION

3.1. Experimental Results

The thermal diffusivity of polymer mesh is regarded as the effective value of the composite material composed of fiber and eithr gas or liquid in the open space of the mesh. In the case of gases used for heat transfer, it is necessary to consider the effect of convection on the effective thermal diffusivity. However, the effect of the convection at atmospheric pressure for the thickness used for this measurement is negligible [7].

Figure 2 shows the volume dependence of α_{ef} of polyamide mesh in air as a function of temperature. The α_{ef} decreases with increasing temperature. The decrease in α_{ef} is almost independent of volume content variation. Thus, the temperature dependence of α_{ef} of polyamide mesh in air is the same as that of polyamide fiber in this temperature range.

The applied sine wave current to the front surface of the polyamide mesh propagates through heat transfer materials. In this case, the heat

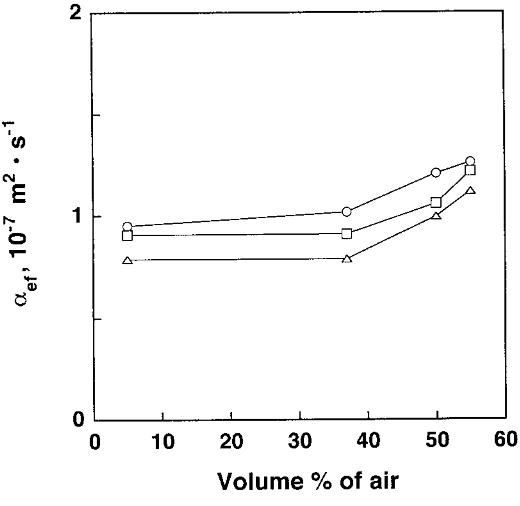

Fig. 2. Volume dependence of the thermal diffusivity as a function of temperature for polyamide mesh in air. 30°C (○), 60°C (□), 100°C (△).

transfer materials are polyamide fiber and air. But polyamide fiber has a higher thermal conductivity than air, such that the heat flow will be largely determined by polyamide fiber. Because the lock-in amplifier used in this measurement detects a signal which is delivered by the fast heat transfer path, and because the measured value does not depend on the contact area of the sensor and sample, the measured thermal diffusivity of polyamide mesh in air is a constant value and is the same as the value of polyamide fiber for any constant volume of gas under 40 vol%.

The α_{ef} of polyamide mesh in air increases with increasing volume content for gas volumes larger than 40 vol%. If the variation of α_{ef} is caused by increasing gas content, the variation of α is small relative to the thermal diffusivity of the gas ($\alpha_{air} = 216 \times 10^{-7}\ m^2 \cdot s^{-1}$) [8]. Namely, it is assumed that the α of the gas has no direct effect on the α_{ef} of the polyamide mesh in the gas, although the reason is not clearly understood.

Figure 3 shows the calculated volume dependence of polyamide mesh in air on the basis of the measured α_{ef} from 0 to 55 vol% and the α of air. The thermal diffusivity is a constant value up to 40 vol%, and then changes suddenly. As a result, we know that the α_{ef} of polyamide mesh in the gas condition has ranges of constant value and an abrupt large change between the two ranges.

Figure 4 shows the α_{ef} of polyamide mesh measured in liquid paraffin. The measured value has a constant value under 37 vol%, as in air. With an increase in volume content, the α_{ef} approaches the α of liquid paraffin.

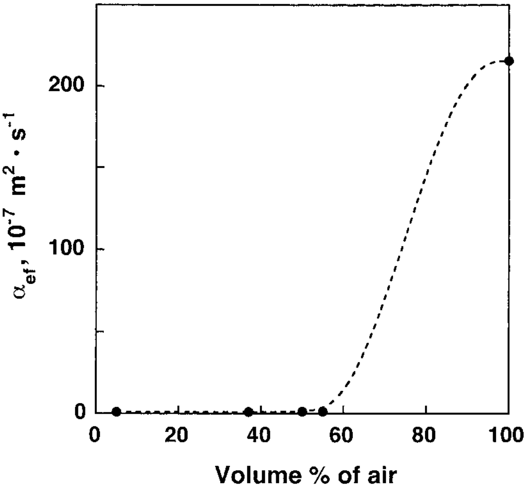

Fig. 3. Volume dependence of the thermal diffusivity for polyamide mesh in air. Measured (●), calculated (---).

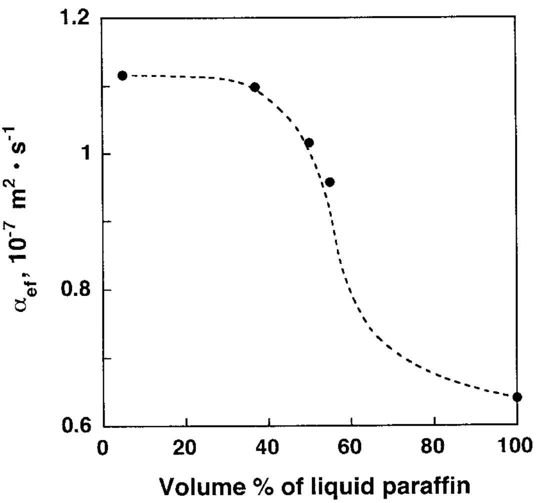

Fig. 4. Volume dependence of the thermal diffusivity for polyamide mesh in liquid paraffin. Measured (●), calculated (----).

The broken line in the figure shows the fitted result from the measured value. This was calculated on the basis of the variation of the measured α_{ef}. As a result, the volume dependence of α_{ef} of polyamide mesh in liquid paraffin showed the same behavior as that of polyamide mesh in air. However, the ranges where the value was constant and the range where there was a sudden change were different for different materials.

3.2. Theoretical Modeling

In order to apply a thermal resistance model, the polyamide mesh was assumed to be a simple mixed system with series and parallel components in an array which describes the fiber and the open space. We applied a calculation method based on a thermal resistance model for the polyamide mesh in liquid paraffin [9].

Figure 5a illustrates the model for the structure of polyamide mesh. Fiber and open space are systematically arrayed to describe the heat flow. The repetition unit of the mesh is indicated as a broken line in Fig. 5a. As one fourth of the repetition unit is enough for theoretical calculations, a simplified unit-cell of the mesh is shown in Fig. 5b.

Figure 6 illustrates the unit-cell model of a series and a parallel array in terms of fiber and open space oriented with respect to heat flow. In the series array, each layer has a different fiber volume content, and three parts

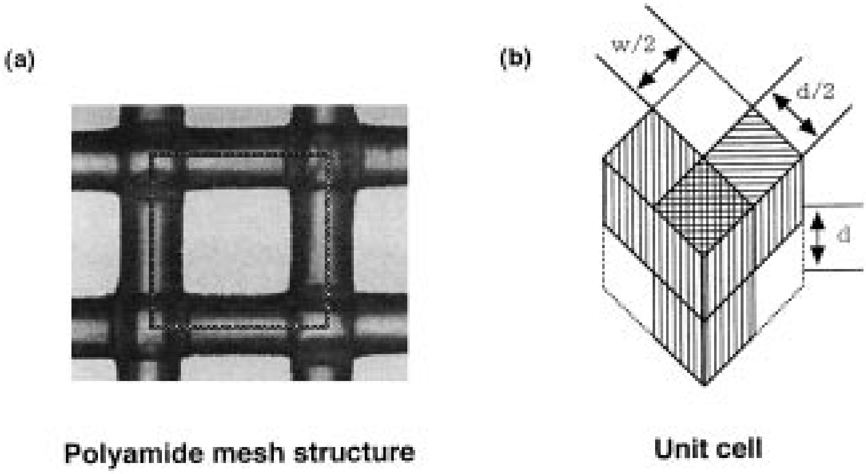

Fig. 5. Schematic representation of (a) real and (b) unit-cells of polyamide mesh.

with different fiber volume content are also in the parallel array. By using a thermal resistance model determined by fiber volume content and the array method, we can derive a thermal conductivity equation as follows for the series array:

$$\frac{1}{\lambda_{\mathrm{ser}}}=\frac{d}{\lambda_{\mathrm{m}}[(d/2)^2+2(d/2)(w/2)]+\lambda_{\mathrm{d}}(w/2)^2}+\frac{d}{\lambda_{\mathrm{m}}(d/2)^2+\lambda_{\mathrm{d}}[(d/2+w/2)^2-(d/2)^2]} \tag{2}$$

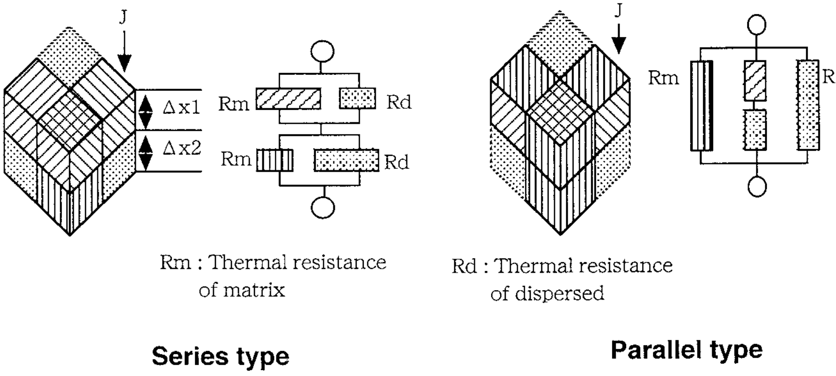

Fig. 6. Porosity distribution and thermal resistance models.

and for the parallel array

$$\lambda_{\text{par}} = \lambda_{\text{m}} \left(\frac{d}{2}\right)^2 + \lambda_{\text{d}} \left(\frac{w}{2}\right)^2 + \frac{\lambda_{\text{m}}\lambda_{\text{d}}}{d} \left[\frac{2(d/2)(w/2)}{\lambda_{\text{m}} + \lambda_{\text{d}}}\right] \tag{3}$$

where d is the diameter of the fiber, w is the width of the mesh, λ_{m} is the thermal conductivity of the matrix, and λ_{d} is the thermal conductivity of the dispersed material.

As the polyamide mesh is described by the series and parallel arrays, the effective thermal conductivity of a plane wave structure is calculated by a geometric average of the series and parallel array contributions,

$$\lambda_{\text{ef}} = \lambda_{\text{ser}} f_{\lambda_{\text{par}}} (1 - f) \tag{4}$$

where f is the volume fraction of open space in the mesh and λ_{ef} is the effective thermal conductivity.

The thermal diffusivity was calculated to from the effective thermal conductivity by using Eq. (5) for comparing with the calculated results using thermal conductivity models [10]:

$$\begin{aligned} \alpha_{\text{ef}} &= \frac{\lambda_{\text{ef}}}{C_{\text{ef}}\,\rho_{\text{ef}}}, \\ \rho_{\text{ef}} &= \rho_{\text{m}} f_{\text{m}} + \rho_{\text{d}} f_{\text{d}}, \\ C_{\text{ef}} &= \frac{\rho_{\text{m}} C_{\text{m}} f_{\text{m}} + \rho_{\text{d}} C_{\text{d}} f_{\text{d}}}{\rho_{\text{m}} f_{\text{m}} + \rho_{\text{d}} f_{\text{d}}} \end{aligned} \tag{5}$$

where C is the specific heat at constant pressure and ρ is the density. Table II lists the values of the thermal properties used to calculate the thermal conductivity.

Figure 7 compares the measured value for the polyamide mesh in liquid paraffin and the results using the unit-cell model, the Rayleigh–Maxwell model, and various conductivity models [11]. The unit-cell

Table II. Properties of Materials

Material	Thermal diffusivity ($10^{-7}\,\text{m}^2\cdot\text{s}^{-1}$)	Specific heat ($\text{J}\cdot\text{g}^{-1}\cdot\text{K}^{-1}$)	Density ($\text{g}\cdot\text{cm}^{-3}$)
Polyamide mesh	1.12	1.92	1.12
Liquid paraffin	0.64	2.9	0.80

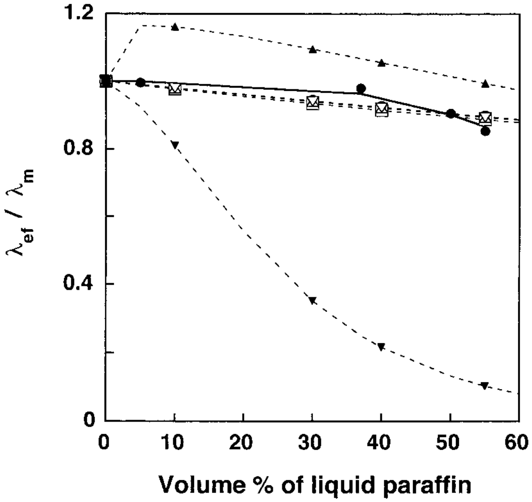

Fig. 7. Comparison of measured and calculated results for polyamide mesh in liquid paraffin. Parallel (○), series (□), Rayleigh–Maxwell (△), Russel (▽), Ribaud (▲), Tye (▼), unit-cell (——), measured (●).

model, in which the structure of the mesh is considered, shows good correspondence with the experimental results. Thus the unit-cell model is useful in the analysis of heat conduction in a mesh having a plane wave structure.

4. CONCLUSION

The effective thermal diffusivity of a polyamide mesh in air or liquid paraffin was measured by a thermal wave analysis method which was developed for measuring the thermal diffusivity of polymers. The effective thermal diffusivity of the polyamide mesh as a function of volume content was divided into a constant-value range and a sudden-change range. The effective thermal diffusivity in the constant-value range was the same as that of polyamide fiber or surrounding material. Thus, it is considered that the temperature wave was propagated through the efficient heat transfer materials. For polyamide mesh in a gas, the applied signal was diffused through the polyamide fiber at a low content of gas. By increasing the volume content of the gas, the effect of the gas increases. Finally, the signal is transferred through the gas.

The polyamide mesh, which is a plane wave structure, was represented by a thermal resistance model. A simplified unit-cell of the polyamide mesh was used to develop an equation for calculating the thermal conductivity of the polyamide mesh in liquid paraffin. The estimated value from the equation shows good agreement with the measured value. Thus, the calculation method using a unit-cell is useful for analyzing the thermal conduction of material having a plane wave structure.

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