EVALUATION OF THERMAL CONDUCTIVITY IN PITCH-BASED CARBON FIBER REINFORCED PLASTICS

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Abstract

Thermal conductivities in longitudinal and transverse directions of a CFRP unidirectional composite are evaluated experimentally. Laser flash method is employed to measure thermal conductivity. To discuss the experimental results, rules of mixture predictions and two-dimensional steady-state and transient heat transfer simulations are conducted. In addition, a heat sink is made with the CFRP. The heat radiation performance under natural convection (the thermal resistance) is compared with heat sinks made of aluminum with different surface treatment. Effect of heat radiation is discussed both experimentally and analytically. Three-dimensional steady-state heat transfer simulations are performed to compare with the experiment result.

1 Introduction

Carbon fiber reinforced plastics (CFRP) are used in various fields, especially in aerospace engineering, due to their high specific modulus and strength. Because pitch-based carbon fibers have high thermal conductivity, their composites are expected to be used as heat control materials [1]. Considering a carbon fiber unidirectional composite, it may have anisotropy in thermal conductivity, that is, it is high in fiber direction whereas low in the direction perpendicular to the fibers. Moreover, it is expected that we can develop a material with higher thermal conductivity. In the present study, thermal conductivities in pitch-based carbon fiber (YS90A) reinforced epoxy unidirectional composites with different fiber volume fractions are experimentally evaluated by using the laser flash method. To discuss the experimental results, rules of mixture prediction and two-dimensional steady-state and transient heat transfer simulations are conducted. In addition, a heat sink is made with the CFRP. The heat radiation performance under natural convection (the thermal resistance) is compared with heat sinks made of aluminum with different surface treatment, that is, with and without alumite treatment. To discuss the experimental results, three-dimensional steady-state heat transfer simulations are conducted.

2 Experiment

2.1 Materials

A pitch-based carbon fiber, YS90A (Nippon Graphite Fiber Ltd.), is used. An epoxy resin is used as the matrix material. Unidirectional composites with different fiber volume fractions (55%, 40%, 20% and 0% (neat resin)) are fabricated for the thermal conductivity measurement by the laser flash method. For thermal resistance measurement, CFRP heat sink of 55% volume fraction is used. Both specimens whose fiber directions are parallel and perpendicular to the heater plane are used. Properties of fiber and matrix in the present study are listed in Table 1.

Table 1 Properties of fiber and matrix

	Thermal Conductivity (W/mK)	Specific heat capacity (J/gK)	Density (g/cm3)
Fiber	500	0.837	1.75
Epoxy	0.26	1.12	1.23

2.2 Measurement of thermal conductivity by the laser flash method

Thermal conductivities in the unidirectional composites are measured by using the laser flash method. In the method, a laser beam is flashed on the top surface of a cylindrical specimen (Fig.1). The temperature change at the bottom surface of the specimen is monitored. Based on the measured temperature history, the halftime $t_{1/2}$ (time for the temperature rise up to the half of the maximum temperature) is determined, which in turn used to calculate specimen thermal diffusivity, α, by using the following equation.

$$\alpha = 0.1388 \frac{L^2}{t^{1/2}} \tag{1}$$

where L is specimen length. The diameter and the length of the specimens are 10mm and 3mm, respectively. Based on the thermal diffusivity, thermal conductivity can be calculated by using following equation.

$$\lambda = \alpha C \rho \tag{2}$$

where C is specific heat capacity and ρ is density.

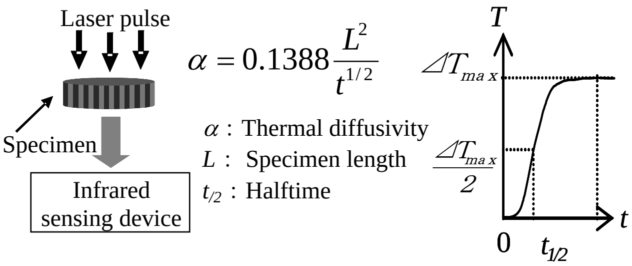

Fig.1 Principle of the Laser Flash Method

2.3 Heat sinks

A heat sink is made with a CFRP prepreg made of a carbon fiber, YS90A (Nippon Graphite Fiber Ltd.), and Epoxy resin. Prepreg sheets are stacked such that the fiber direction is parallel to the fin height. The heat sink is made with integrated molding. The size of the heat sink is shown in Fig.2. Commercially available heat sinks of the same size made of aluminum alloy (Ryosan Inc.) are also used. Both aluminum heat sinks with and without alumite treatment are used. Properties of each heat sink are shown in Table 2.

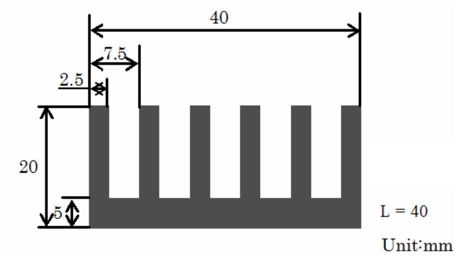

Fig.2 Size of heat sink

Table 2 Properties of heat sinks

	Al (A6063-T5)	Al(A6063-T5)-alumite treatment	CFRP (YS90A)
Density (g/cm^3)	2.70	2.70	1.75
Thermal conductivity (W/mK)	209	209	270
Mass (g)	44.62	44.80	30.28

2.4 Measurement of thermal resistance

Heat radiation performance was evaluated by measuring thermal resistance under the condition of natural convection. The thermal resistance R is defined by

$$R(℃/W) = \frac{(T_1 - T_\infty)}{Q} \tag{3}$$

where T_1 is the highest temperature at the bottom surface of the heat sink, T_∞ is the ambient temperature and Q is the heat flux which into the heat sink.

The experimental setup used in the present study is shown in Fig.3. A rubber heater was used as a heat source. Heat flux sensors were used to measure the heat flux which flows in to the heat sink, Q. thermocouples of type T were used to the temperatures T_1 and T_∞. The measurements were conducted until the system reaches the steady state.

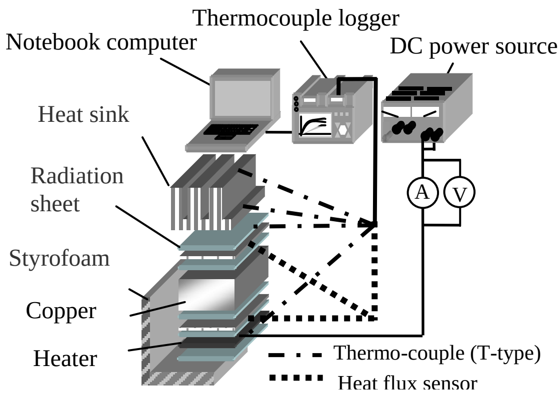

Fig.3 Experimental setup for thermal resistance measurement

3 Analysis

3.1 Rules of mixture predictions

Thermal conductivity of a unidirectional composite in the fiber direction, λ_L, can be predicted by the rules of mixture as

$$\lambda_L = \lambda_f V_f + \lambda_m V_m \tag{4}$$

λ is thermal conductivity, V is volume fraction and subscripts f and m denote fiber and matrix, respectively. Thermal conductivity of a transverse composite in the fiber direction, λ_T, can be predicted by the rules of mixture as

$$\frac{1}{\lambda_T} = \frac{V_f}{\lambda_f} + \frac{V_m}{\lambda_m} \tag{5}$$

Analytical models of the rules of mixture are shown in Fig.4.

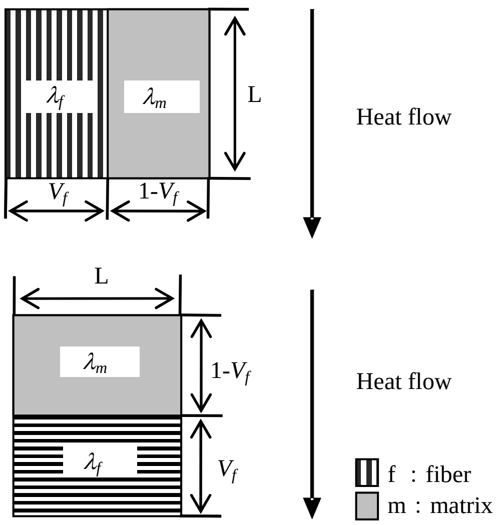

Fig.4 Models of the rules of mixture prediction

3.2 Calculation of thermal conductivity by two-dimensional steady-state heat transfer simulation

Composite thermal conductivity is calculated by using the two-dimensional steady-state heat transfer simulation. Finite element method is applied. Analytical models are shown in Fig.5. The top edge of the model is fixed at 30℃ and the bottom edge is fixed at 10℃, and the right and left edges are thermally isolated. Heat flux q was calculated by summing the node heat flux at the bottom surface [2]. The calculation of thermal conductivity λ was conducted from the next expression by using the value of this heat flux.

$$\lambda = \frac{q}{\Delta T/d} \tag{6}$$

Where ΔT is the temperature difference, that is 30-10=20℃, and d is the model thickness.

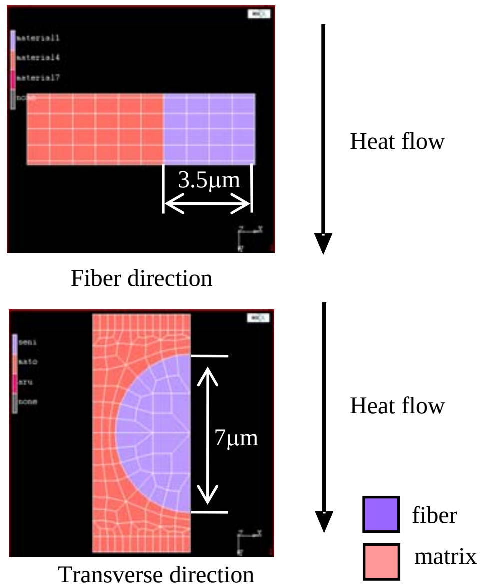

Fig.5 Models of two-dimensional steady-state heat transfer simulation (FEM)

3.3 Calculation of thermal conductivity by two-dimensional transient heat transfer simulation

Composite effective thermal conductivity is also evaluated by using a two-dimensional transient heat transfer simulation. In the analysis, the laser flash method is simulated. Analytical models are shown in Fig.6. Finite element method is applied. To simulate laser flash method, the top layer of 30μm thick is set 10 degrees hotter as the initial condition, and the right and left edge are thermally isolated. We monitor the temperature rise at the bottom edge of the model which enables us to determine the halftime $t_{1/2}$. Based on the halftime calculated, we can determine the composite effective thermal diffusivity.

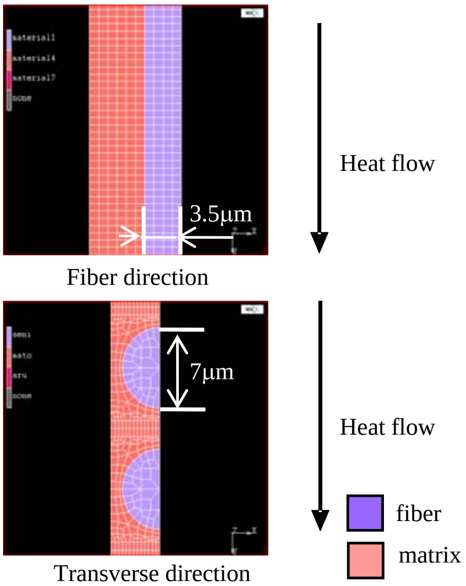

Fig.6 Models of Two-dimensional transient heat transfer simulation (FEM)

To calculate the thermal conductivity, composite effective specific heat capacity C_c and density ρ_c are determined by using the following rules of mixture as

$$C_C = C_f \times \frac{\rho_f V_f}{\rho_f V_f + \rho_m V_m} + C_m \times \frac{\rho_m V_m}{\rho_f V_f + \rho_m V_m} \quad (7)$$

$$\rho_c = \rho_f V_f + \rho_m V_m \quad (8)$$

where λ is thermal conductivity, V is volume fraction and subscripts f and m denote fiber and matrix, respectively.

3.4 Calculation of thermal resistance by three-dimensional steady-state thermo-fluid analysis

The heat radiation performances of each heat sink are calculated by steady-state thermo-fluid analysis. To calculate the thermal resistance, composite effective specific heat capacity C_c and density ρ_c are determined by Eq. 7 and Eq. 8. Analytical models are shown in Fig.7.

To simulate the experimental setup, all the components, the heater, the heat radiation sheets, the copper and the heat sink, and the styrene foam are modeled. Only the half part of the experimental setup is modeled due to symmetry.

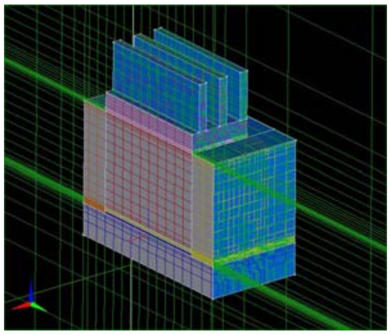

Fig.7 Model of three-dimensional steady-state thermo-fluid analysis

As the initial condition, the model is set to be 24℃. The effect of radiation is considered. The emissivities of CFRP, Aluminum alloy with and without alumite treatment are 0.94, 0.80, and 0.13, respectively. The gravitational acceleration was set to be 9.8 m/s^2. The thermal resistance is calculated from Eq. 3.

4 Results and discussion

4.1 Laser flash method and analytical result

Table 3 and Fig.8 shows the experimental results of the unidirectional composite thermal conductivity in the fiber direction and results of the predictions of the analysis as a function of fiber volume fraction. In the case of fiber direction, the thermal conductivity increases linearly with increasing fiber volume fraction. Experimental results of thermal conductivity of CFRP agree with the rules of mixture predictions and the predictions of both two-dimensional steady-state and transient heat transfer analysis.

Table 3 Results of thermal conductivity in fiber direction measurements and analytical predictions

Volume fraction (%)	55	40	20
Experiment (W/mK)	270.44	190.12	91.63
Rules of mixture prediction (W/mK)	275.12	200.16	100.21
Steady-state simulation (W/mK)	275.12	200.16	100.21
Transient simulation (W/mK)	271.55	197.44	97.47

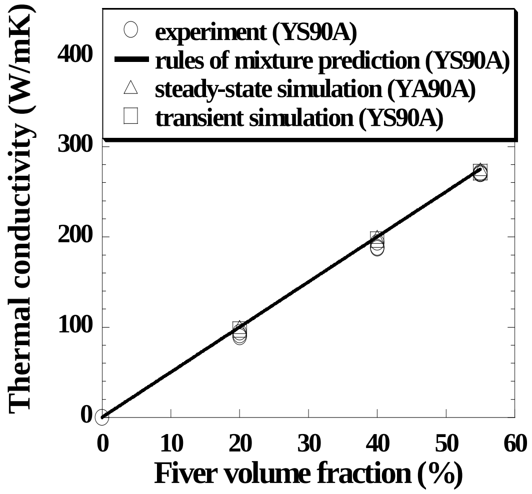

Fig.8 Thermal conductivity of CFRP in fiber direction as a function of fiber volume fraction for CFRP using YS90A. Comparison with the rules of mixture predictions and heat transfer simulations (FEM)

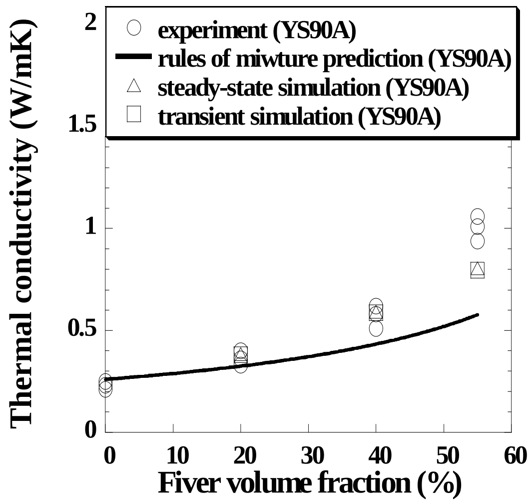

Fig.9 Thermal conductivity of CFRP in transverse direction as a function of fiber volume fraction for CFRP using YS90A. Comparison with the rules of mixture predictions and heat transfer simulation (FEM)

Table 4 and Fig.9 shows the experimental results of the unidirectional composite thermal conductivity in the transverse direction and results of the predictions of the analysis as a function of fiber volume fraction. In the case of transverse direction, the increase in the thermal conductivity due to fiber volume fraction is very small. The rules of mixture gave lower prediction than the experimental results but the FEM predictions show a fair agreement with the experimental results.

Table 4 Results of thermal conductivity in transverse direction measurements and analytical predictions

Volume fraction (%)	55	40	20
Experiment (W/mK)	1.17	0.73	0.36
Rules of mixture prediction (W/mK)	0.58	0.43	0.32
Steady-state simulation (W/mK)	0.81	0.59	0.38
Transient simulation (W/mK)	0.80	0.59	0.38

The anisotropy of the thermal conductivity in pitch-based carbon fiber reinforced epoxy unidirectional composites is confirmed. It is understood that the laser flash method is effective to the measurement of the thermal conductivity in the direction of the fiber. It is also understood the thermal conductivity can be predicted by the rules of mixtures, and two-dimensional transient heat transfer simulation.

4.2 Experimental and analytical results of thermal resistance

Fig.10 shows the experimental results of temperatures of T_1. And Fig.11 shows the experimental results of the thermal resistance under natural convection using each heat sink and results of the predictions of steady-state thermo-fluid analysis. As for the CFRP heat sink, the heat radiation performance is higher than the aluminum heat sink without alumite treatment, and it can be understood that it is the same heat radiation performance as the aluminum heat sink with alumite treatment under the natural convection. Moreover, experimental and analytical results show a good agreement.

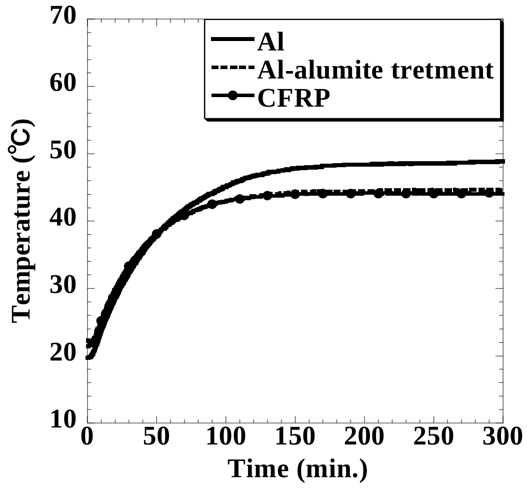

Fig.10 Temperature of T_1

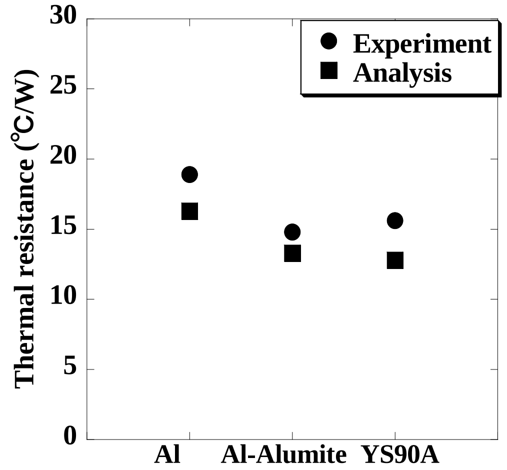

Fig.11 Experimental and analytical results of thermal resistance

5 Conclusion

Unidirectional composites consisting of a pitch-based carbon fiber and epoxy matrix is fabricated and thermal conductivity in the fiber direction and transverse direction with various fiber volume fractions is evaluated experimentally by using the laser flash method. To discuss the experimental results, the rules of mixture prediction and two-dimensional steady-state and transient heat transfer simulations are conducted. As a result, the experiment result of unidirectional composites is almost corresponding to results of each analysis. From this, it is understood the thermal conductivity can be predicted by the rules of mixture, and two-dimensional transient heat transfer simulation. Moreover, the anisotropy of the thermal conductivity of unidirectional composites can be confirmed.

The heat radiation performance under natural convection is compared with heat sinks made of CFRP and aluminum alloy with different surface treatment, that is, with and without alumite treatment. To discuss the experimental results, three-dimensional steady-state heat transfer simulations are conducted. As a result, the heat radiation performance is higher than the aluminum alloy heat sink without Alumite treatment, and it is understood that heat sink made of CFRP is the same heat radiation performance as the heat sink made of aluminum alloy with alumite treatment under the natural convection. Moreover, experimental and analytical results show a good agreement.

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