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Abstract

Evaluation of fiber orientation in carbon fiber-reinforced polymer composites using simple and low-cost infrared measurement system: Application to unidirectional carbon fiber composites †

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Abstract: Carbon fiber-reinforced polymer (CFRP) composites exhibit higher strength in the longitudinal direction than in the transverse direction of the fibers, making their fiber orientation evaluation crucial. In this study, a method for evaluating fiber orientation using halogen spot periodic heating and a non-lock-in type infrared camera is employed and applied to a unidirectional carbon fiber composite—a CFRP composite with unidirectional continuous fibers. Experimental results show that the in-plane thermal diffusivity in the fiber direction is significantly higher than in other directions. Therefore, the employed method successfully evaluates fiber orientation in the unidirectional carbon fiber composite.

Keywords: Carbon fiber-reinforced polymer composite; Fiber orientation; Thermal diffusivity; Halogen spot periodic heating; Non-lock-in type infrared camera

1. Introduction

Recently, carbon fiber-reinforced polymer (CFRP) composites have attracted interest in the automotive industry [1]. These composites exhibit higher strength in the longitudinal direction than in the transverse direction of the fibers [2], making their fiber orientation evaluation crucial. Carbon fibers have a higher thermal diffusivity than resin [3]. Consequently, the thermal diffusivity along the carbon fibers in CFRP composites is high. As a pioneering study on fiber orientation evaluation in CFRP composites, Fujita and Nagano [3] proposed a method based on the in-plane thermal diffusivity distribution obtained using laser spot periodic heating and a lock-in type infrared camera. However, this method requires an expensive infrared measurement system to synchronously obtain the laser heating signal and temperature response. Therefore, the development of a simple and low-cost method for evaluating fiber orientation is beneficial.

In this study, a method for evaluating fiber orientation using halogen spot periodic heating and a non-lock-in type infrared camera was employed. Moreover, the employed method was applied to a unidirectional carbon fiber composite—a CFRP composite with unidirectional continuous fibers.

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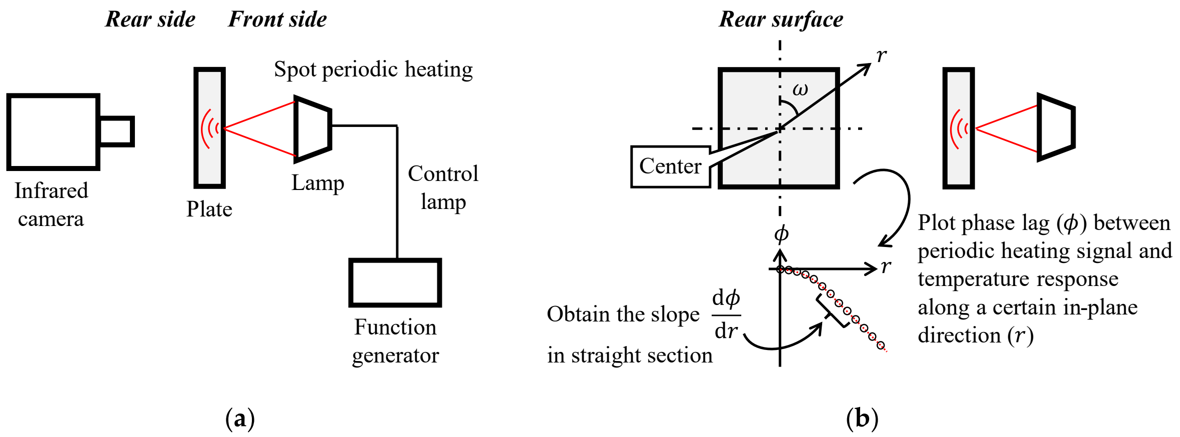

Figure 1. Procedure for measuring the in-plane thermal diffusivity to evaluate fiber orientation: (**a**) Experimental setup; (**b**) Calculation of the slope $\mathrm{d}\phi/\mathrm{d}r$ for a certain in-plane direction.

2. Evaluation of fiber orientation

The employed method requires no synchronous measurement of the heating signal and temperature response. Figure 1 depicts the procedure for measuring the in-plane thermal diffusivity to evaluate fiber orientation. As depicted in Figure 1(a), a plate is subjected to spot periodic heating using a lamp controlled by a function generator, and its periodic temperature response on the rear surface is measured using an infrared camera. As depicted in Figure 1(b), the slope $\mathrm{d}\phi/\mathrm{d}r$ for a certain in-plane direction is calculated. In Figure 1(b), the center corresponds to a point directly behind the heating spot. Furthermore, the thermal diffusivity for a certain in-plane direction is calculated using the following equation [3].

$$\alpha_{\mathrm{in}}|_{\omega} = \frac{\pi f}{(\mathrm{d}\phi/\mathrm{d}r)^2} \tag{1}$$

where $\alpha_{\mathrm{in}}|_{\omega}$ is the in-plane thermal diffusivity for the direction at an angle ω from the vertical axis and f is the heating frequency. Herein, the phase lag (ϕ) between the periodic heating signal and temperature response is calculated using the following equation.

$$\phi = \theta - \theta_0 \tag{2}$$

where θ and θ_0 are the initial phases of the fundamental harmonic in the periodic temperature response at any point and the center, respectively.

In this study, fiber orientation in CFRP composites is evaluated based on their in-plane thermal diffusivity distribution.

3. Materials and Methods

A square flat plate of a unidirectional carbon fiber composite, fabricated by laminating 10 plies of prepreg sheets via autoclave molding, was utilized. It had a side length of 150 mm and a thickness of 2 mm. In the square flat plate, the mass content of polyacrylonitrile-based continuous carbon fibers in an epoxy resin was 67%, and the carbon fibers were aligned unidirectionally. Herein, this square flat plate is referred to as a UD specimen. Additionally, a blackbody paint was sprayed on the UD specimen's surface.

A halogen lamp capable of heating a spot on the UD specimen's surface with a diameter of 1.5 mm was utilized. The halogen lamp, controlled by a function generator, provided the central portion of the UD specimen with sinusoidal spot periodic heating at a frequency of 0.01 Hz. On the rear side, the temperature distribution images on the UD specimen's surface, subjected to the sinusoidal spot periodic heating, were captured using a non-lock-in type infrared camera with a spatial resolution of 0.2 mm/pixel. Then, the time-series temperature distribution images, consisting of 100 frames with a frame rate of 0.2 Hz, were analyzed in the frequency domain. Consequently, the amplitude and initial phase of the fundamental harmonic in the periodic temperature response were obtained pixel-by-pixel.

4. Results and Discussion

In the experiments to evaluate fiber orientation in CFRP composites, the UD specimen was placed with its carbon fibers oriented horizontally. Figure 2 shows the distributions of the amplitude and initial phase of the fundamental harmonic in the periodic temperature response of the UD specimen. As shown in Figure 2, both the amplitude and initial phase exhibit anisotropic distributions.

The in-plane thermal diffusivity distribution was obtained. First, a point, at which the maximum amplitude of the fundamental harmonic in the periodic temperature response was observed in Figure 2(a), was regarded as the center. Subsequently, the phase lag (ϕ) between the periodic heating signal and temperature response was calculated pixel-by-pixel using the initial phases shown in Figure 2(b) and Equation (2). Finally, the thermal diffusivities for specific in-plane directions were calculated using Equation (1),

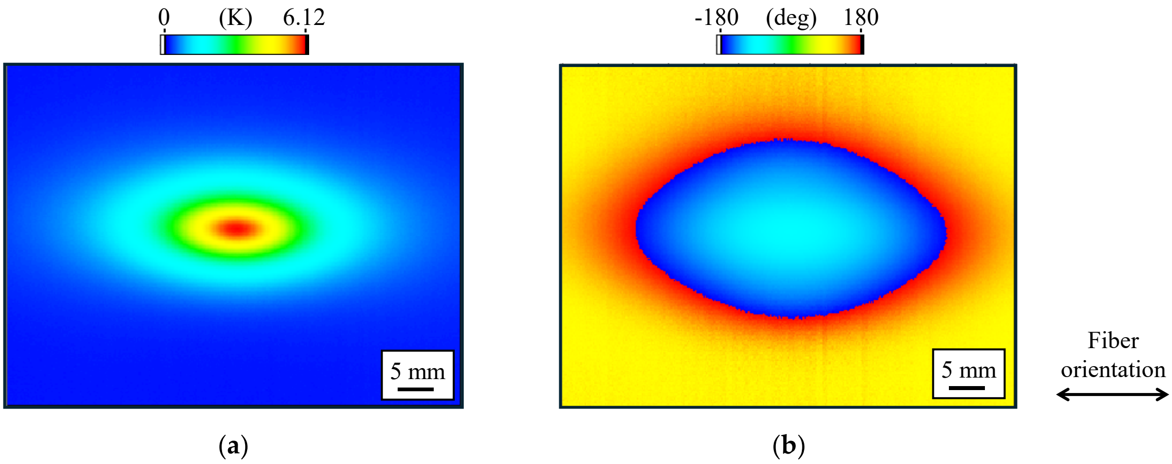

Figure 2. Distributions of the amplitude and initial phase of the fundamental harmonic in the periodic temperature response of the UD specimen placed with its carbon fibers oriented horizontally: (**a**) Amplitude; (**b**) Initial phase.

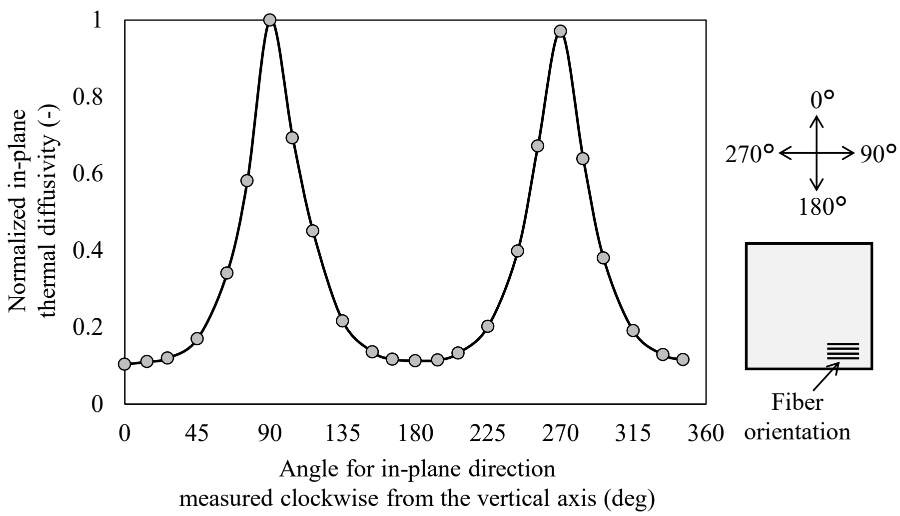

Figure 3. Distribution of the normalized in-plane thermal diffusivity of the UD specimen placed with its carbon fibers oriented horizontally.

and the results are shown in Figure 3. The x-axis values in the figure represent the angles for in-plane directions measured clockwise from the vertical axis. The y-axis values in the figure represent the in-plane thermal diffusivities normalized by the maximum thermal diffusivity among all in-plane directions. The slope $\mathrm{d}\phi/\mathrm{d}r$ was calculated using data in the straight section (2 mm $< r <$ 5 mm) for each in-plane direction. As shown in Figure 3, the in-plane thermal diffusivity in the fiber direction is significantly higher than in other directions. We attributed this anisotropy to the higher thermal diffusivity of carbon fibers than that of the resin. Consequently, the employed method successfully evaluated fiber orientation in the unidirectional carbon fiber composite.

5. Conclusions

In this study, a method for evaluating fiber orientation using halogen spot periodic heating and a non-lock-in type infrared camera was employed and applied to the unidirectional carbon fiber composite. The employed method required no synchronous measurement of the heating signal and temperature response. Experimental results showed that the in-plane thermal diffusivity in the fiber direction was significantly higher than in other directions. We attributed this anisotropy to the higher thermal diffusivity of carbon fibers than that of the resin. Therefore, the employed method successfully evaluated fiber orientation in the unidirectional carbon fiber composite.

Supplementary Materials: No supporting information is publicly available.

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