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Study on in-plane thermal conduction of woven carbon fiber reinforced polymer by infrared thermography

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ABSTRACT

Infrared thermography (IRT) is introduced to measure the in-plane thermal conduction of woven carbon fiber reinforced polymers (CFRP). According to the principle of modulated laser heating, the relationship between the phase gradient and the in-plane thermal diffusivity has been deduced, and the experimental platform was established to test the 6 groups of CFRP test specimens with varied porosity. The measured infrared radiation signal was normalized by taking glassy carbon as the reference material, and the Gaussian filtering was applied to removing the noise of infrared thermal images. The experiment results show that the in-plane thermal conduction law in various directions is related to its conduction direction owing to the anisotropy of the CFRP. The in-plane thermal diffusivity of test specimens with different levels of porosity in each direction can be measured when the modulated laser frequency is lower than 1 Hz. In addition, the thermal diffusivity in each direction decreases with the increase of test specimens' porosity.

1. Introduction

With the development of lightweight construction in the aeronautics and astronautics industry, the new materials in the field of composites are developed and optimized. Nowadays safety-critical structures, such as primary aircraft components, are manufactured from carbon fiber reinforced polymer (CFRP) [1], which is a kind of structural material with high strength, light weight, small thermal expansion coefficient, and many other advantages. CFRP is using resin or rubber as matrix and utilizing carbon fiber or its woven fabric as reinforcement. The fiber-woven structure is one of the important factors that affect the thermal physical properties of CFRP, the existence of anisotropy in CFRP also leads to different thermal performance parameters in different directions [2]. It is inevitable that there will be pore during the manufacturing process of CFRP. The existence of pore not only affects the mechanical properties, but also the thermal performance [3]. Therefore, it is significant to study the influence of the pore on the thermophysical parameters of the composites and to analyze the distribution of thermal conduction inside the materials for ensuring the reliability of CFRP. As a consequence, this work deals with the thermal diffusivity of CFRP with varied porosity by using Infrared thermography (IRT).

IRT represents one of the most promising nondestructive testing and evaluation (NDT&E) technique for the inspection of materials and structures through measuring the emitting infrared radiation. It can collect infrared radiation signals from the surface of the object and obtain the thermal diffusivity of the object through signal processing and thermal image analysis [4]. The surface preparation is not required in advance when using IRT to detect the aerospace composite material. The structure parts with complex shape have stronger adaptability using IRT method [5]. This technique has been used in aerospace composite plastic, unglued, fault and other non-destructive testing [6,7]. American scholars began to try to apply this technology in the aerospace field in a variety of equipment in-service real-time monitoring; European countries have carried out the fatigue damage detection of a large force on the building support with sensitive parts, the inspection of the internal defects of steel bar connection parts etc. [8] Therefore, the IRT has great prospects for application in the near future.

In this paper, IRT is used to study the in-plane thermal conduction law of 6 groups of woven CFRP test specimens with different levels of porosity, and the modulation laser scanning frequency is controlled in the range of 0.1–10 Hz. The experimental apparatus and method were introduced in details, and the experimental results show that there is a

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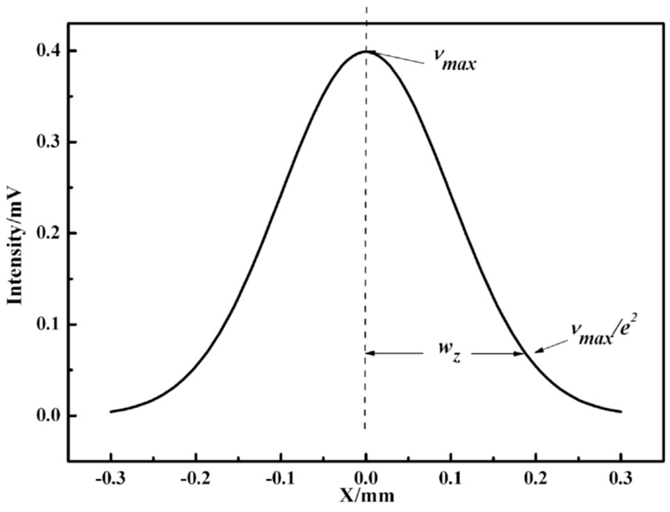

Fig. 1. Gaussian spot lateral distribution.

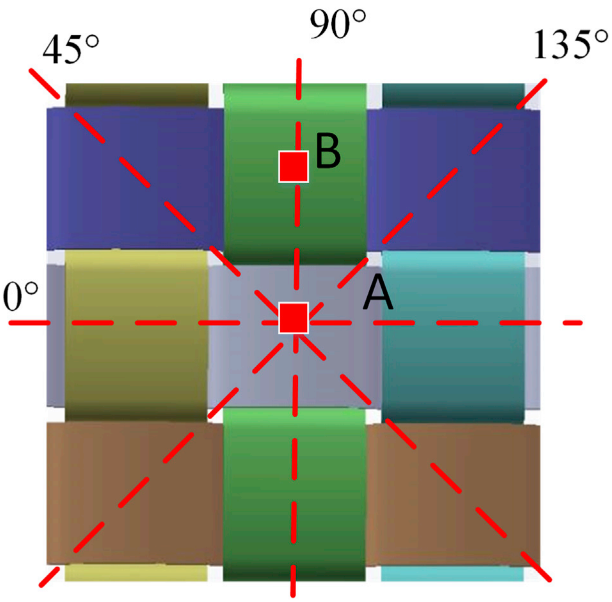

Fig. 2. Structures of fiber preforms.

close relationship between the direction of woven fiber bundle and the in-plane thermal conduction distribution of the CFRP. The thermal diffusivity in each in-plane direction of CFRP can be calculated when the modulation laser scanning frequency is lower than 1 Hz, as a result, the relationship between the thermal diffusivity and the porosity of the CFRP can be obtained.

Table 1
Porosity and thickness of CFRP test specimens.

No.	S1	S2	S3	S4	S5	S6
Porosity (φ,%)	0.00	0.45	1.55	5.30	10.00	18.32
Thickness (L,mm)	4.25	4.36	4.42	4.66	4.83	5.30

2. Theory

2.1. Laser-spot periodic heating method

When a modulation laser projected onto the material surface, it will produce a distribution of temperature field on the surface, which is called "thermal wave". A unifying framework for treating diverse diffusion-related periodic phenomena under the global mathematical label of diffusion-wave fields has been developed by Mandelis [9]. In case of a heat source that heats a point on a thin opaque sample with a modulation frequency f, the AC temperature at the point distant r from the heat source is expressed as follows [10]:

$$T_{AC} = T_0 e^{\mathrm{j}\left(\omega t - \frac{r}{l} - \frac{\pi}{4}\right) - \frac{r}{l}} r^{-1} \tag{1}$$

Where T_0 is constant, and r is the inverse of the thermal diffusion length l.

Heat wave propagation in the material decays particularly fast, and the propagation distance associates with the modulation frequency f, which can be expressed as follows [11]:

$$k = \sqrt{\pi f/\alpha} = l^{-1} \tag{2}$$

At the point r, the phase θ, with respect to the heat source is expressed as:

$$\theta = -kr - \pi/4 \tag{3}$$

Thermal diffusivity, α, is calculated from the spatial dependence of the phase, $d\theta/dr$, can be expressed as follows:

$$d\theta/dr = -\sqrt{\pi f/\alpha} \tag{4}$$

2.2. Gaussian beam laser

In the ideal state, the infrared radiation phase signal presents Gaussian distribution, its transverse sectional chart was shown in Fig. 1, and the in-plane distribution function can be expressed as follows [12]:

$$\begin{cases} f_T(x) = \dfrac{\nu_{\max}}{2\pi\omega_z^2} \exp\left[-\left(\dfrac{x-x_0}{\sqrt{2}\omega_z}\right)^2\right] \\ \omega_z = |X_{\nu_{\max}} - X_{\nu_{\max}/e^2}| \end{cases} \tag{5}$$

Where $\nu_{\max}$ is the maximum value of the infrared radiation signal, and ω_z is the equivalent Gaussian width.

The phase value of ω_z can be calculated when knowing $\nu_{\max}$, the phase slope between the phase peak and the equivalent Gaussian width can be obtained by the once degree polynomial fitting. The phase slope is different due to the number of points taken. The R-square correlation coefficient can be obtained in the polynomial fitting. And if the R-square is closer to 1, the phase slope is more reliable. Therefore, $d\theta/dr$ is calculated, and then it is substituted in Equation (4) to obtain α.

3. Experiment

3.1. Test specimen preparation

The CFRP test specimens examined in this study were made of prepregs of a plain woven structure and the test specimens were fabricated by using 20 ply laminate, the schematic diagram is shown in Fig. 2. The size of image capture area in the specimen is about 2.5 mm × 2 mm. The direction parallel to the weft yarn is defined as a transverse direction (0°), a direction parallel to the warp yarns is a longitudinal direction (90°), a left diagonal direction to the lower right direction is the main-diagonal direction (45°), the direction along the upper right to lower left is the counter-diagonal direction (135°). Taking the specific structure of woven CFRP into account, point A and point B are projected by the modulation laser during the experiment, and they are located at the intersection of longitudinal and transverse fiber bundles. At point A, the thermal wave propagates transversely in the first layer and longitudinally in the second layer along the fiber bundles. While the thermal wave propagates

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