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Inspection on SiC coated carbon–carbon composite with subsurface defects using pulsed thermography

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HIGHLIGHTS

- The heat transfer model has been built and solved.
- Experiments were performed on the built pulsed thermography system.
- SBIM, PPT and TtLFM algorithms are used to process the thermal wave signals.

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ABSTRACT

An investigation on SiC coated carbon–carbon (C/C) composite plates has been undertaken by pulsed thermography. The heat transfer model has been built and the finite element method (FEM) is applied to solve the thermal model. The simulation results show that defects with DA/DP smaller than one can hardly be detected by an infrared camera with the sensitivity of 0.02 °C. Certificated experiments were performed on the built pulsed thermography system. The thermal wave signals have been processed by subtracting background image method (SBIM), pulsed phase thermography (PPT), and temperature–time logarithm fitting method (TtLFM). The limit DA/DP of defects in SiC coated C/C composite plates with the thickness of 6 mm that can be detected by pulsed thermography with the presented signal analysis algorithms has been obtained.

1. Introduction

In recent years, the study of SiC coated C/C composite materials has been of great interest owing to their widespread applications in thermal protection system. However, despite theoretical supposition concerning their uniformity in structure and form, flawless manufacturing techniques are rarely achieved [1–3]. The delamination is one of the most significant damages, which greatly reduces the thermal protection performance of SiC coated C/C composite [4,5]. Many nondestructive testing and evaluation (NDT&E) techniques have been used for delamination inspection and failure analysis of the thermo structural composites. Consistent improvements in infrared camera technology, coupled with the evolution of the personal computer and the standardization of protocols and hardware for high-speed data transfer between camera and computer, have enabled significant growth in the acceptance and implementation of infrared thermography as a nondestructive testing method [6].

Pulsed thermography (PT) is a popular stimulation method in infrared thermography whose protocol consists of pulse heating the specimen and recording the temperature decay with an infrared camera. One reason for the popularity of PT is the quickness of inspection, relying on a short thermal stimulation pulse with duration ranging from a few milliseconds for high-conductivity material (such as metal) to a few seconds for low-conductivity specimens (such as plastics, graphite epoxy laminates). A schematic representation of the method is given in Fig. 1. The temperature of the material changes rapidly after the initial thermal perturbation because the thermal front propagates, by diffusion, under the surface and also because of radiation and convection losses. The presence of a defect reduces the diffusion rate so that when observing the surface temperature, defects appear as areas of different temperatures with respect to a surrounding sound area [7–9].

In the present work, the aim of this investigation focuses on the building and solving the thermal model of SiC coated C/C composite materials under heat pulse excitation. In order to certificate the simulation results, experiments were performed on the built

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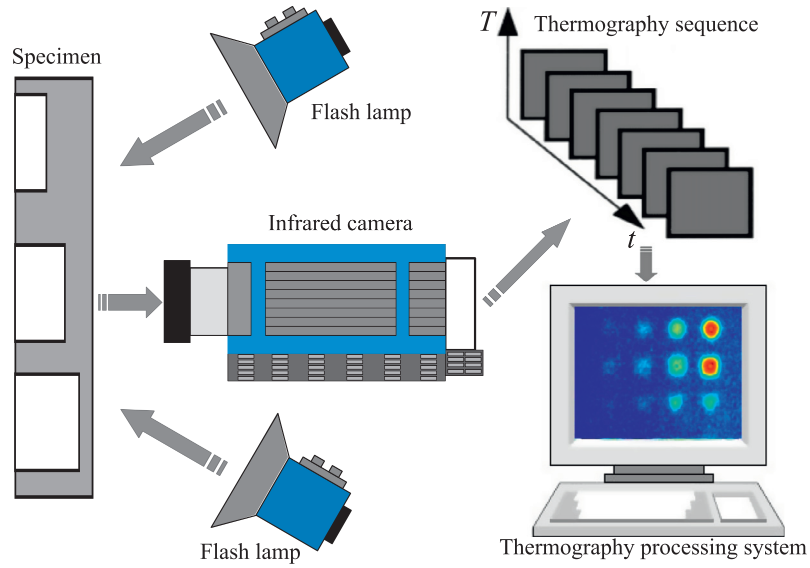

Fig. 1. Schematic representation of pulsed thermography.

pulsed thermography system. Signal analysis algorithms are applied to process the thermal wave signals in order to improve the signal-to-noise ratio. And the limit DA/DP of defects in SiC coated C/C composite materials that can be detected by pulsed thermography with the presented signal analysis algorithms has been obtained.

2. Presentation of the heat transfer model and FEM simulation

2.1. Presentation of the heat transfer model

In this section, the heat transfer model for defects of SiC coated C/C composite detection is established. The relatively uniform SiC layer on the surface of C/C composite is with a thickness of 150–200 μm. Fig. 2 shows the geometry of the test specimens which contain discontinuity defects used in this investigation as well as the defects size are listed in Table 1.

Given (x, y, z) the Cartesian coordinates and (l, L, e) the length, width and thickness of the studied sample, as shown in Fig. 2, and under the assumption that transverse and longitudinal conductivities are uniform in the sample, the following system (balance equation, boundary and initial conditions) is obtained [10].

$$\lambda_x \cdot \frac{\partial^2 T}{\partial x^2} + \lambda_y \cdot \frac{\partial^2 T}{\partial y^2} + \lambda_z \cdot \frac{\partial^2 T}{\partial z^2} = \rho c \cdot \frac{\partial T}{\partial t} \tag{1}$$

The front face net heat pulse flux and the rear face heat flux are established with regard to the convection heat transfer.

$$-\lambda_z \frac{\partial T(x,y,z,t)}{\partial z}\Big|_{z=e} = Q\delta(t) + h_f[T_{am} - T(x,y,0,t)] \tag{2.a}$$

$$-\lambda_z \frac{\partial T(x,y,z,t)}{\partial z}\Big|_{z=0} = h_r[T_{am} - T(x,y,0,t)] \tag{2.b}$$

The SiC coated C/C composite domain is assumed to insulate heat flows on the other boundaries.

$$-\lambda_x \frac{\partial T(x,y,z,t)}{\partial x}\Big|_{x=0} = -\lambda_x \frac{\partial T(x,y,z,t)}{\partial x}\Big|_{x=l} = 0 \tag{2.c}$$

$$-\lambda_y \frac{\partial T(x,y,z,t)}{\partial y}\Big|_{y=0} = -\lambda_y \frac{\partial T(x,y,z,t)}{\partial y}\Big|_{y=L} = 0 \tag{2.d}$$

The initial condition expresses the temperature distribution in the whole domain at the time $t = 0$.

$$T(x,y,z,t)|_{t=0} = T(x,y,z,0) = T_{am} \tag{3}$$

where $T(x, y, z, t)$ designates the temperature of the pixel at location (x, y, z) at time t; λ_x, λ_y, λ_z are the thermal conductivities in the x, y, and z directions; ρ and c are the mass density and specific heat, respectively; Q is the pulse intensity; $\delta(t)$ is the Dirac function; h_f and h_r are the convective heat transfer coefficient of the front and rear face of the specimen; T_{am} is the ambient temperature.

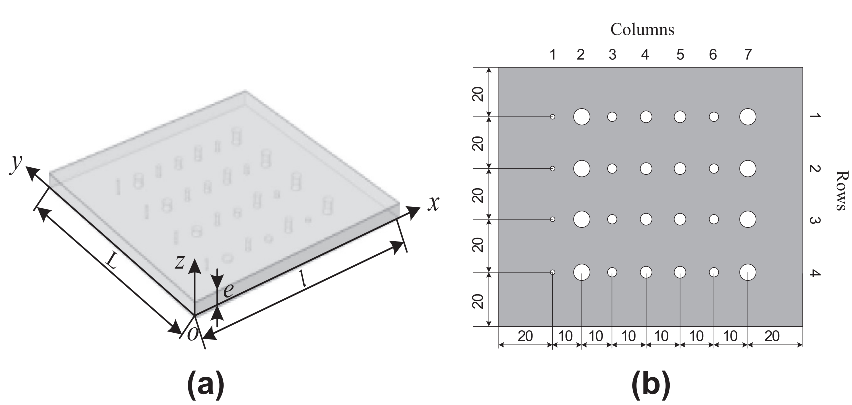

Fig. 2. Geometric model of the studied samples: (a) 3D model and (b) 2D model.