In-plane Thermal Diffusivity Measurements of C/C Brakes Using Thermography

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ABSTRACT

In order to evaluate the in-plane thermal diffusivity of C/C brake, infrared thermography with periodic mask is used The principal characteristic is that the thermal diffusion along in-plane must to be generated. Here, heat is still applied to the front face of the sample by flash lamps and the periodic mask is added between the specimen and the lamps. After flashing, the heat is distributed over the rear face with such a designed periodic pattern along principle in-plane direction. The thermography is then performed to record the entire transient temperature image on the rear face of the sample. The masks were specially designed to determine the radial and circumferential diffusivities by generating heat gradient along these two orthotropic directions on the carbon disk sample. The period was carefully chosen as a function of sample thickness and an estimation of the ratio of through-thickness and in-plane diffusivity. The in-plane thermal diffusivity profile is then obtained by doing a Fourier transform analysis over one period of the grid mask. The results represented the average diffusivity value in that one period area. The tests have been conducted for aluminum plate and half C/C specimen. The resulting in plane diffusivity then compared with the value obtained from conventional laser flash method and literatures.

Keywords: Infrared thermography, in-plane, thermal diffusivity, C/C composites, flash technique.

1 INTRODUCTION

Many C/C composite materials are used for their thermal characteristics, as in the case of the C/C brakes and thermal protections for hypersonic vehicles. Thermal diffusivity, as a fundamental property of the material, is one of the important parameters when heat transfer phenomena are involved. The research work provided a method capable of determining the whole-filed through-thickness thermal diffusivity of brake pads. For carbon brakes, the ratio of in-plane diffusivity to through-thickness diffusivity is one of important parameters to maintain the composites in high performance. This addressed the needs of in-plane thermal diffusivity evaluation for the thermal characteristic. A thermography technique with mask will present a flash method for simultaneously imaging the in-plane diffusivity of anisotropic composites over the entire sample.

Thermographic methods for measuring in-plane thermal diffusivity of anisotropic samples are reported [1, 2]. One of the proposed procedures consists of applying any geometrically non-uniform heat impulse on the front face and recording the entire transient temperature image on the rear face. The approach has two limitations: the sample must be a thin plate; the sample must be pained with a uniform emissivity paint to achieve accurate rear face temperature. Another procedure drew a preliminary result by using a shadow mask for the measurement of thermal diffusivity of anisothropic materials in three orthogonal directions. These thermographic techniques typically can allow one to measure the in-plane diffusivity that is mostly very difficult to be estimated by the conventional methods. And they are especially of value for characterizing anisotropic samples from a thermal point of view. Some techniques and their theoretical assumption s are only limited to a thin rectangular plate [3, 4]. One of them presents a thermographic technique inducing a continuous lamp heat to the front surface of a plate sample by a circular Gaussian source. The in-pane thermal diffusivity is obtained by monitoring the temperature changes of the rear face by an infrared camera [5]. However, this method can only work out for isotropic material. The methods used for determining the in-plane diffusivity exploit the in-plane heat diffusion subsequent to non-uniform heating of the sample surface by using non-uniform heat source or masking the sample surface in a suitable way with a uniform source. So the thermal diffusivity can be obtained by analyzing the time evolution or spatial distribution of the temperature on the rear surface of the sample.

2 THEORETICAL MODEL

The flash thermography technique with a periodic mask relies on the use of a grid mask between the flash lamp and the inspected material. An IR camera is monitoring the temperature on the rear surface of the sample.

The thermal images might be analyzed under a global point of view or focusing on a local treatment of the thermal signal. With local data analysis, one can obtain an average value of the diffusivities on the interested local area. Thus, focusing the analysis on areas limited to one mask's period may achieve the requested diffusivity values.

After the light pulse the appearance of a periodic pattern, the growth and decrease of heat diffusion can be observed. The temperature on the rear face of the sample disk is monitored by the IR camera.

A schematic diagram of a transient thermography system with grid mask is shown in Figure 1. The data can be easily stored as digital thermal images and temperature profiles for further analysis and retrieval. To obtain thermal diffusivity in ambient temperature, a very short burst of heat can be introduced the front surface by flash lamps, and the temperature rise is investigated at rear face. The two-sided configuration points to the chosen mask geometry and orientation, which helps to image the profiles of the principal diffusivity in x directions. The diffusivity in y direction could be obtained by rotating the mask 90º.

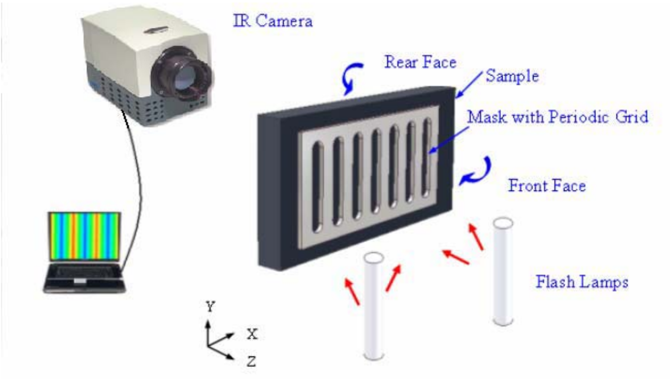

Figure 1. A typical transient thermography system with grid-like mask

The hypothesis of the periodic grid-mask model that has been considered for the heat transition is:

- Linear heat losses on front and rear faces
- Infinite plate with uniform thickness
- Uniform initial temperature distribution
- Flash pulse with non-uniform distribution along in-plane
- Recording of the temperature distribution on the rear side

The heat equation, boundary conditions with heat loss on both surfaces are:

$$\rho c\frac{\partial T}{\partial t}=k_x\frac{\partial^2 T}{\partial x^2}+k_y\frac{\partial^2 T}{\partial y^2}+k_z\frac{\partial^2 T}{\partial z^2} \tag{1}$$

$$T(x,y,z,0)=Q(x,y)Q_z(z)/\rho c \tag{2}$$

$$-k_z\frac{\partial T}{\partial z}\Big|_{z=0}=-h_0T(x,y,0,t),\quad -k_z\frac{\partial T}{\partial z}\Big|_{z=l}=-h_lT(x,y,l,t), \tag{3}$$

Through a Fourier transform in x and y directions, followed by a Laplace transform on time varible, the Fourier transforms of the temperature at (ω_x,ω_y) and at (0, 0) is:

$$\tilde{\tilde{T}}(\omega_x,\omega_y,z,t)/\tilde{\tilde{T}}(0,0,z,t)=\tilde{\tilde{Q}}(\omega_x,\omega_y)/\tilde{\tilde{Q}}(0,0)\exp(-a_x\omega_x{}^2t-a_y\omega_y{}^2t) \tag{4}$$

For x-direction diffusivity measurement, $\omega_x=2\,\pi/\Delta$, $\omega_y=0$, the data are averaged along the y-direction, The mean temperature *T(0,0,z,t)* is obtained by averaging temperatures along x and y direction.:

$$\tilde{\tilde{T}}(\omega_x,0,z,t)/\tilde{\tilde{T}}(0,0,z,t)=\tilde{\tilde{Q}}(\omega_x,0)/\tilde{\tilde{Q}}(0,0)\exp(-a_x\omega_x{}^2t) \tag{5}$$

The following linear relationship can be used in order to infer the in-plane thermal diffusivity:

$$Ln\left[\tilde{\tilde{T}}(\omega_x,0,z,t)/\tilde{\tilde{T}}(0,0,z,t)\right]=Ln\left[\tilde{\tilde{Q}}(\omega_x,0)/\tilde{\tilde{Q}}(0,0)\right]-a_x\omega_x{}^2t \tag{6}$$

At the rear face of the sample, $z = l$, the thermal diffusivity in x direction a_x can be evaluated by getting the slope of Eq.6.

In order to properly choose the period Δ (grid pitch), an assumption on the ratio of the two principle diffusivities has to be made. The *thermal aspect ratio* A is introduced below to consider periodic pattern with respect to the sample thickness ***l*** [2]:

$$A = \frac{\Delta}{l}\sqrt{\frac{\alpha_z}{\alpha_x}}$$

The accuracy of the measurements increases with *A* increasing. When A is greater than 4-5, the improvement for the accuracy is negligible.

3 EXPERIMENTAL SET UP

Sample Description and Mask Design

The experiments were performed on an aluminum 6061-T6 plate and a half C/C disk HWCCD as shown in figure 2. The aluminum alloy plate has dimension of 380×280×6.43 mm. The C/C disk, which is unmachined and non-heat treated, has outer diameter of 368 mm, inner diameter of 200 mm and thickness of 19.5mm. The Al specimen was painted by graphite black to enhance the surface emissivity.

C/C disk

Al alloy plate

Figure 2. Specimen used in in-plane diffusivity measurement by thermography

The Masks were made by Al 4032. Because of the low emissivity of the Al surface, the heat flow will be reflected by the masked area, so that the heat radiance can only pass through the apertures on the masks. In figure 3, two masks were specially designed for circumferential (X direction) and radial (Y direction) diffusivity measurements.

A

B

Figure 3. A) Mask for circumferential diffusivity (α_x) measurement of C/C disk, B) Mask for radial diffusivity (α_y) measurement of C/C disk.

Description of Instruments Setup

In the experiments, the infrared camera INDIGO PHOENIX working with TWI (Thermal Wave Imaging) system was used. The IR camera with wave length 3-5 μm is able to generate 640×511 pixels focal plane array to create infrared images at 60 Hz frequency rate. The heat source is applied by two Xenon megawatt flash lamps, which generated 22.4 kJ/m^2 energy within 0.004 seconds. The space between the specimen and the mask is 1 mm.

4 EXPERIMENTAL RESULTS

Two principle in-plane diffusivity tests on C/C/ disk and one x-direction diffusivity test on Al plate sample have been conducted for in-plane diffusivity determination. The total measurement time is 22 seconds for 19.5 mm thick carbon disk and 0.8 seconds for 6.43 mm thick Al sample.

For circumferential diffusivity measurement of carbon disk, across one period window, temperature files were extracted from the arrayed points on the rear side. Each point represents 5×5 pixels. The normalized temperature averaged along the radial and circumferential directions across one period, which is the mean temperature T_0 shown in figure 5. In one period, the normalized temperatures averaged only along the radial direction were used to perform the Fourier transform at spatial pulsation $\omega_x=2\pi/\Delta$. The resulting temperature spatial amplitude (T_1) at frequency Δ^{-1} can be obtained. For a particular position of the Δ-window, the first Fourier component of temperature $T_1(t)$ vs. time were plotted in figure 6. Thus, the circumferential diffusivity identification was based on the analysis of Ln[(T(1)/T(0)] vs. $\omega^2 t$. The equation 6 reduces to a linear regression where time is the independent variable. The slope yields the local value of $-a_x \omega_x{}^2$.

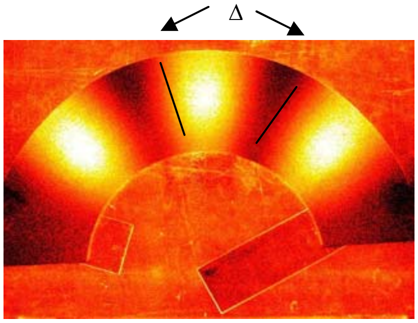

Figure 4. Thermal Image taken after the flash pulse on the side of the disk specimen.

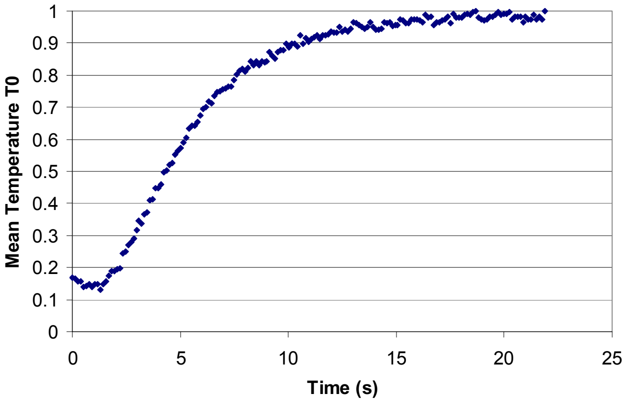

Figure 5. Mean temperature T0 averaged in X and Y direction

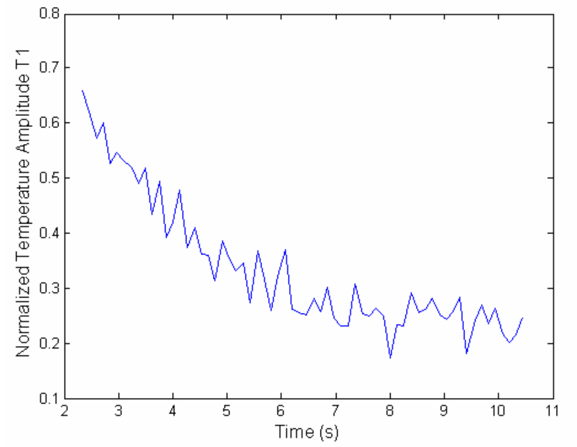

Figure 6. A fast Fourier transform of normalized temperature averaged along Y over one period

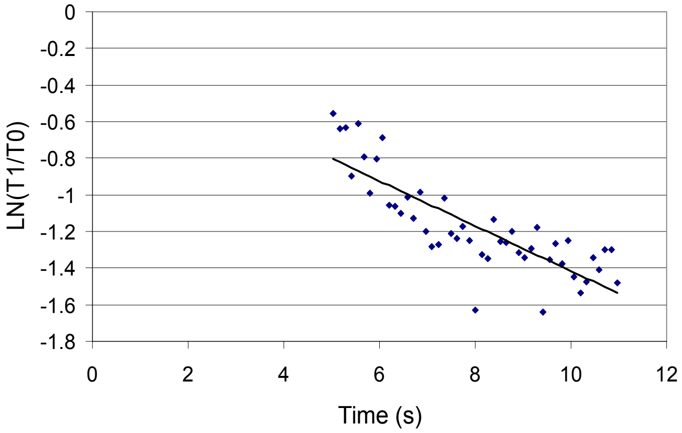

Figure 7. For a Particular position of one Δ period window, the observable variable Ln[(T(1)/T(0)] vs. time is plotted for circumferential diffusivity identification of C/C brake.

Similar analysis was performed for diffusivities determination in radial direction for carbon disk and in X direction for Al alloy plate, respectively. Figure 8 shows thermal images extracted from the measurements of radial diffusivity in C/C sample and in-plane diffusivity in Al alloy sample. The results indicated the average value of diffusivity of selected area across period Δ.

(a)

(b)

Figure 8. (a) Thermal image for radial diffusivity determination of C/C brake, (b) thermal image for In-plane diffusivity determination of Al plate sample

In Table 1, the thermal diffusivity value obtained from the infrared thermography method was compared to the value given by laser flash method or literature. The diffusivity measurements using laser flash method were also performed. The samples with

10 mm diameter and 5mm thickness were prepared from the same specimen used in the thermography method. Before laser heating, the sample front surface was painted with graphite black.

Table 1. Data comparison with other resources

Samples	Thermal diffusivity (cm^2/s)				
	Infrared Thermography		Laser flash	Published
Al plate (isotropic)	X	0.697±0.022	0.726	0.690
	Y	-	-	-
C/C brake (Orthotropic)	X	0.388±0.033	0.265±0.016	-
	Y	0.0464±0.015	0.101±0.0015	-

5 DISSCUSSION

The test shall be performed on certain number of measurements by turning the disk sample in different positions relatively to the mask and the heat source to evaluate the result dispersion and influence of heat flux non-uniformity. The small period, limited by the width of the brake, led to diffusivity measurement error in the radial direction of C/C brake. The differences of the diffusivity from the Thermography method and other methods may lie in the following factors:

- Calibration of the infrared camera
- Uniformity adjustment of heat
- Ambient temperature influence
- Sudden large temperature increase at the front surface
- Proper selection of the period Δ
- The surface treatment between laser and thermography methods (graphite coating or not)
- Numbers of data point extraction
- Accuracy of the IR camera

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