Porosity Measurement in Laminate Composites By Thermography and FEA

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ABSTRACT

This paper presents the correlation between the through-thickness thermal diffusivity and the porosity of composites. Finite element analysis (FEA) was used to determine the transient thermal response of composites that were subjected to laser heating. Series of finite element models were built and thermal responses for isotropic and orthographic materials with various thermal diffusivities subjected to different heating conditions were investigated. Experiments were conducted to verify the models and to estimate the unknown parameters such as the amount of heat flux. The analysis and experimental results show good correlation between thermal diffusivity and porosity in the composite materials. They also show that both laser and flash heating can be used effectively to obtain thermal diffusivity. The current infrared thermography system is developed for use with flash heating. The laser heating models and the FEA results can provide useful tools to develop practical thermal diffusivity measurement scheme using laser heat.

Keywords: porosity, NDE, thermography, thermal diffusivity, thermal contrast, composite materials, FEA modeling.

1   INTRODUCTION

Laminate composite materials have been used in aerospace structures for many years. Recently, efforts have been made in designing and constructing composite cryogenic fuel tanks and feedlines. The porosity and cracking are two critical properties that affect the performance of the composite structures and tanks. This paper describes the use of finite element analysis to model the thermal response in laminate composite panels which are subjected to laser heating. Finite element models of composite panels with various thermal diffusivities were built and analyzed. The results were used to determine the correlation between porosity and thermal diffusivity in the panel.

The porosity and cracking in a composite panel usually reduce its through-thickness thermal diffusivity. Studies have shown a good correlation between porosity and the apparent thermal diffusivity. Connolly used a high power laser to heat one side of the composites and observed the thermal response on the other side [1]. The porosity and defects modify the apparent thermal diffusivity and reduce the heat flux to the rear face. The results show that the temperature rise on the rear face is lower for samples with high porosity. The time for the temperature to reach its maximum value is also longer for high porosity samples. Zalameda measured the through-the-thickness thermal diffusivity of laminate composites using infrared thermography system with flash lamps as the heat source [2]. Although the focus was to study the potential of imaging the fiber volume fraction in composites, the results show a good correlation between apparent thermal diffusivity and the porosity.

The TIA-PC thermal imaging system developed by NDE Branch at NASA Langley Research Center is designed to obtain diffusivity map of a panel with front-side uniform pulse heating and rear-side imaging [3]. Basically, the temperature-time curve (T-t curve) of every pixel on the thermal image is curve-fitted using Lavenberg-Marquardt method with the equations that are the solution to the heat conduction equation. The parameter αL^2 is determined from the best least squares fit, where α is the thermal diffusivity and L is the thickness of the panel. With known panel thickness L, the diffusivity map can be generated easily. Figure 1 shows the normalized thermal response based on this analytical solution.

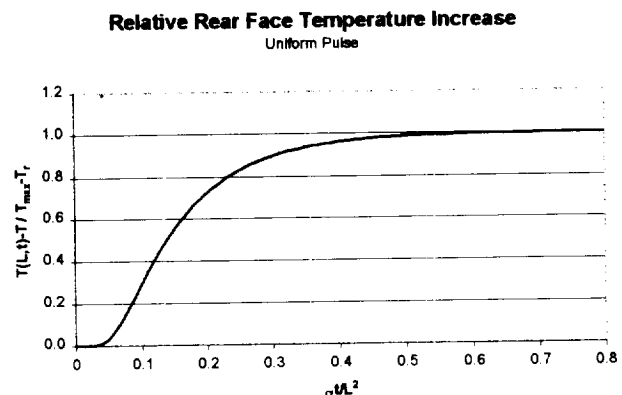**Relative Rear Face Temperature Increase**
Uniform Pulse

Figure 1. Normalized thermal response of a panel subjected

To determine the thermal diffusivity in the in-plane direction for anisotropic materials, a laser-heating source can provide some information on the diffusivity values in the principal directions.

Fatigue cracking may reduce the thermal diffusivity in the in-plane directions. By comparing the thermal diffusivity, values before and after fatigue cracking developed may provide some measurement on the degree of damage. Laser coupled with fiber optics can also provide heating to areas that are difficult to use the flash lamps. Experiments conducted earlier by the NDE group at NASA/MSFC have shown some good correlation between porosity and thermal diffusivity using laser-heating method (Figure 2). This shows that flash heating and laser heating can both be used to measure porosity in composite materials.
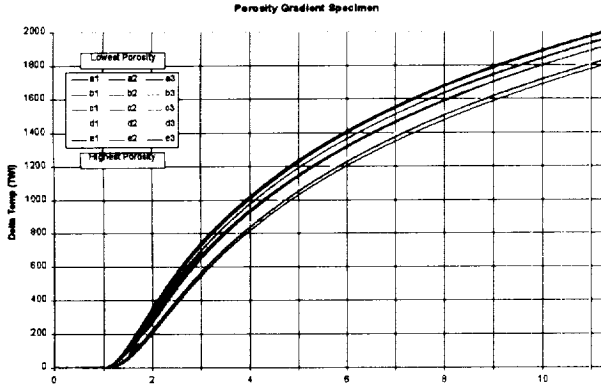

Figure 2. ΔT-t curves of porosity gradient specimen inspected by TWI thermographic system using laser heating source

2 THEORETICAL BACKGROUND

The general heat conduction equation for homogeneous anisotropic solids is

$$\rho c \frac{\partial T}{\partial t} = k_x \frac{\partial^2 T}{\partial x^2} + k_y \frac{\partial^2 T}{\partial y^2} + k_z \frac{\partial^2 T}{\partial z^2} + u'''$$

where k_x, k_y, and k_z are the thermal conductivities in three principal directions and u''' is the rate of heat generated per unit volume. For uniform heat pulse applied to one face of an infinite plate, the heat equation is reduced to

$$\frac{\partial T}{\partial t} = a \frac{\partial^2 T}{\partial x^2}$$

where $\alpha = \frac{k}{\rho c}$ is the through-the-thickness thermal diffusivity. Assume the thickness of the plate is L, the boundary conditions are

$$\frac{\partial T(0,t)}{\partial x} = \frac{\partial T(L,t)}{\partial x} = 0, \qquad t > 0$$

The general solution to the heat conduction equation is [4]

$$T(x,t) = \frac{1}{L} \int_0^L f(x)dx + \frac{2}{L}\sum_{n=1}^{\infty} \exp(-n^2\pi^2\alpha t/L^2) \times \cos\frac{n\pi x}{L} \int_0^L f(x)\cos\frac{n\pi x}{L} d ,$$

where $n = 1,2,3 \cdots \infty$. The function $f(x)$ represents the temperature distribution in the plate caused by the heat pulse Q absorbed in a thin layer g. The initial conditions are

$$f(x) = Q / \rho c g, \qquad 0 \le x \le g$$
$$f(x) = 0, \qquad g < x \le L$$

For a small ratio of g/L and at rear face $x = L$,

$$V(L,t) = \frac{T(L,t) - T_r}{T_{Lmax} - T_r} = 1 + 2\sum_{n=1}^{\infty}(-1)^n e^{-(n\pi)^2 \frac{\alpha t}{L^2}}$$

where T_{Lmax} is the maximum temperature and T_r is the initial reference temperature. When $t \to \infty$, $T_{Lmax} - T_r = Q/\rho c L$.

Connolly [1] solved the heat conduction equation for isotropic materials for the case of Gaussian laser source. He obtained a general solution by using Green's function for a point source and integrated it with Gaussian heat flux. The full solution for the thermal response at a point at the opposite side of the laser source is then obtained by further integration of the general solution. The solution consists two parts, the first reflects the influence of the uniform heat and the second represents the Gaussian heat distribution. The solution is expressed in an infinite series form. To obtain the thermal diffusivity, the measured thermal response at rear side is curve-fitted to the equation representing the approximate solution. The solution is not exact and cannot be used for anisotropic materials. FEA model can be used to modify the analytical results for orthotropic materials to obtain accurate thermal responses.

3 FINITE ELEMENT ANALYSIS

Finite element analysis (FEA) has been successfully used to model defects in composite panels in order to determine the optimal thermographic inspection parameters [5]. It has also been used to study the effect of thermal diffusivity on the detectability of thermographic non-destructive evaluation [6]. Series of finite element models (FEM) have been built to determine the effectiveness of the diffusivity mapping techniques using thermography.

A set of quarter-symmetric finite element models was built. The model represents a small region centered at the laser heat source. The radius of the plate is 5 mm and the thickness is 1.5 mm. A laser heat flux is applied to the center of the plate (corner of the model). The radius of the laser heating area is assumed to be 0.35 mm. The model has 10 layers of elements through the thickness. Each layer is meshed into 155 elements. The thermal conductivity of the model is modified for various materials. Heat flux and time curves are also modified for different cases. Following is a description of these models.

- Sets of thermal conductivity values were used to study the thermal responses for isotropic, quasi-isotropic, and orthotropic materials.
- Various conductivity values were used for isotropic FEA models to determine the effect of diffusivity on thermal responses.
- Time curves with duration of one, two, three, and four-second heat flux duration were generated to modify FEA models to determine the effect of heat length.

- Conductivity values were also changed for orthotropic FEA models. The objective is to develop methods to measure in-plane thermal diffusivity.

Series of models of rectangular shapes were also built to study the thermal response of a pulse heat from flash lamps. The results were compared to the analytical solutions. This model is very useful in generating T-t (temperature rise vs. time) curves on both sides of the plate. This model and a spreadsheet Excel file based on the analytical solutions provide very efficient tools to estimate the temperature rise.

Unit cell FEM was considered originally to investigate the effect of porosity pore sizes and shapes on the apparent thermal diffusivity. However, from existing study on C/C composite, the effect seems very small. Nevertheless, unit cell micro-FEM should be built and analyzed in the future to gain more insight to the pore size and shape effects.

4 RESULTS AND DISCUSSION

The thermal response of continuous laser heating of plates with different thermal diffusivity shows that for materials with lower thermal diffusivity, the heat arrives slower to the rear side than the higher diffusivity materials. However, the temperature for the lower-diffusivity material becomes higher at later stage because the heat is slow conducting laterally. Theses curves can be used to determine the duration of laser heat required to generate enough thermal contrast for reasonable measurements. The effect of laser heating duration can be seen from the resulting T-t curves from FEA. These curves show that the maximum temperature does not occur immediately after the laser is shut down because the heat is still conducting to the rear face. The time for the temperature to reach its maximum after laser heating is longer for shorter heat duration.

Experiments were conducted on an IM6/3501-6 composite panel with [0, 45, 90, -45]s lay-up. A Coherent DPSS model 532-400 Nd:YAG laser was used as heat source. The output power is 400mW and the beam diameter is 0.7 mm. The duration of laser heating time ranges from 1, 2, 3, 4, 5 to 10 seconds. The trends of thermal response are similar to those predicted by the FEA. Figure 3 shows the thermal responses for materials with thermal diffusivity of 2.04, 3.06, and 4.08 x 10^{-7} m^2/sec with one-second laser heating. The T-t curves show that, for lower diffusivity, the temperature at the rear side opposite to laser heat is higher and the time required to reach the maximum temperature is longer.

To determine the laser heat flux for future FEM, experiments were conducted on an aluminum block which was painted black to increase the emissivity. Flash heating was used to determine the thermal diffusivity of the block which was estimated to be 5.3 x 10^{-5} m^2/sec. The temperature rise on the rear surface is 0.54 °C. The block was measured and the density was calculated to be 2365.6 kg/m^3. Using specific heat c = 883 J/kg-K obtained from the handbook, the heat flux from the flash lamps is calculated to be 2900 kW/m^2. The laser heat flux and distribution can be calculated by building more FEM using the experimental data.
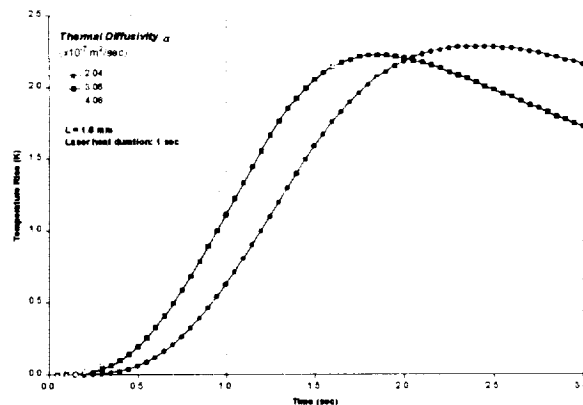

Figure 3. Thermal response with one second laser heating for materials with various thermal diffusivities

Tests were also conducted on the IM6/3501-6 composite panel using different lamps to heat the entire front surface. The TIA-PC thermal imaging system was used to observe the thermal responses on the rear face. Thermal diffusivity was calculated using the software function provided with the system. Table 1 shows the average thermal diffusivity values obtained from the TIA-PC system with two different heat sources and the comparison to the calculated values based on the property data found in handbooks. Apparently the duration of heat using long exposure heat lamps seems have no effect on the measured diffusivity values from TIA-PC. However, since the software is based on the analytical solution with the assumption of very short heat pulse, using flash lamp should provide more accurate measurement with the current system.

Table 1. Thermal diffusivity measured from TIA-PC with various heat sources

Source	Thermal Diffusivity (m^2/sec)
Heat lamps 1 second	3.7 x 10^{-7}
Heat lamps 0.33 second	3.7 x 10^{-7}
Flash lamp 0.004 second	4.7 x 10^{-7}
Calculated value (60% fiber volume fraction)	3.62 x 10^{-7}
Calculated value (65% fiber volume fraction)	4.09 x 10^{-7}
Calculated value (70% fiber volume fraction)	4.66 x 10^{-7}

The spatial distribution of temperature contours of orthotropic materials subjected to laser heating can be used to determine the thermal diffusivity in the in-plane direction. It may also be used to find fatigue cracking due to thermal cycling. An FEM with thermal properties of IM6/3501-6 was built to simulate the effect of one-second laser heating. The temperature distribution on the laser heating side along two principal directions at t = 1 second were obtained by generating two path graphs from the FEA results. By comparing these two curves, the thermal diffusivity along both principal directions can be determined. A temperature contour map is shown in Figure 4. During the laser heating period, it seems that the shape of the temperature curve remains the same.
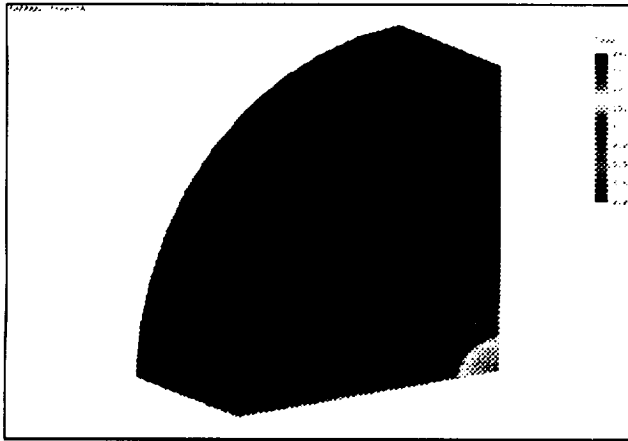
Figure 4. Contour map showing temperature rise on the front face of the IM6/3501-6 FEA model at t = 1 second.

5 CONCLUSION AND RECOMMENDATIONS

Series of FEM were built and thermal responses for various types of materials subjected to different heating conditions were investigated. Experiments were conducted to verify the models and to estimate the unknown parameters such as heat flux. The analysis and experimental results show good correlation between thermal diffusivity and porosity in the composite materials. They also show that both laser and flash heating can be used effectively to obtain thermal diffusivity. The current TIA-PC system is developed for use with flash heating. The laser heating models and FEA results can provide useful tools to develop practical diffusivity measurement scheme using laser heating.

The following is a list of recommendations based on the findings of the tasked work and the need to better understanding the current techniques as well as providing more accurate measurements with confidence.

- Shadow masking the test articles during flash heating may provide information on in-plane diffusivity.

- Modify the laser heat flux applied to the finite element model to reflect the Gaussian distribution of the laser beam. Comparison should be made between the new model and the previous one. The change in thermal diffusivity measurement of using Gaussian laser heat flux model should be small. However, it may slightly change the temperature contours close to the heat source.

- The laser FEA model is not large enough to reflect the true size of the composite plate. The temperature may be higher for high diffusivity materials with small model. The size restriction is due to the limits of the computer. Larger models should be built and analyzed to see the effect of model sizes. Since the thermal diffusivity of the current models is somewhat small, the results should be fairly accurate.

- Effects of uniform heating duration should be investigated. The flash heating FEM can be modified with proper heat flux values and time curves. A series of calibration curves may be obtained for various heat sources and duration for use with the current TIA-PC system.

From the results and the information gathered so far, it seems that using a reference panel may be necessary in order to obtain quantitative measurements of apparent diffusivity. The matrix, fiber volume fraction, and the porosity affect the apparent diffusivity. The results from unit-cell models should tell us the effect of the pore shape and distributions. The recommended future work will definitely provide more insight to improve the current techniques and help develop practical approaches for porosity and fatigue cracking measurements.

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