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Thermal Imaging and Air-Coupled Ultrasound Characterization of a Continuous-Fiber Ceramic Composite Panels*

by

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DISCLAIMER

THERMAL IMAGING AND AIR-COUPLED ULTRASOUND CHARACTERIZATION OF A CONTINUOUS FIBER CERAMIC COMPOSITE

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SYLRAMIC™ continuous fiber ceramic-matrix composites (Nicalon™ fiber/SiNC matrix) were fabricated by Dow Corning Corporation with the polymer-impregnation and pyrolysis (PIP) process. The composite macrostructure and its uniformity, and the completeness of infiltration during processing were studied as a function of number of PIP cycles. Two nondestructive evaluation (NDE) methods, i.e., infrared thermal imaging and air-coupled ultrasound (UT), were used to investigate flat composite panels of two thicknesses and various sizes. The thermal imaging method provided two-dimensional (2D) images of through-thickness thermal diffusivity distributions, and the air-coupled UT method provided 2D images of through-thickness ultrasonic transmission of the panel components. Results from both types of NDEs were compared at various PIP cycles during fabrication of the composites. A delaminated region was clearly detected and its progressive repair was monitored during processing. The NDE data were also correlated to results obtained from destructive characterization.

INTRODUCTION

SYLRAMIC™ continuous fiber ceramic-matrix composites (Nicalon™ fiber/SiNC matrix) used in this study were fabricated by a polymer-impregnation and pyrolysis (PIP) process developed by Dow Corning Corporation. During PIP processing, the composite macrostructure and its uniformity must be controlled to obtain a desired final density or open porosity. Typically, 15 PIP processing cycles are required to reduce the open porosity to the desired level (e.g., <5%).

In this study, two nondestructive evaluation (NDE) methods, i.e., infrared (IR) thermal imaging and air-coupled ultrasound (UT), were used to investigate flat composite panels of two thicknesses and various sizes after several PIP cycles. The thermal imaging method provided two-dimensional (2D) images of through-thickness thermal diffusivity distributions, and the air-coupled UT method provided 2D images of through-thickness ultrasonic transmission of the panel components. A delaminated region was clearly detected and its progressive repair during processing was monitored. Results from the two NDEs were correlated and compared with results from destructive characterization.

THERMAL DIFFUSIVITY MEASUREMENT SYSTEM

The experimental apparatus for measuring through-thickness thermal diffusivity is illustrated in Fig. 1. The apparatus includes an IR camera that consists of a focal-plane array of 256 x 256 InSb detectors, a 200 Mhz Pentium-based PC equipped with a digital frame grabber, a flash lamp system for the thermal impulse, a function generator to operate the camera, and a dualtiming-trigger circuit for the camera and external trigger control. An analog video system is used to monitor the experiments. Processing time to measure a typical diffusivity image with 256 x 256 pixels ranges from 8 to 20 min, depending on the number of frames taken.

The thermal diffusivity is calculated on the basis of the theory of Parker et al. (1961), which assumes that the front surface of the sample is heated instantaneously. The rate of heat conduction through the sample, which is related to the thermal diffusivity of the material, is determined by measuring the speed of temperature rise at the back surface. Figure 2 shows theoretically predicted back-surface temperature T as a function of time t and specimen thickness L, where T_M is the maximum back-surface temperature and α is the thermal diffusivity. One method to determine the thermal diffusivity is the "half-rise-time" ($t_{1/2}$) method. When the back-surface temperature rise has reached half of its maximum, i.e., $T/T_M = 0.5$, we have $\alpha = 1.37L^2/\pi^2 t_{1/2}$. The accuracy of the thermal diffusivity measurement determined by this method has been calibrated with a NIST standard graphite specimen (Stuckey et al., 1997).

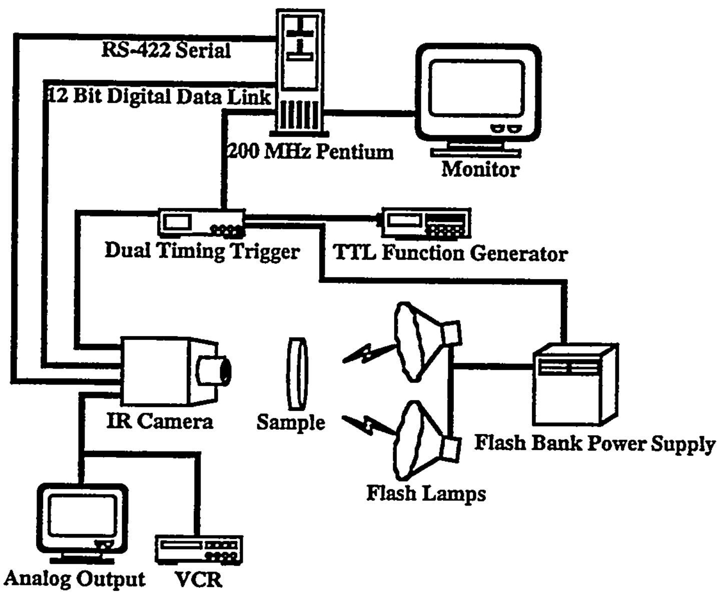


Fig 1. Schematic diagram of experimental thermal imaging apparatus.

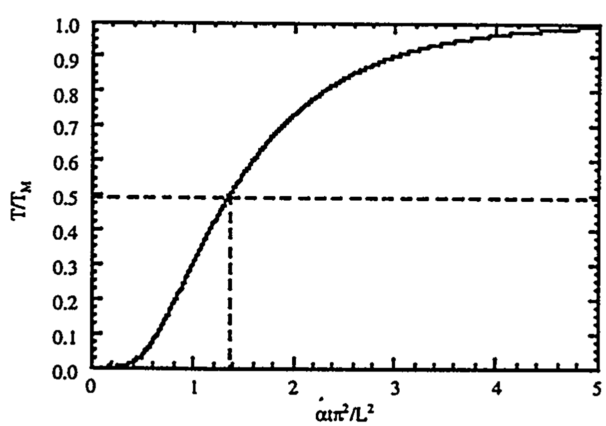


Fig. 2. Theoretical prediction of back-surface temperature rise.

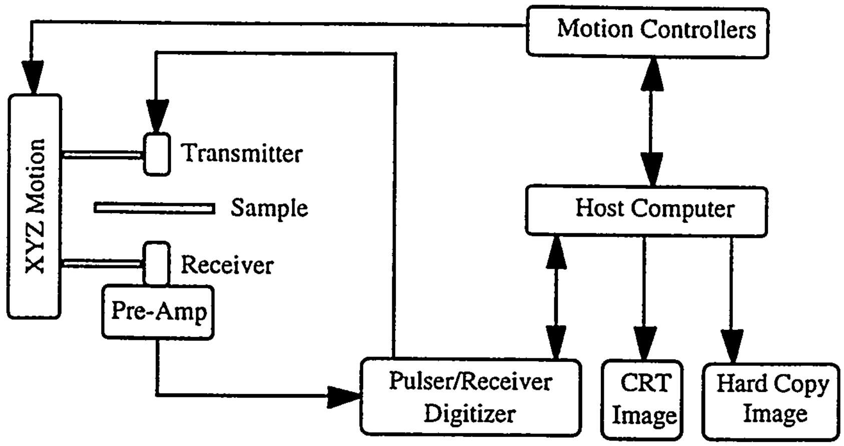


Fig. 3. Schematic diagram of air-coupled ultrasonic system.

AIR-COUPLED ULTRASONIC IMAGING SYSTEM

The experimental setup of the air-coupled ultrasonic system (Pillai et al., 1997) consists of a traditional xyz positioning system with two matched air-coupled transducers in a coaxial transmission geometry, as shown in Fig. 3. The yoke assembly on which the transducers are mounted is connected to xy scan stepper motors that are controlled by the host computer. The sample is mounted on an adjustable support so that the focal point of the transducers is within the thickness of the sample. A C-scan image of the sample is then built up with a nominal 0.08-cm step size in both x and y directions. Tone bursts of acoustic energy at 0.4 MHz are incident on the sample from the transmitter side. These ultrasonic waves propagate through the sample and emerge to be detected by the receiving transducer. The detected signal is preamplified by a low-noise pre-amp attached directly to the receiving transducer and is then fed to a tuned amplifier and to an electronic gate. The digital value of the peak in the gate (PIG) is displayed and stored as a color-coded image. The resulting image consists of a large number of pixels, the colors of which depend on the transmitted amplitude. Image color thus depends on the physical property of the medium. As acoustic waves propagate through the medium, they are scattered by defects in the medium. Areas with defects (such as pores and delaminations) appear as different colors on the image, because the amplitudes of the through-transmitted waves (PIG values) differ in these regions.

SYLRAMIC™ COMPOSITE SAMPLES

Two sets of SYLRAMIC™ composite samples were characterized by the NDE methods. The first set included eight 8-ply 51-mm x 51-mm (2-in. x 2-in.) coupons processed with 1, 3, 5, 7, 9, 11, 13, and 15 PIP cycles, respectively. The coupons were used to determine their thermal diffusivity and UT transmission properties. The second set contained an 8-ply and a 16-ply panel, each of which measured 203-mm x 203-mm (8-in. x 8-in.). After the first PIP processing cycle, the panels were cut into smaller pieces that measured 102-mm x 203-mm (4-in. x 8-in.), 102-mm x 102-mm (4-in. x 4-in.), 51-mm x 102-mm (2-in. x 4-in.), 51-mm x 51-mm (2-in. x 2-in.), 25-mm x 51-mm (1-in. x 2-in.), and 6-mm x 51-mm (0.25-in. x 2-in.). NDE tests were conducted on these panels after 1, 5, 10, and 15 PIP cycles.

NDE RESULTS

Thermal diffusivity and UT transmission data obtained from the set of 51-mm x 51-mm coupons are plotted in Figs. 4a and b as a function of sample density. From these figures, it is

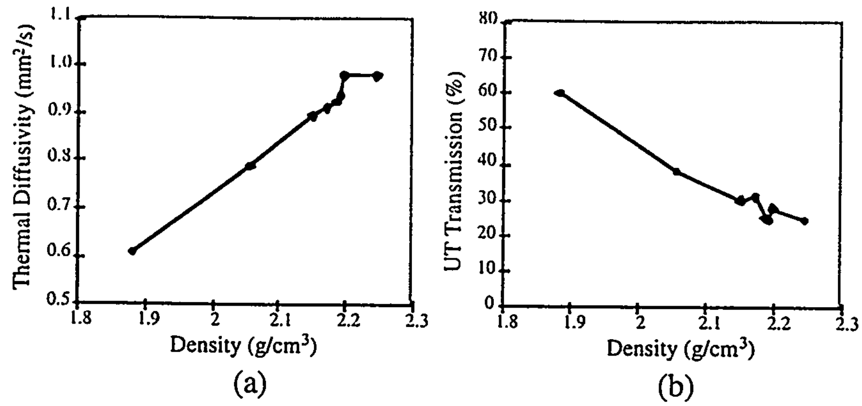


Fig. 4. (a) Thermal diffusivity and (b) UT transmission as a function of SYLRAMIC™ composite density.

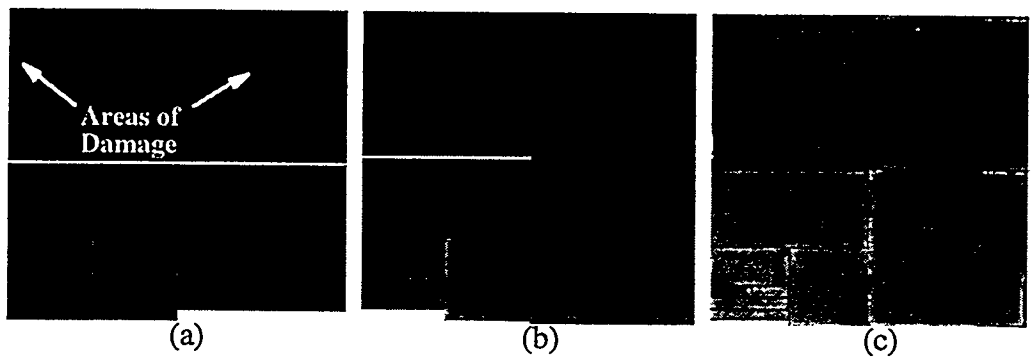
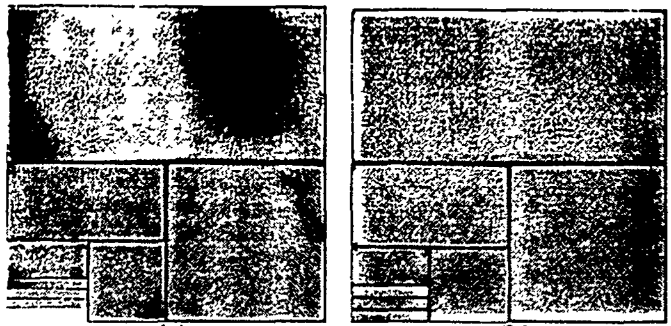


Fig. 5. Thermal diffusivity images of 8-ply SYLRAMIC™ composite panel obtained after (a) 1, (b) 5, and (c) 10 PIP cycles.

evident that both thermal diffusivity and UT transmission are approximately linear functions of density (Sun et al., 1997).

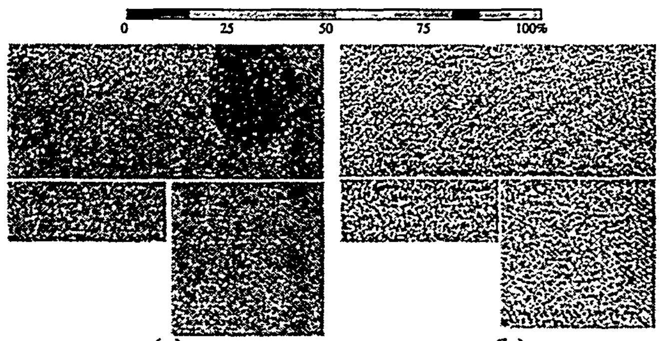
Figures 5a-c and 6a show the thermal diffusivity images of the 8-ply panel after 1, 5, 10, and 15 PIP cycles, respectively. The images clearly show several regions of damage in the panel. The damage was in a form of delamination that occurred after the first and before the fifth PIP cycle. The damaged regions were progressively repaired after the fifth PIP cycle, as shown in Figs. 5b and c and 6a. On the other hand, the 16-ply panel was not damaged, and its diffusivity images after various PIP cycles were uniform. Figure 6b shows the thermal diffusivity image of the 16-ply panel after 15 PIP cycles. The white (or high diffusivity) bands near some edges are due to reduced thickness at these edges.

Similar results were obtained from the air-coupled ultrasonic tests. Figures 7a and b show the UT transmission images of the 8- and 16-ply panels, respectively, after 15 PIP cycles. The smaller pieces (<3 cm) were not imaged because of excessive edge scattering effect of the acoustic waves. Figures 6 and 7 show good correlation between thermal diffusivity and air-coupled UT data.



(a) (b)

Fig. 6. Thermal diffusivity images of (a) 8-ply and (b) 16-ply SYLRAMIC™ composite panels after 15 PIP cycles.



(a) (b)

Fig. 7. Air-coupled UT transmission images of (a) 8-ply and (b) 16-ply SYLRAMIC™ composite panels after 15 PIP cycles.

An additional study to examine the edge effect was conducted on the 8-ply panel, because the edge effect is of interest for both composite processing and thermal imaging. The 102-mm x 203-mm (4-in. x 8-in.) sample shown in Figs. 5-7 was cut into two 51-mm x 203-mm (2-in. x 8-in.) pieces. The upper portion was further tested with thermal imaging, whereas the lower portion was tested by a destructive method. Two thermal diffusivity images of the upper 51-mm x 203-mm piece that were obtained with front and back surface facing the IR camera are shown Figs. 8a and b. Because of the diffusive nature of the thermal imaging, a feature near the surface that faces the camera will not be greatly diffused and thus give a better resolution in the image. When judged by the amount of diffusion in these images, it is evident that the delaminated (black) regions at the left edge and at the right center are near the front and back surfaces, respectively. Typical thermal diffusivity profiles from this sample are plotted in Figs. 9a-c, with the x-y coordinates illustrated in Fig. 8a. Of particular interest is the comparison of the diffusivity profiles near the cut edge, which were obtained before and after the edge was cut. An edge effect which causes spurious results on the order of 2-3% is evident in the measured diffusivity; however, this effect must be studied further.

The lower 51-mm x 203-mm (2-in. x 8-in.) sample was further sectioned into 25-mm x 25-mm (1-in. x 1-in.) coupons; their bulk densities were measured, as shown in Fig. 10. An attempt was made to estimate the bulk density of these coupons from the thermal diffusivity image shown in Fig. 6a and the correlation between the density and thermal diffusivity shown in Fig. 4a. The estimated density is also plotted in Fig. 10. Although the trends between the measured and estimated densities are the same, the estimated values exaggerate the variation. However, this problem is expected because the correlation was obtained from uniform composite materials whereas the measured density variation in the sample was due to delamination.

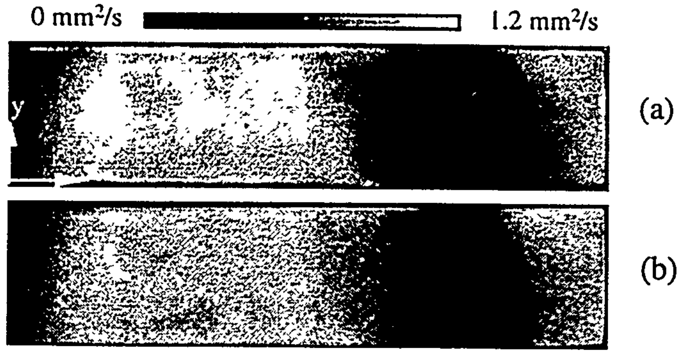


Fig. 8. Thermal diffusivity images of a 51-mm x 203-mm 8-ply SYLRAMIC™ composite sample with (a) front and (b) back surface facing the IR camera.

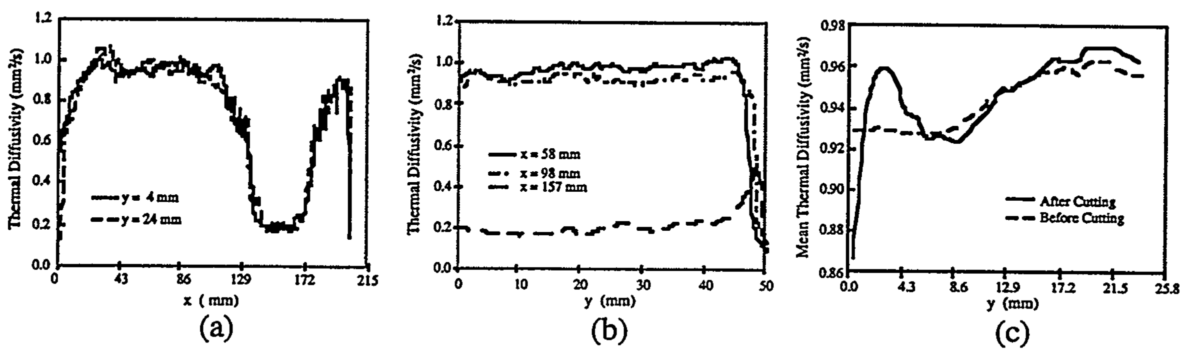


Fig. 9. Typical thermal diffusivity profiles in (a) x direction, (b) y direction, and (c) y direction with details near cut edge at y = 0.

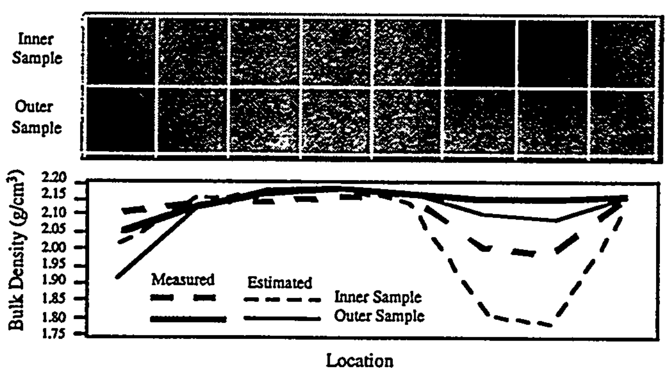


Fig. 10. Measured and estimated bulk density of 51-mm x 203-mm 8-ply SYLRAMIC™ composite sample.

CONCLUSIONS

It was found that NDE by thermal diffusivity and air-coupled ultrasonic imaging methods can be used to characterize SYLRAMIC™ composites during processing. Both thermal diffusivity and UT transmission are approximately linear functions of the composite density (or porosity). A delaminated region was clearly detected by both of the NDE methods and its progressive repair during processing was monitored. The correlation between the results of thermal and UT imaging was good. The correlation between NDE data and results obtained from destructive characterization was also good.

ACKNOWLEDGMENTS

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