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NONDESTRUCTIVE EVALUATION OF COMPOSITES USING INFRARED IMAGING

MARK E. TODARO
MARK A. DOXBECK

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US ARMY ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER
CLOSE COMBAT ARMAMENTS CENTER
BENÉT LABORATORIES
WATERVLIET, N.Y. 12189-4050

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Mark E. Todaro and Mark A. Doxbeck

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13. ABSTRACT *(Maximum 200 words)*
Benet Laboratories is pursuing methods for nondestructively evaluating composite materials and structures associated with large caliber gun tubes, including items already being manufactured, such as the bore evacuator, as well as experimental items, such as the thermal shroud and composite-reinforced gun tubes. Typical needs include identifying delaminations between the composite and a substrate, delaminations between composite layers, damage from later manufacturing processes, and impact damage during use. Recent in-house work included obtaining images of delaminations in fiber-reinforced, layered composite plates using an infrared video system. The surface of the composite was briefly heated by quick pass with a hot air gun, while an infrared video camera recorded the changing pattern of infrared radiation emitted from the heated surface. From the intensity of this radiation, the system calculated the temperature at each scanned element of the surface for subsequent display, storage, and processing. The surface cools primarily by diffusion of heat into the bulk of the material; and discontinuities, therefore, tend to block the flow of heat and inhibit cooling. In these experiments, the surface of the composite above a delamination did not cool as quickly after heating as the surrounding regions. In the frames recorded immediately after the pass of the hot air gun, the surfaced above delaminations were clearly visible as hot spots. A one-dimensional finite difference algorithm was used to model transient surface temperatures due to an energy pulse incident on a layered material, such as a composite, with or without delaminations. This model forms a useful basis for guiding, analyzing, and interpreting infrared imaging measurements on composites. Future work may involved using a laser to heat the surface and using temperature versus time data to obtain information on the depth and extent of damage.

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INTRODUCTION

In many applications, composite materials offer significant advantages over traditional homogeneous materials. For various reasons, however, it is often desirable to perform a nondestructive evaluation of these materials to ensure their structural and mechanical integrity. Some of our needs include identifying delaminations between the composite and a substrate material such as steel, delaminations between composite layers, damage from later manufacturing processes, and damage during use. For example, in the gun tube reinforcement application, an inner steel liner could be reinforced with an outer jacket of a carbon fiber and organic-matrix composite. In such an application, one would like to identify and locate any gaps between the composite and the steel liner that might be caused by such factors as dimensional changes during and after curing. A further manufacturing process involves expanding and overstressing the steel liner to introduce compressive stress at the bore. However, this process, referred to as autofrettage, could damage the composite or leave a gap between the composite and steel when the system relaxes after stressing. Also, during use, such a gun tube would be subject to all sorts of impact damage that could weaken the composite.

Various thermographic techniques involving infrared imaging have shown potential in identifying delaminations and other defects of interest in a wide variety of composite materials and structures (refs 1-3). An important advantage of such techniques is that they can usually be used to inspect large areas fairly quickly and can be made reasonably portable. Our work focused on identifying and demonstrating some simple thermographic techniques that would be suitable for evaluating composite structures, particularly those associated with tank guns.

The basic approach in infrared imaging thermography is to subject the composite specimen to a thermal excitation (heat) and observe the surface temperature by measuring the infrared radiation emitted. Subsurface defects result in thermal discontinuities that perturb heat propagation in the material and, therefore can often be identified by monitoring the surface temperature during and after thermal excitation.

HEAT DIFFUSION MODEL

We developed a computer program to predict the surface temperature as a function of time due to a transient thermal excitation at the surface of a layered material. The program uses a simple one-dimensional finite difference algorithm to model the diffusion of heat into the material, neglecting heat loss at the surface. It has been used to predict temperature profiles for a number of different composite systems with or without delaminations due to a variety of thermal excitations.

Analytical Solution for A Semi-Infinite Solid

First, we consider a case for which the diffusion equation can be solved analytically: a semi-infinite solid. Suppose an instantaneous pulse of heat is absorbed at the surface of a semi-infinite solid and that the solid loses no heat at the surface. In other words, to a first approximation, we shall neglect cooling of the surface by air convection or radiation, and consider only diffusion into the material. Since the material is semi-infinite, the diffusion is then one-dimensional. The change in surface temperature T due to the heat pulse as a function of time t after the pulse is (ref 4)

$$T(t) = \frac{Q}{\sqrt{\pi \rho c k t}} \tag{1}$$

where Q is the energy absorbed per unit area, ρ is the density, c is the specific heat, and k is the thermal conductivity. As a result, ln(T) plotted versus ln(t) will yield a straight line of slope -1/2.

If the heat pulse is continuous rather than instantaneous, then the surface temperature T as a function of time t from the beginning of the pulse is given by

$$T(t) = \frac{1}{\sqrt{\pi \rho c k}} \int_0^t \frac{q(t')dt'}{\sqrt{t-t'}} \tag{2}$$

where q(t) is the energy absorbed per unit area per unit time. For the simple case of a rectangular pulse given by

$$\begin{aligned} q(t) &= S \qquad 0<t<t_{off} \\ &= 0 \qquad t>t_{off} \end{aligned} \tag{3}$$

the result simplifies to

$$T(t) = \frac{2S}{\sqrt{\pi \rho c k}} \sqrt{t} \qquad 0<t<t_{off} \tag{4a}$$

$$T(t) = \frac{2S}{\sqrt{\pi \rho c k}} \left(\sqrt{t} - \sqrt{t-t_{off}}\right) \qquad t>t_{off} \tag{4b}$$

Finite Difference Solution for Layered Material

In general, if the material is layered with varying thermal properties as a function of depth, an analytical solution is no longer possible. In this case, a one-dimensional finite difference algorithm can be used to find approximate values for the temperature change at the surface or at various depths. Following Dusinberre's treatment (ref 5), we can subdivide the system into regions as shown schematically in Figure 1.

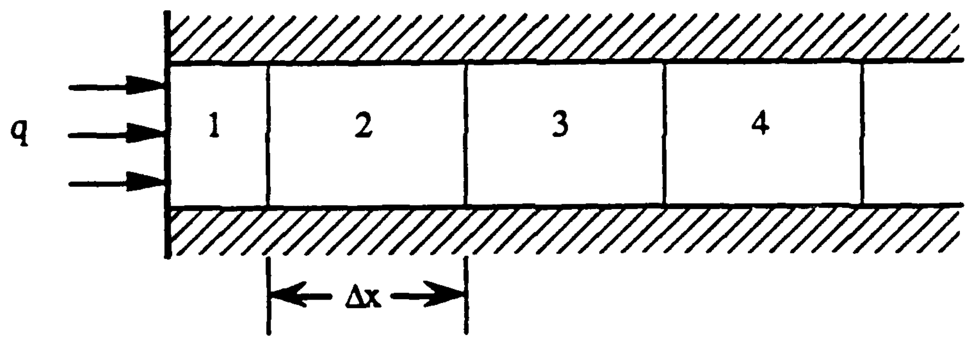


Figure 1. One-dimensional system for finite difference calculations.

The first region has a thickness $\Delta x/2$; all other regions have thickness Δx. The temperature T_i' for the i^{th} region after each time interval Δt is calculated from the temperatures of the adjacent regions before the time interval using

$$T_1' = \frac{4k_2}{k_1+k_2}\frac{1}{M_1}T_2 + \left(1 - \frac{4k_2}{k_1+k_2}\frac{1}{M_1}\right)T_1 + \frac{2\Delta t}{\rho_1 c_1 \Delta x}q \tag{5a}$$

and for i > 1,

$$T_i' = \frac{2k_{i-1}}{k_{i-1}+k_i}\frac{1}{M_i}T_{i-1} + \frac{2k_{i+1}}{k_i+k_{i+1}}\frac{1}{M_i}T_{i+1} + \left[1 - \left(\frac{2k_{i-1}}{k_{i-1}+k_i} + \frac{2k_{i+1}}{k_i+k_{i+1}}\right)\frac{1}{M_i}\right]T_i \tag{5b}$$

where

$$M_i = \frac{\rho_i c_i (\Delta x)^2}{k_i \Delta t} \tag{6}$$

where q is the energy absorbed per unit area per unit time. An arbitrary time-varying energy input can be approximated by using different values of q for each time interval. Typically, q is set to finite values for a "pulse on" period, then to zero for the rest of the calculation. The best results are obtained when each M is greater than or equal to 2.

Computational Results

For a rectangular energy input pulse incident on a semi-infinite homogeneous solid, the finite difference calculations agreed quite well with the analytical solution given by Eq. (4).

The finite difference model was used to simulate the surface temperature changes for a variety of systems involving subsurface thermal discontinuities. The thermal discontinuities are intended to model flaws such as delaminations between composite plies. Figure 2 shows some typical results for a graphite-epoxy composite of density 1.602 g/cm^3, heat capacity 0.7782 J(g K), and thermal conductivity 0.006486 W/(cm K). (These are typical values reported in the literature (ref 6).)

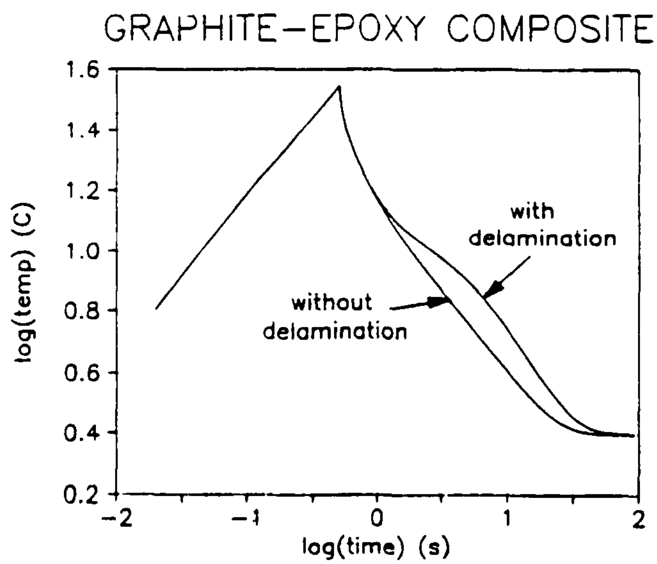


Figure 2. Finite difference calculation of ln(T) versus ln(t) with and without delamination.

The energy input was assumed to be 4 W/cm^2 for a period of 0.5 second. The top curve in the figure represents the case when a region of material having 0.00065 W/(cm K) is assumed to lie 1.3 to 1.5 mm below the surface. Such a thermal discontinuity could represent a poor bond between plies. The flattening of the curve at longer times is a result of limiting the thickness of the model to 5 mm (and represents the ultimate thermal discontinuity: no heat diffusion at all).

BLACK-BODY RADIATION

All objects emit electromagnetic radiation due to the thermal excitation of electrons in the molecules of the object. Theoretical calculations of the intensity of this radiation as a function of wavelength or frequency can be made for an ideal black body--an object that absorbs all electromagnetic radiation incident upon it. The theory is fairly straightforward and can be found in introductory texts on modern physics or quantum optics (refs 7,8). The theoretical result is often written as

$$I_\nu(\nu) = \frac{2\pi h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1} \tag{7}$$

where $I_\nu(\nu)d\nu$ is the intensity of emitted radiation having frequencies between ν and $\nu+d\nu$, h is Planck's constant, k is Boltzmann's constant, and c is the speed of light in vacuum. T is the absolute temperature of the body.

However, one can also define $I_\lambda(\lambda)d\lambda$ as the intensity of emitted radiation having frequencies between λ and $\lambda+d\lambda$. By requiring $I_\lambda(\lambda)d\lambda = I_\nu(\nu)d\nu$, one can then obtain

$$I_\lambda(\lambda) = \frac{2\pi hc^2}{\lambda^5}\frac{1}{e^{hc/k\lambda T}-1} \tag{8}$$

Some potential for confusion exists because $I_\lambda(\lambda)$ and $I_\nu(\nu)$ are not the same. $I_\lambda(\lambda)$ can be thought of as an intensity per unit wavelength, whereas $I_\nu(\nu)$ is an intensity per unit frequency.

Figure 3 shows $I_\lambda(\lambda)$ versus λ for several temperatures near room temperature. Near room temperature, nearly all of the black-body radiation is emitted in the infrared region of the spectrum at wavelengths longer than those of visible light. Although a small amount of this black-body radiation is in the visible range, the human eye cannot perceive it at such a low intensity. Virtually all the light that we see from objects at room temperature is either reflected from other sources or emitted by other mechanisms, such as electronic transitions, including luminescence, fluorescence, lasing, and electron-hole recombination. As the temperature of an object increases, it emits more black-body radiation at shorter wavelengths. If the temperature is raised high enough, the black-body radiation becomes easily visible to the naked eye, as with molten metal or the filament of an incandescent light bulb.

Not all materials, however, behave as ideal black bodies. At a given temperature and for radiation at a given wavelength, the ratio of actual intensity emitted to the intensity that would be emitted by an ideal black body is called the spectral emittance. An ideal black body has an emittance of 1. All other materials have smaller values, although many have values very close to 1. The emittance of a particular material depends largely on its surface characteristics, such as roughness and the presence of an oxide. Most nonmetallic and painted surfaces have an emittance greater than 0.8.

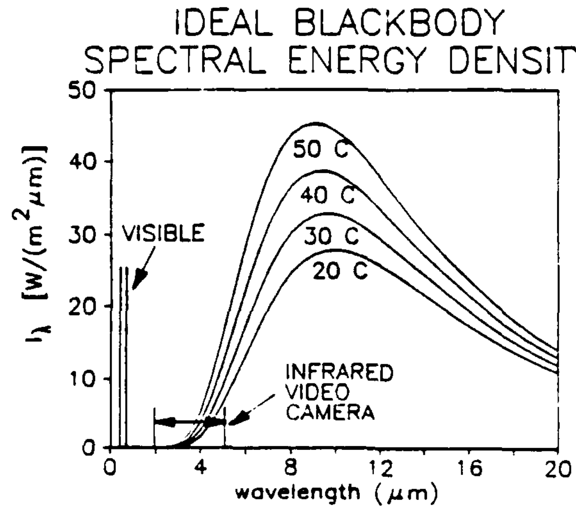


Figure 3. $I_\lambda(\lambda)$ versus λ.

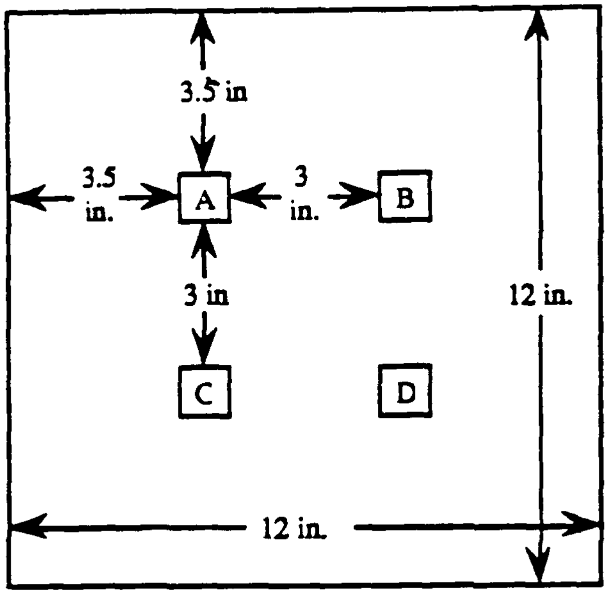
MEASUREMENT OF RADIATION AND TEMPERATURE

The temperature of the composite surface was measured during and immediately after heating using an infrared video camera and image analysis system (Agema Infrared Systems Model 870 scanner and TIC-8000 computer system). The camera and detector are sensitive to infrared radiation in the 2- to 5-μm wavelength range. This infrared radiation from the object is focused to form an image that is scanned across the detector. From the intensity of radiation measured for each scanned element of the image, the system calculates the temperature for the corresponding point on the object. Digitized images can be recorded on video cassette at thirty frames per second or saved to a RAM disk at six frames per second. Storage on RAM disks allows subsequent analysis of individual frames.

EXPERIMENTAL MEASUREMENTS

Specimen

Various experimental measurements were attempted on a carbon fiber/bismaleimide matrix composite plate measuring 12 by 12 inches, as shown in Figure 4. Nine total plies were used in a 0/90 degree layup. To simulate delaminations, double layers of Teflon film were placed between plies 1 and 2 at A, plies 2 and 3 at B, plies 3 and 4 at C, and plies 4 and 5 at D.



(ply 1 toward viewer)

Figure 4. Carbon fiber/bismaleimide matrix composite specimen with simulated delaminations.

Thermal Excitation

In this study, the following heat sources were used:

- photographic flashlamps,
- an array of heat lamps,
- a hot air gun.

The hot air gun gave good results, but the flashlamps and heat lamps did not. Hot air guns, although seemingly crude, can work out quite well in an actual testing situation, for example, as reported for rotor blades (ref 9). We did not try heating with a laser pulse, although this seems like a promising alternative.

For the best results with the hot air gun, we equipped it with a hand-crafted aluminum foil nozzle to focus and spread the air. The gun was held at a grazing angle to the composite plate, as shown in Figure 5, and swept across the surface at roughly one foot per second.

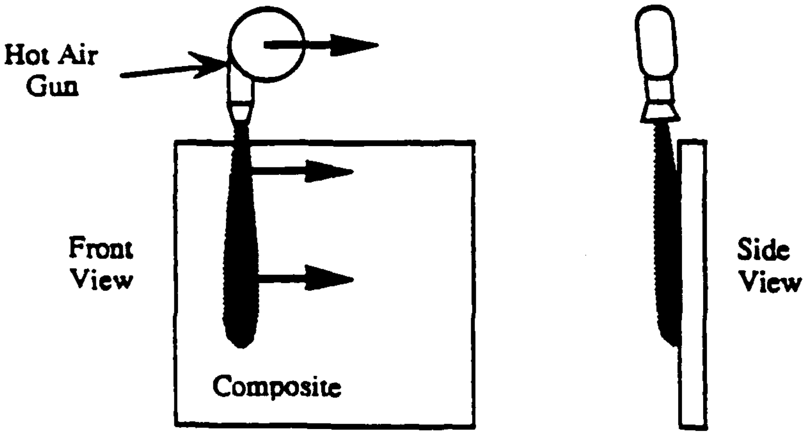


Figure 5. Method of sweeping hot air gun output across composite specimen.

Results

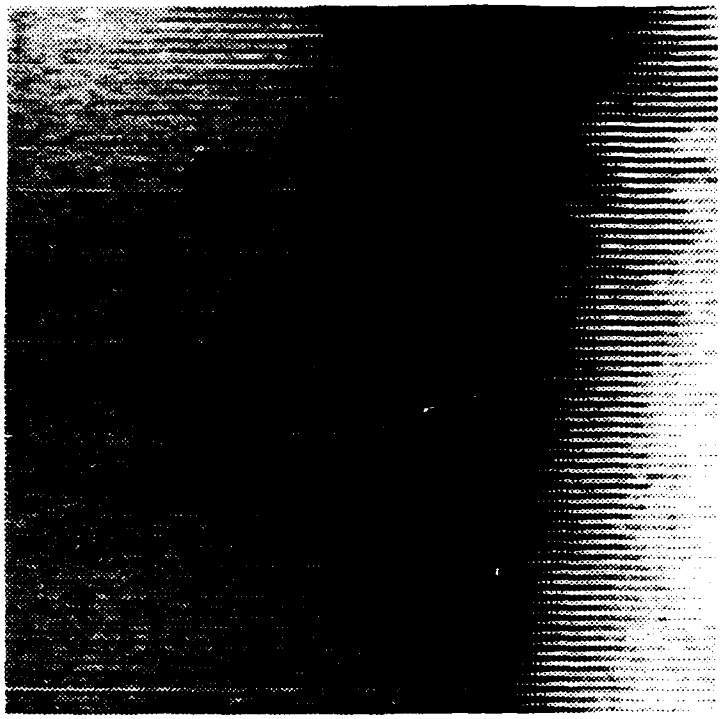
Figures 6(a) through 6(f) show a sequence of infrared images of the graphite-bismaleimide composite plate as the output from the hot air gun is swept across the surface as described above. Warmer areas are dark, and cooler areas are light in these images. The delaminations nearest the surface (upper left) show up soon after the hot air passes and are most sharply defined. The other delaminations seem to appear after a longer time interval and are less well-defined. The deepest delamination (lower right), below the fourth ply, is barely perceptible in the last two images shown, 6(e) and 6(f). The various other hot spots seen in the images could be from delaminations caused by degradation of the resin before the plate was constructed and cured.

CONCLUSION

Infrared imaging seems to offer a good deal of potential for evaluating carbon fiber composite laminates in certain circumstances. We found that the fairly crude heating technique of using a hot air gun gave good images of delaminations below the first, second, and third plies. A more sophisticated heating technique, such as a laser pulse, may yield better and more reproducible images. The high thermal conductivity of such carbon fiber composites along the fibers, compared to that transverse to the fibers, tends to degrade the sensitivity to and resolution of deeper flaws.

FUTURE DIRECTIONS

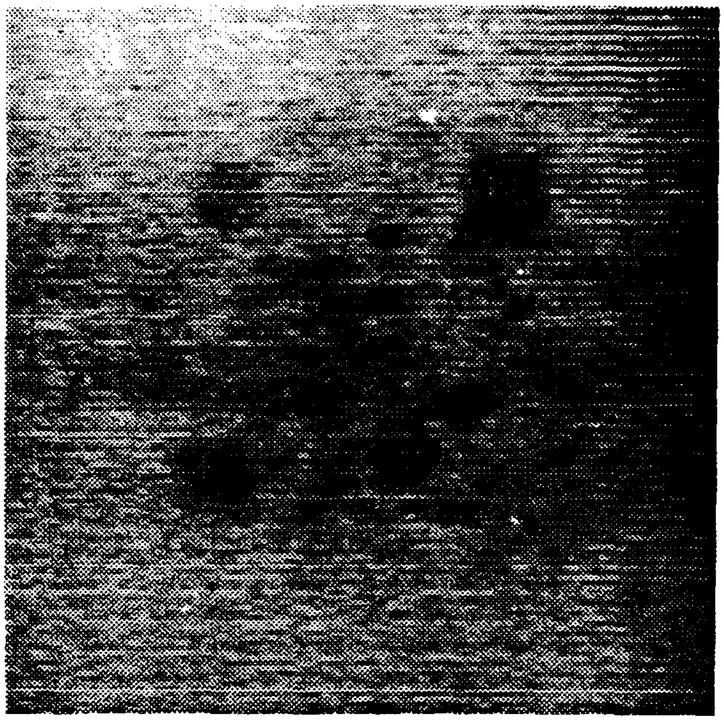
Future work, if undertaken, would probably involve using a neodymium-doped glass (Nd:Glass) laser to heat the surface. The particular laser available provides a 50 J pulse within about 0.9 ms. With a suitable lens system, the beam could be spread out to provide a fairly uniform intensity over a region several inches in diameter. A laser would provide repeatable surface heating, allowing comparisons to be made between different specimens and offering the possibility of doing quantitative, rather than qualitative, work. For example, one might plot ln(T) versus ln(t) as was done for the one-dimensional finite difference model. This may offfer information about the depth of the delamination as well as the severity of the flow.



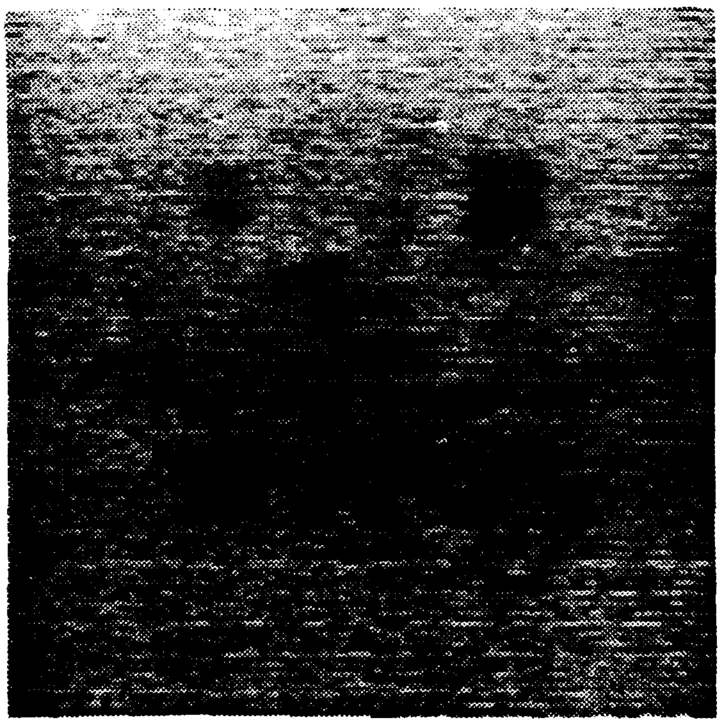
(a)

(b)

Figure 6. Infrared images of delaminations in carbon fiber/bismaleimide matrix composite.



(c)



(d)

Figure 6. Continued.

(e)

(f)

Figure 6. Continued.

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