DETECTION OF ULTRASONIC WAVES PROPAGATING IN
BORON/ALUMINUM AND STEEL/LUCITE COMPOSITE MATERIALS

Stephen Huber*, William R. Scott, and Randall Sands

Aero Materials Laboratory
Naval Air Development Center
Warminster, PA 18974-5000

INTRODUCTION

In this paper we report preliminary results of investigations into the nature of ultrasonic wave propagation and resulting surface displacements in two selected fiber reinforced composite materials: aluminum with boron fiber reinforcement and lucite with steel rod reinforcement. These materials have reinforcing fiber diameters that are small and large respectively when compared with the propagating ultrasonic wavelengths. The ultrasonic waves are observed by detecting surface displacements using a scanning micro-interferometer designed for this purpose and discussed in detail elsewhere.[1]

APPARATUS

A schematic diagram of this interferometer is shown in Figure 1. This device has been developed for imaging surface displacements with a transverse spacial resolution of 1 to 2 microns or less. The device operates by making measurements of the phase shift in a 40 MHz signal resulting from the beating of two single mode HeNe laser beams. One beam is a reference coming directly from the laser, while the other beam, which interrogates the sample, is shifted by 40 MHz using an acousto-optic modulator.

Displacements of the sample surface are manifested in phase shifts in the beat signal arriving at the photodetector. These phase shifts are equal to twice the phase shift of the HeNe beam arriving at the displaced surface of the sample and can be detected dynamically using an FM demodulator such as a phase locked loop detector. Thus, we are able to detect and monitor surface displacements (for example, from ultrasonic waves) in real time. A diagram of the signal processing electronics is shown in Figure 2.

*Present Address:
Department of Chemistry and Physics
Beaver College
Glenside, PA 19038
Figure 1. Microinterferometer

Figure 2. Signal processing electronics for microinterferometer.
THEORETICAL MODEL

The structure of composite materials chosen for analysis are of the form of a matrix composed of a homogeneous material with embedded unidirectional reinforcing fibers. We are interested in studying the properties of the material by analyzing the propagation characteristics of ultrasonic waves traveling parallel to the fibers. Depending upon the diameter \( D \) (corresponding to cross-section) and separation distance \( L \) of the fibers as well as wavelength of the ultrasonic waves, this type of structure will fall into one of several categories which include: \( D \) and \( L \) less than wave length and \( D \) and \( L \) greater than the wavelength of the propagating waves.

For the first case (\( D \) and \( L \) less than the wavelength) the material should appear to be relatively homogeneous to the propagating waves, since neither component of the composite material will guide the waves. Also, if the reinforcing fiber is made of a material with a propagating velocity greater than that of the matrix, then there should be continual leakage of wavefront into the matrix.

To test this assumption we chose to investigate the longitudinal wave propagation characteristics in boron fiber reinforced aluminum. The characteristic propagation velocity in aluminum is approximately \( 6400 \text{ m/s} \) \[2\], while that for boron calculated from published values of its material properties is approximately \( 12,600 \text{ m/s} \) \[3\]. The typical diameter for the boron fibers is approximately 125 microns and the wavelength of a 5 MHz ultrasonic longitudinal wave in aluminum is approximately 1280 microns.

For our second case where \( D \) and \( L \) are greater than (but not much greater than) the wavelength, the material may not fully exhibit a geometric propagation of the ultrasonic waves (that is, a "ray optic" type of propagation). If the propagation velocity in the reinforcing fiber is greater than that of the matrix then one would also expect leakage of wavefront from the reinforcing fiber into the matrix. However, this effect would depend upon the interface properties between the matrix and reinforcing fibers. Since a geometric propagation would clearly lead to two or more distinct arrival times, it is reasonable to expect two arrival times for wave propagation through this type of composite medium. To test this assumption we chose a lucite matrix with steel reinforcing rods. Typical propagation velocities for longitudinal waves in lucite and steel are 2680 m/s and 5960 m/s respectively.\[2\] The steel rods are approximately 2000 microns in diameter while the wavelength of a 5 MHz ultrasonic wave through lucite and steel are 536 and 1190 microns respectively.

EXPERIMENTAL PROCEDURE

To evaluate the propagation characteristics for Case I a boron/ aluminum sample (16 mm x 1.5 mm and 14 mm in depth) embedded in a phenolic was oriented so that the reinforcing fibers were perpendicular to the two opposite, exposed sample surfaces. One of these surfaces was carefully polished. A thin layer of gold was then applied to the polished surface to increase the reflectance and thereby the signal to noise ratio of the interrogating beam from the single mode HeNe laser. A diagram of the sample embedded in phenolic and its placement in the interferometer is shown in Figure 3.

A diagram of the micro-structure of the polished surface of the Boron/Aluminum composite material facing the interrogating beam is shown in Figure 4. The boron fiber of circular cross-sectional area has a diameter of 125 microns and coaxially surrounds a tungsten core. The spatial reso-
Figure 3. Diagram of boron/aluminum sample embedded in phenolic.

Figure 4. Diagram of the micro-structure of boron/aluminum sample.
olution of the micro-interferometer is adequate to interrogate across a fiber, resolve the fiber-matrix interface, and continue into the matrix material.

The amplitude of the interference signal due to the beating of the two HeNe beams monitored directly from the photodetector to the oscilloscope (Tektronix 7854 Waveform Digitizer) is used to focus the interrogating beam and maximize the signal to noise ratio at each scan position. This signal is monitored on input A as shown in Figure 2. Since the 7854 Waveform Digitizer is triggered from the pulser, there is a delay of approximately 2.2 microseconds before the signal generates displacements on the polished, opposite surface from which the observation is made.

To evaluate the wave propagation characteristics of the second case described above we used a steel reinforced lucite composite and carried out measurements as with the boron/aluminum.

RESULTS

To measure variations in propagation of the ultrasonic waves along the cross-section of a boron fiber embedded in aluminum we ran a scan across the diameter of a selected fiber. The signals were recorded at 15 micron intervals and are shown in Figure 5. The similarity in structure of these waveforms suggests that there is uniformity in wave propagation (in the range of 5 MHz) across the cross-section of the fiber as expected theoretically.

Data were also taken on amplitude and arrival time of extrema in the phase signal received by the 7854 Waveform Digitizer. An example of a smoothed phase signal is shown in Fig. 6. These data yield information on amplitude of surface displacement at each interrogation point and its associated arrival time. The surface was sampled in an array of 10X10 points in a window size of .2 mm by .2 mm. The size of this window insured that one complete fiber as well as matrix was contained within the scan array. These data for the first extrema and arrival time are shown on a contour plot in Figs. 7 and 8.

Figure 5. Phase signals at 15 micron intervals along the diameter of a boron fiber.
Figure 6. Smoothed phase signal from microinterferometer.

Figure 7. Boron/aluminum first extrema for all points in scan array.

Figure 8. Boron/aluminum first extrema arrival times for all points in scan array.
The location of the fiber is readily apparent from the contour plot in Figure 7. The large amplitudes correspond to interrogation on the fiber surface. The depressions in the contour near points (1,1), (9,10), (9,4), and (1,4) correspond to locations that are in the aluminum matrix bounding the boron fiber. This suggests that there seem to be larger surface displacements on the fiber itself than in the aluminum matrix. This suggests that the ultrasonic wavefront is propagating as if through a homogeneous material. This is expected since the boron fiber diameter is smaller than the wavelength of the propagating waves.

The same results are present for subsequent major extrema of the monitored waveform. That is, surface displacements are clearly greater on the boron fiber than on the aluminum matrix and the arrival times are rather uniform across the composite surface.

Moreover, data from the surface displacements did not show two propagation times, one for each material in the composite. Rather, the longitudinal waves propagated with only one characteristic arrival time suggesting propagation through a homogeneous material.

Similar measurements were made on the steel reinforced lucite specimen. A scan was made beginning in the lucite matrix across the interface and into the steel rod. The corresponding waveforms are shown in Figure 9. In this figure the waveforms at the top of the graph are representative of points in the lucite matrix. Midway down the graph the scanning interferometer is crossing the steel/lucite interface and the lower waveforms are representative of points on the steel rod. Each of these waveforms was triggered by the ultrasonic pulser. There is a clear delay in the signal received from the lucite as compared to that received from the steel rod. This suggests that there are two distinct arrival times for longitudinal waves for this type of medium in agreement with our theoretical model.

Figure 9. Scan profile across steel/lucite interface.
Contour plots of dimension 10x4 each showing a first extremum and its corresponding arrival times are shown in Figures 10 and 11 where the steel rod is present in the back left hand corner of the plot window. A fair degree of complexity is present in Figure 10. Furthermore, the delay in signal arrival time in the lucite compared to that in steel is apparent in Figure 11 where the back left portion (representing the steel rod) of the contour graph is depressed relative to that of the lucite portion.

These preliminary results correspond to qualitative models and a formal analysis is not being offered at this time. However, these results suggest that the technique is capable of interrogating the fiber matrix interaction in composite materials.

Figure 10. Steel/lucite first extrema for all points in scan array.

Figure 11. Steel/lucite first extreme arrival times for all points in scan array.
REFERENCES


2. Handbook of Chemistry and Physics, 52nd ed., Chemical Rubber Company, Cleveland, OH.