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Structural Health Monitoring of Composites Using Integrated and Flexible Piezoelectric Ultrasonic Transducers

MAKIKO KOBAYASHI[1], KUO-TING WU[2], LI Song[2], CHENG-KUEI. JEN*[1] AND NEZIH. MRAD[3]
[1]Industrial Materials Institute, National Research Council of Canada, 75 Blvd. de Mortagne, Boucherville, Quebec J4B 6Y4, Canada;
[2]Department of Electrical and Computer Engineering, McGill University, 3480 University Street, Montreal, Quebec H3A 2A7, Canada
[3]Department of National Defence, Defence R&D Canada, Air Vehicles Research Section, National Defence Headquarters, Ottawa, Ontario, K1A 0K2, Canada
Tel: 1-450-6415085; Fax: 1-450-6415106
Email: cheng-kuei.jen@cnrc-nrc.gc.ca

ABSTRACT: Two types of ultrasonic sensors are presented for structural health monitoring (SHM) and non-destructive testing (NDT) of graphite/epoxy (Gr/Ep) composites of thickness ranging from 1mm to 12.7mm. These piezoelectric film based sensors are fabricated using a sol-gel spray technique. The center operation frequency of these sensors ranges from 1.3MHz to 14.5MHz. For the first sensor type, piezoelectric films of thickness ≥30μm were deposited directly onto planar and curved Gr/Ep composites surfaces as integrated sensors. Ultrasonic signals propagating in a distance of more than 300mm have been obtained. Anisotropy of 0° and 90° cross ply Gr/Ep composite is measured and delamination detected. For the second sensor type, piezoelectric films are coated onto a 50μm thick polyimide membrane as flexible sensors that may be attached to a host composite structure with planar or curved surfaces. An induction type non-contact method for the interrogation of the Gr/Ep composites using integrated sensors is also presented.

Key words: integrated ultrasonic transducer, flexible ultrasonic transducer, graphite/epoxy composite, structural health monitoring, non-destructive testing, non-contact method.

INTRODUCTION

Composite materials such as graphite/epoxy (Gr/Ep) laminates are becoming the materials of choice for aerospace structures because of the high strength to weight ratio. Diagnostic structural health monitoring (SHM) and non-destructive testing (NDT) technologies are increasingly being investigated by the aerospace industry to enable condition-based maintenance for cost-effective increased safety and eco-efficient designs (Gandhi and Thompson, 1992; Giurgiutiu, Zagrai and Bao, 2002; Ihn and Chang, 2004; Birks, Green and McIntire, 1991). Ultrasonic techniques are frequently used for SHM and NDT purposes because of their subsurface inspection capabilities, fast inspection speed, simplicity and ease of operation. In this investigation two types of ultrasonic sensors are presented for SHM and NDT of Gr/Ep composites of thickness ranging from 1mm to 12.7mm with planar or curved surfaces. These piezoelectric film based sensors were fabricated using a sol-gel spray technique (Kobayashi and Jen, 2004; Kobayashi et al., 2005). All measurements will be carried out in pulse/echo mode.

The first sensor type is that piezoelectric films of thickness greater than 30μm will be deposited directly onto planar and curved Gr/Ep composites surfaces as integrated ultrasonic transducers (IUTs). These composite substrates may have high or low electrical conductivity and their resistivity will be measured using a standard four-point-probe. For high electrical conductivity material, the Gr/Ep will be used as the bottom electrode of the IUT. For low electrical conductivity material, the bottom electrode will be made by an electroless nickel plating or a colloidal silver spray technique. For the second sensor type, a 50μm thick polyimide membrane will be used as the substrate. Due to the insulating nature of the polyimide film a ~2μm thick silver layer will be first coated onto the film as the bottom electrode. Then piezoelectric films will be coated onto the bottom electrode as flexible ultrasonic transducers (FUTs) that could be bonded onto a host composite structure with planar or curved surfaces. The strength of the IUT and FUT is evaluated using a commercially available handheld pulser-receiver EPOCH (model LT) because it is used commonly in the ultrasonic NDT field.

This study will further present a current development of an induction type non-contact method for the interrogation of the Gr/Ep composites using IUTs (Greve et al., 2007). Such non-contact technique may be desired for SHM and NDT of rotating composite components.

FABRICATION OF IUT AND FUT

The detailed fabrication process of sol-gel spray technique can be found from previous publications (Kobayashi and Jen, 2004; Kobayashi et al., 2005). Piezoelectric lead-zirconate-titanate (PZT) powders in this study were purchased. Fine and submicron size powders were dispersed into PZT sol-gel solution by the ball milling method to achieve the paint for spray. If Gr/Ep has high conductivity, it is used as the bottom electrode of the IUT. When poor-conductive substrates i.e. some Gr/Ep composites and insulating polyimide membranes are used, it is required to fabricate the bottom electrode layer before spray coating of piezoelectric PZT/PZT composite film. In this investigation, electroless plating of nickel layer is used for one poor conductive Gr/Ep composite and colloidal silver spray for two poor conductive Gr/Ep composites and polyimide membranes to form the bottom electrode layer of IUT or FUT. For electroless plating of nickel layer, Gr/Ep composites are immersed in electroless nickel bath containing nickel salt, reducing agent such as sodium hypophosphite, and complexing agent for nickel, after pretreatment process. The electroless bath was heated up to 90°C and the immersion time was about 10 minutes. The thickness of electroless plated nickel alloy layer was ~1μm. For spray coating, silver colloid was sprayed directly onto poor conductive Gr/Ep composites or polyimide membranes using an airbrush, and cured around 120°C. The thickness of the sprayed silver layer was ~2μm. Another airbrush was then used to spray the PZT/PZT sol-gel composite directly onto bottom electrodes of the Gr/Ep composites or polyimide membranes. Paper masks were used to serve as the shadow mask during the spray coating. PZT sol-gel solution contributed as bonding material between the PZT powder and the bottom electrode. After each PZT/PZT coating, thermal treatments were carried out. Multiple layers were made in order to reach desired film thickness leading to proper ultrasonic operating frequencies of IUT or FUT. Then corona poling was used to obtain piezoelectricity of the PZT/PZT film. Finally the top electrode pattern was made by silver paste painting or colloidal silver spray with a paper mask. Such electrode fabrication approach enables to achieve desired sensor array configurations easily and economically. Both IUTs and FUTs can operate in the temperature range between -100°C and 150°C and can be made on site. In this investigation longitudinal ultrasonic wave transducers are used.

ULTRASONIC MEASUREMENTS OF GR/EP COMPOSITES

IUT Deposited Directly onto Gr/Ep Composites

Figure 1 illustrates two IUTs that are directly deposited onto planar and curved surfaces of a Gr/Ep composite with a thickness of 12.7mm thick and a radius of 50.8mm. It is noted that such IUTs can be fabricated on site by a portable fabrication kit. This composite was made of 0° and 90° cross plies. The measured resistivity of this composite on the top surface was 0.72Ω-m which is low enough to serve as the bottom electrode of IUT. For the IUT coated onto the planar surface (IUT_P) the thickness of the PZT/PZT composite film was 96μm and the top circular electrodes has a diameter of 8mm, defining the IUT_P active area. The thickness of the PZT/PZT composite film for the IUT sprayed onto the curved surface (IUT_C) was 99μm and the top rectangular electrode had an area of 6mm by 7mm. The choices of circular and rectangular electrodes were carried out arbitrarily. It is noted that since the PZT/PZT composite film has a large area, several IUTs with diameters of 7.5mm may be made within the same film area. The advantages of such IUTs are that they can be directly deposited or coated onto curved surfaces without the need of couplant. The maximum fabrication temperature of these transducers was 175°C, which was the maximum fabrication temperature of these Gr/Ep composites used in this study. Such low temperature fabrication is to avoid material damages during to heat treatment process during IUT fabrication. However, the lower is the fabrication temperature the weaker the ultrasonic signal strength of IUTs. These IUTs can be employed in operational temperatures, ranging from -80°C to 100°C, commonly experienced in aircraft environments.

Figure 2 shows the IUT_P deposited onto a 12.7mm thick Gr/Ep composite plate and measured by the commercial handheld pulser-receiver EPOCH LT. L^n is the nth round trip L echo through the plate thickness. In this measurement 70dB out of the available 100dB receiver gain and no averaging was used. It indicates that this L wave IUT_P is efficient even though the IUTs have been fabricated below the temperature of 175°C. Figures 3a and 3b show the measurement results of IUT_P and IUT_C, respectively, with a lab pulser/receiver and data acquisition system. In Figure 3a L^1, L^2 and L^3 traveled a distance of 25.4mm, 50.8mm and 76.2mm, respectively in the thickness direction of the composite. The ultrasonic velocity and attenuation in the thickness direction are 2883m/s and 6.3dB/cm, respectively. However, the L^1, $L^2$and L^3 shown in Figure 3b traveled a distance of 101.6mm, 203.2mm and 304.8mm, respectively in the radial direction of the composite. The ultrasonic velocity and attenuation in the radial direction are 6350m/s and 0.8dB/cm, respectively. It means that the anisotropy introduced by the 0° and 90° cross plies can be evaluated. The low ultrasonic attenuation observed in these ultrasonic signals indicates that the composite has good quality (density). The center frequencies & 6 dB bandwidth of the L^1 signals in Figures.3a and 3b are 1.8MHz & 2.1MHz and 1.3MHz & 1.2MHz, respectively. Later this sample will be used for non-contact measurements.

For the experiments a 1mm thick uni-directional Gr/Ep composite as shown in Figure 4 was also used. This composite has dramatic different resistivity ranging from 0.2Ω-m to 22,000Ω-m at different locations, and in general, its resistivity is higher than several hundreds Ω-m. Therefore it was decided that an electroless plating of 1μm thickness of nickel was carried out to serve as the bottom electrode of the IUT. The description of the electroless plating of nickel was given in the FABRICATION Section. The area of nickel plated layer is shown in Figure 4 with graded shade. A layer of 95μm thick PZT/PZT composite film was then deposited on top of this nickel layer and poled. A top electrode of 7mm diameter was made using silver paste. The measured ultrasonic signals gone through a 1MHz high pass filter are given in Figure 5 and the gain was 31dB out of the available 100dB when the EPOCH LT was used. The center frequency and 6dB bandwidth of the L^1 echo are 10.5MHz and 13.6MHz, respectively. In the later section this sample will be also used for non-contact measurements.

In order to show that IUT can be deposited onto braid structure composites a Gr/Ep cylindrical tube sample shown in Figure 6 is selected. The resistivity measured for this sample was ~1.5Ω-m. A ~2μm thick colloidal silver layer as the bottom electrode of the IUT was coated and cured as shown in Figure 6. In our experience the colloidal silver spray coating of bottom electrode is much simpler that electroless nickel plating. They both work well as the bottom electrode of IUT though. A layer of 58μm thick PZT/PZT composite film was then deposited and poled. Silver paste was used to form the top electrode of IUT. Here only the measured ultrasonic signals gone through a 1MHz high pass filter using the IUT indicated in Figure 6 are shown in Figure 7. The thickness of the Gr/Ep sample at the IUT location is 3.3mm. The center frequency and 6dB bandwidth of the L^1 echo are 2.7MHz and 3.7MHz, respectively. For this composite sample the gain was 60dB out of the available 100dB receiver gain when the EPOCH LT was used. Figure 7 clearly shows that IUT can be deposited and operated on such braid structure composite.

A 6.9mm thick Gr/Ep sample with delaminations caused by an impact damage shown in Figure 8 is also used for the demonstration of the defect detection capability of IUT. This sample was firstly inspected by the ultrasonic C-scan and the locations of the good and delaminated regions were identified. IUTs of 30μm thick were then deposited directly onto one location with no delamination and another with delamination. Figures 9 and 10 show the measured ultrasonic signals in time domain gone through a 1MHz high pass filter at room temperature at locations without and with delamination, respectively. The center frequency & 6dB bandwidth of the L1 echo in Figures 9 and 10 are 11.6MHz & 15.2MHz and 14.5MHz & 16.0MHz, respectively. The gain was 52dB out of the available 100dB receiver gain when the EPOCH LT was used.

FUT Attached onto Gr/Ep Composites

In certain situations, accessibility to desired locations of aircraft Gr/Ep components is limited for the fabrication of the IUTs, thus an alternative approach using the second sensor type, FUT, may be used. The fabrication of FUTs can be made off-line in a laboratory environment. Thereafter, they can be attached to desired sensor locations using adhesives that can sustain operational temperatures. Such adhesives can further be used as ultrasonic couplant. Although FUTs have been reported (Frankle and Rose, 1995; Wang and Huang, 2000; Kobayashi, Jen and Lévesque, 2006), in this investigation an alternative FUT approach is used. For this method a 50µm thick polyimide membrane was chosen due to its excellent flexibility. Firstly a ~2µm thick colloidal silver layer is sprayed onto the polyimide membrane as the bottom electrode. Then nearly the same coating process used and described above for IUT coated onto Gr/Ep composites is applied to fabricate FUTs. The thickness of the PZT/PZT composite film is 60µm. The schematic diagram and an actual four-transducer FUT array used for this study are shown in Figures 11a and 11b, respectively. The top four electrodes have an average diameter of 8.5mm and made by silver paste of ~20µm thick. The flexibility of such FUTs is achieved due to the thin polyimide, porous PZT/PZT ceramics (~20% porosity) and electrodes (Kobayashi and Jen, 2004; Kobayashi et al., 2005). The piezoelectric strength of these FUTs is nearly the same as the IUT deposited onto the Gr/Ep composite as shown in Figure 1 and such FUT can operate up to at least 150°C, but require ultrasonic couplant for SHM or NDT applications.

Due to the excellent flexibility of the FUT it can be wrapped around human fingers. Here the FUT shown in Figure 11b is attached to the cylindrical tube made of braid Gr/Ep composite of 3.3mm thickness shown in Figure 6 with an ordinary ultrasonic couplant as shown in Figure 12. Figure 13 shows the measured ultrasonic signals using one of the four FUTs in Figure 9. The gain was 51dB out of the available 100dB receiver gain when the EPOCH LT was used. The center frequency and 6dB bandwidth of the L^1 echo are 1.9MHz and 3.0MHz, respectively.

FUTs can be also used to evaluate the integrity of the Gr/Ep composite. The same FUT shown in Figure 11b is attached to the Gr/Ep composite shown in Figure 8 with a normal ultrasonic couplant. The measured ultrasonic signals gone through a 1MHz high pass filter using one of the four FUTs in Figure 11 at the region without and with delaminations are given in Figs.14a and 14b, respectively. The center frequency & 6dB bandwidth of the L^1 echo are 9.9MHz & 7.8MHz (with delamination), and are 6.8MHz & 10.0MHz (without delamination) respectively. The gain was 55dB out of the available 100dB receiver gain when the EPOCH LT was used. It is clearly demonstrated that FUTs may be used for SHM and NDT of Gr/Ep composites.

NON-CONTACT ULTRASONIC MEASUREMENTS

In order to achieve SHM, fast NDE and NDE of rotating components non-contact ultrasonic measurements approaches are desired. Here an induction based method is used and the Gr/Ep samples coated with IUT as shown in Figures 1 and 4 are chosen for demonstration purposes (Greve et al., 2007). Firstly a flat coil made of thin lacquer wires serves as a main component for induction coupling. The two ends of this coil are connected to the top electrode of the IUT and the Gr/Ep substrate which serves as the bottom electrode of the IUT as shown in Figure 1. Beneath this coil a thin ferrite disk of 1 mm thick was inserted. Directly on top of such coil connected to the IUT there is the other coil surrounding a ferrite and the two ends of this coil are connected to the coaxial cable of the pulser/receiver. The schematic diagram of this inductive non-contact measurement configuration is given in Figure 15a. At room temperature the measured ultrasonic signals in this composite using such a non-contact configuration are shown in Figure 15b. The ultrasonic signals shown in Figure 15b were 9dB stronger in non-contact than contact configuration for which the results were given in Figure 5. The possible reason of this 9dB increase could be the improved impedance matching between the coil and the IUT. The center frequency and 6dB bandwidth of the L^1 echo are 2.2MHz and 1.3MHz, respectively. Since the impedance matching between the inductive coils and the pulser-receiver is not optimized yet, the L^1 echo is buried into the receiver gain recovery oscillating signals as shown in Figure 14b. Further studies concerning the impedance matching and selection of ferrite and its thicknesses and locations will be carried out.

For SHM of Gr/Ep structures it is sometimes desired to embed the sensors into the host material. Even though, at present, it is not known that the FUT shown in Figure 11b can be embedded into the Gr/Ep composites without creating unwanted voids or defects, a simulation is carried out here. The poor conductive 1mm thick Gr/Ep composite shown in Figure 4 is selected for demonstration purposes. At first, the two ends of a flat coil are connected to the top electrode of the IUT and the nickel bottom electrode coated on the 1mm thick Gr/Ep plate. Then an identical Gr/Ep but bare plate without IUT and nickel coating is put on top of IUT with the coil as shown in Figure 16a. When the gap is 1mm, the measured ultrasonic signals gone through a 1MHz high pass filter in this configuration are shown in Figure 16b. The ultrasonic signals shown in Figure 16b were 3dB weaker in non-contact than contact configuration for which the results were given in Figure 3a. The center frequency and 6dB bandwidth of the L^1 echo are 5MHz and 5.2MHz, respectively. When the top 1mm thick Gr/Ep composite is removed from the measurement setup shown in Figure 15a and the 1 mm gap is kept unchanged, the measured ultrasonic signals when the 1mm thick Gr/Ep composite plate is rotated at 1000rpm are near the same as those shown in Figure 16b. Therefore the inductive non-contact method may be an excellent tool for SHM, fast NDT and NDT of rotating Gr/Ep composite parts.

CONCLUSIONS

Two types of ultrasonic sensors, IUTs and FUTs, are presented for in-situ characterization of Gr/Ep composites of thickness ranging from 1mm to 12.7mm. These piezoelectric PZT/PZT film based sensors with a film thickness $\geq 30\mu m$ were fabricated using a sol-gel spray technique. The top electrodes can be made using silver paste or colloidal silver spray to form desired array configuration with ease. In this investigation the center operation frequency of these sensors ranged from 1.3MHz to 14.5MHz. All measurements were carried out in pulse/echo mode. Both IUTs and FUTs can operate in the temperature range between -100°C to 150°C.

For demonstration purposes IUTs have been deposited directly onto planar and curved Gr/Ep composites with high and low electrical conductivities and different shapes. It is noted that such IUTs can be fabricated on site using a portable fabrication kit. For high electrical conductivity material, the Gr/Ep is used as the bottom electrode of the IUT. For low electrical conductivity material, the bottom electrodes of the IUTs were made either by electroless nickel plating or by a colloidal silver spray technique. The later is found to be simpler that the former approach. Ultrasonic signals obtained showed that IUTs could generate and receive longitudinal waves propagating in composite for more than 300mm. Also delaminations in the composite were detected and the ultrasonic anisotropy of 0° and 90° cross ply composite was measured. The commercially available handheld device can be used.

In certain situations, accessibility to desired locations of Gr/Ep components of, for example, an aircraft, is limited for the fabrication of the IUTs, thus FUT may be used. The fabrication of FUTs can be made off-line in a laboratory environment. Here, FUTs were made using 50μm thick polyimide membranes as substrates. A silver layer of ~2μm is coated onto the insulting polyimide film to serve as the bottom electrodes of the FUTs. The flexibility of such FUTs is achieved due to the thin polyimide, porous PZT/PZT ceramics and electrodes. The piezoelectric strength of these FUTs is nearly the same as the IUT deposited onto the Gr/Ep composite. Such FUTs could be attached to or bonded onto a host composite structure with planar or curved surfaces on-site. In this study FUTs have been used to evaluate Gr/Ep composites with planar and curved surfaces conveniently.

The preliminary results of an induction type non-contact method for the interrogation of the Gr/Ep composites using the IUTs are presented. Such non-contact technique is desired for SHM, NDT using an embedded sensor and NDT of rotating composite components. Results of ultrasonic measurements of a 1mm thick Gr/Ep composite plate rotated at 1000rpm were obtained. Future studies on the fabrication of IUT and FUT and the selection of ferrites, coils, etc to improve the ultrasonic signals in contact and non-contact configurations will be carried out.

ACKNOWLEDGMENTS

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Figures Captions

Figure 1. IUTs deposited onto the planar and curved surfaces of a 12.7mm thick and a radius of 50.8mm Gr/Ep composite plate.

Figure 2. The IUT_P shown in Figure1 operated by a contact configuration using a commercial handheld pulser-receiver.

Figure 3. Measured ultrasonic signals in time domain at room temperature using the (a) IUT_P and (b) IUT_C shown in Figure1.

Figure 4. An IUT deposited onto a 1mm thick Gr/Ep composite plate.

Figure 5. Measured ultrasonic signals in time domain at room temperature using the IUT shown in Figure4.

Figure 6. An IUT deposited onto a cylindrical braid 3.3mm thick Gr/Ep composite tube.

Figure 7. Measured ultrasonic signals in time domain at room temperature using the IUT shown in Figure6.

Figure 8. IUTs deposited onto a 6.9mm thick Gr/Ep composite plate having impact damages.

Figure 9. Measured ultrasonic signals in time domain at room temperature using an IUT at a location without delamination.

Figure 10. Measured ultrasonic signals in time domain at room temperature using an IUT at a location with delamination.

Figure11. (a) Schematic and (b) an actual FUT using 50μm thick polyimide membrane as the substrate.

Figure12. An FUT attached onto the external surface of a cylindrical braid Gr/Ep composite plate of 3.3mm thickness.

Figure13. Measured ultrasonic signals in time domain at room temperature using the FUT shown in Figure11.

Figure 14. Measured ultrasonic signals in time domain at room temperature at a region (a) without and (b) with delaminations using the FUT shown in Figure 11.

Figure 15. (a) Schematic diagram of an inductive non-contact measurement performed on the IUT_P shown in Figure1a. (b) Ultrasonic performance at room temperature.

Figure 16. (a) Schematic diagram of an inductive non-contact measurement performed on the IUT shown in Figure 4. (b) Ultrasonic performance at room temperature.

Figures:

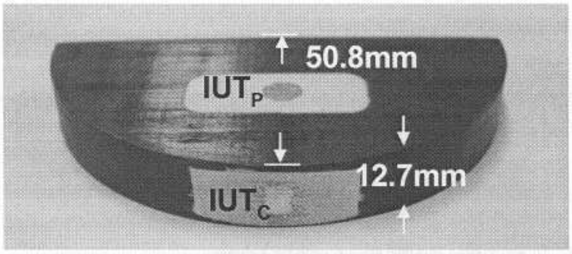


***Figure 1.** IUTs deposited onto the planar and curved surfaces of a 12.7mm thick and a radius of 50.8mm Gr/Ep composite plate.*

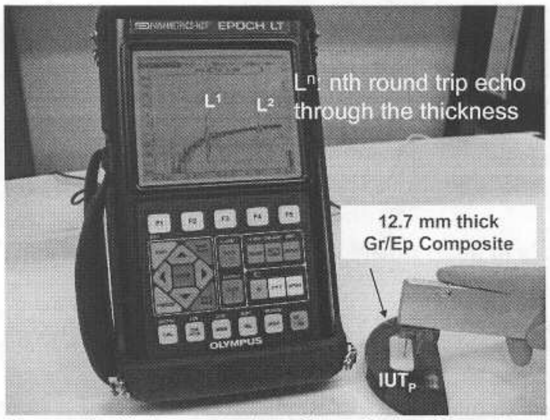
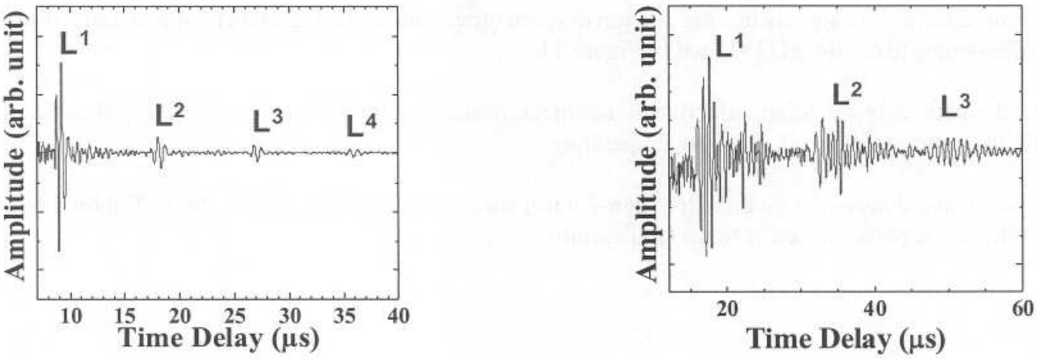


***Figure2.** The IUT_P shown in Figure1 operated by a contact configuration using a commercial handheld pulser-receiver.*



(a)

(b)

***Figure 3.** Measured ultrasonic signals in time domain at room temperature using the (a) IUT_P and (b) IUT_C shown in Figure1.*

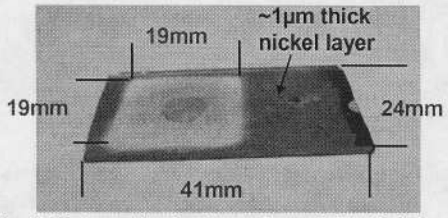


Figure 4. An IUT deposited onto a 1mm thick Gr/Ep composite plate.

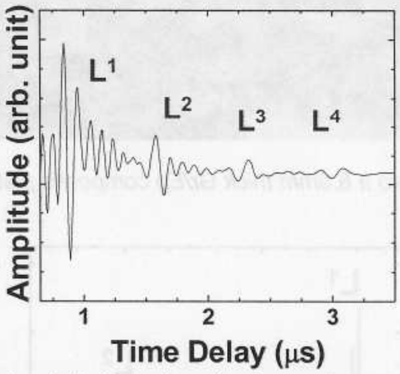


Figure 5. *Measured ultrasonic signals in time domain at room temperature using the IUT shown in Figure4.*

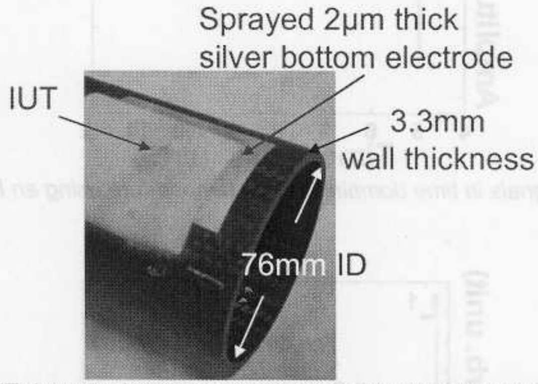


Figure 6. *An IUT deposited onto a cylindrical braid 3.3mm thick Gr/Ep composite tube.*

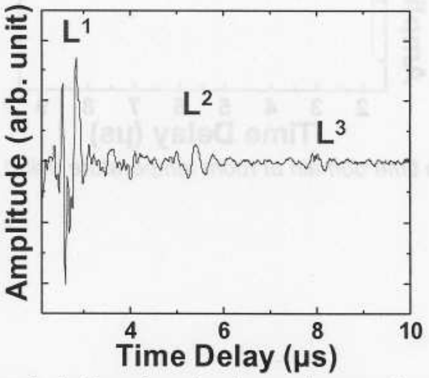


Figure 7. *Measured ultrasonic signals in time domain at room temperature using the IUT shown in Figure6.*

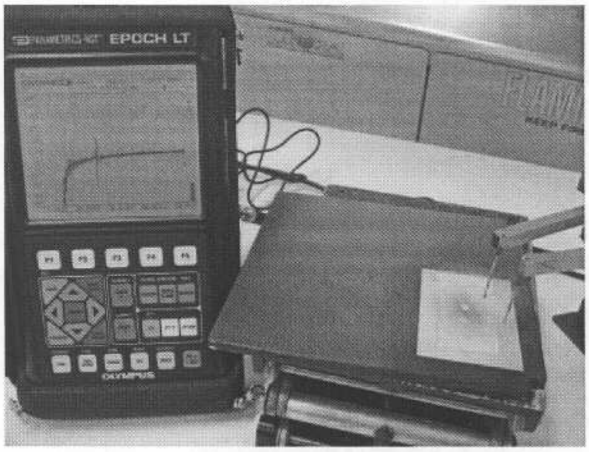


Figure 8. *IUTs deposited onto a 6.9mm thick Gr/Ep composite plate having impact damages.*

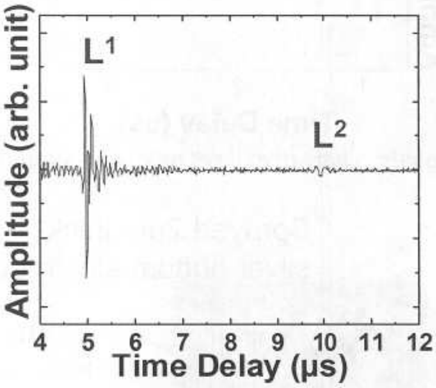


Figure 9. *Measured ultrasonic signals in time domain at room temperature using an IUT at a location without delamination.*

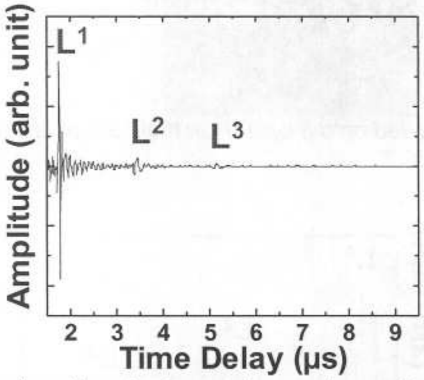
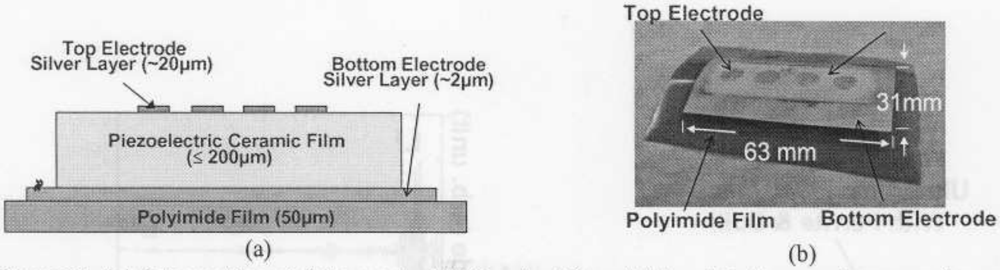


Figure 10. *Measured ultrasonic signals in time domain at room temperature using an IUT at a location with delamination.*



(a) (b)

Figure11. *(a) Schematic and (b) an actual FUT using 50µm thick polyimide membrane as the substrate.*

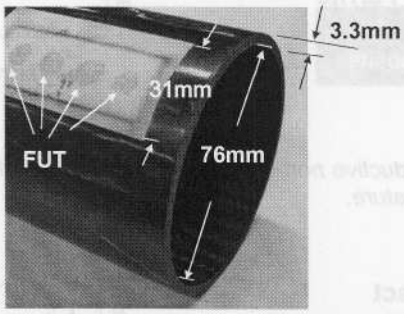


Figure12. *An FUT attached onto the external surface of a cylindrical braid Gr/Ep composite plate of 3.3mm thickness.*

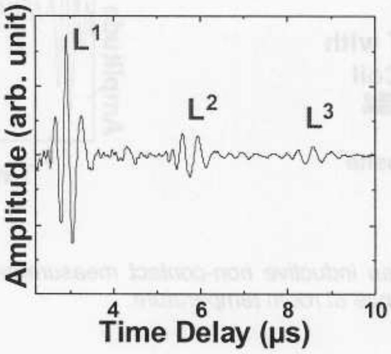
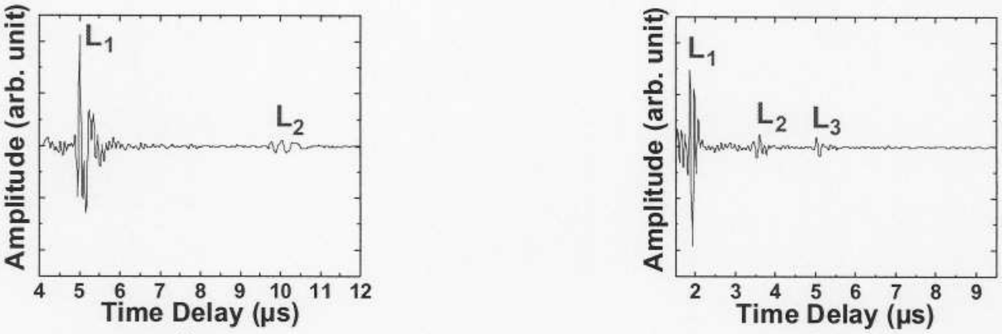
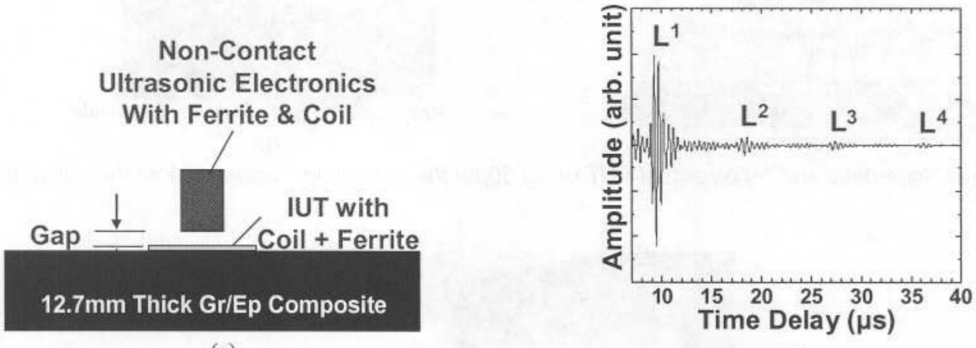


Figure13. *Measured ultrasonic signals in time domain at room temperature using the FUT shown in Figure 11.*



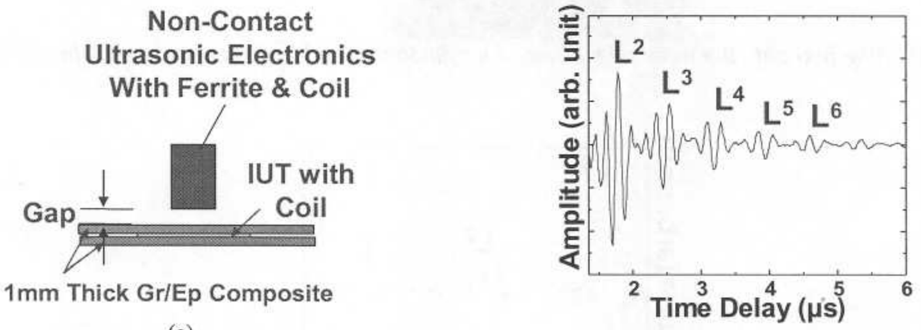
(a) (b)

Figure 14. *Measured ultrasonic signals in time domain at room temperature at a region (a) without and (b) with delaminations using the FUT shown in Figure 11.*



(a) (b)

Figure15. *(a) Schematic diagram of an inductive non-contact measurement performed on the IUT_P shown in Figure 1a. (b) Ultrasonic performance at room temperature.*



(a) (b)

Figure 16. *(a) Schematic diagram of an inductive non-contact measurement performed on the IUT shown in Figure 4. (b) Ultrasonic performance at room temperature.*