PVP-Vol. 484, Recent Advances in Nondestructive Evaluation
Techniques for Material Science and Industries
July 25-29, 2004, San Diego, California USA
PVP2004-2823

DESIGN AND PERFOMANCE OF A BROADBAND 10MHZ TRANSDUCER FOR ELEVATED TEMPERATURE, LEAVE-IN-PLACE APPLICATIONS

Michael Pedrick*, B.R. Tittmann*, and Jim Seliga*
* Department of Engineering Science and Mechanics, The Pennsylvania State University,
University Park, PA 16802

Abstract

This paper describes the novel design of an ultrasonic normal beam transducer for prolonged use in elevated temperature environments. Through the use of a Carbon/Carbon composite backing layer, prolonged exposure to elevated temperature had minimal effect on transducer performance. The conductive nature of the Carbon/Carbon allowed for an innovative electrical coupling technique. A clamping mechanism combined with the use of an annealed gold quarter-wave matching layer allowed for joint-free, dry coupling. This simple design allows for easy field assembly and eliminates temperature dependencies in the acoustic coupling. The transducer was tested initially at room temperature for reference data. Further tests after 100+ hours of exposure to a 77^0C environment showed little overall change in the transducer performance. The transducer showed consistent -6dB bandwidths on the order of 54-67%, along with negligible change in centerline frequency. The insertion loss as a function of temperature showed an increase from approximately 6.8dB to 8.5dB over a temperature range from 25^0C to 85^0C. Regression lines show bandwidth changes of -0.01% per ^{0}C and insertion loss changes of 0.03dB per ^{0}C. These results show potential use for a transducer of this design at even higher temperatures.

Introduction

Often times, industrial applications for ultrasonic non-destructive evaluation require sensors capable of withstanding elevated temperatures. Typical commercial transducers are designed for temperatures less than 50^0C [1]. More robust commercial transducers still have temperature limitations. Epoxy-based backing materials tend to soften at temperatures above 170^0C [2]. Another limitation is the drying of typical coupling fluids at elevated temperatures. All of these factors can contribute to the degradation of transducer performance over prolonged exposure to elevated temperature environments. In order for commercial transducers to be used in these types of environments, apparatus must be developed to allow for momentary contact of the sensor with the high temperature medium [2,3]. This requires more elaborate systems and is not often cost effective. Therefore, an ultrasonic transducer for these types of applications must employ a rugged design, ability to withstand elevated temperatures, and performance comparable to commercially available transducers.

A conventional design of an ultrasonic transducer consists of a piezoelectric element, backing block, and a protective front face. This "stack" is often spring loaded to ensure minimal movement among the layers. The choice of each of these materials along with their dimensions plays a crucial role in the performance of the transducer. Often times, the backing layer consists of epoxy-based material with a concentration of tungsten which can be altered to achieve certain acoustic impedance characteristics [2,4,5]. Other transducers have incorporated ceramic backings [1] which can cause difficulty in electrical and acoustic coupling. Lead Zirconate Titanate (PZT) is most often used as the piezoelectric element in commercial transducers. Due to its relatively low Curie Temperature, PZT in not useful above 300^0C [2].

Although thermal properties play a crucial role in the choice of materials, attention must be paid to the transducer performance. One must consider the electrical coupling from cable connector to the
element, impedance matching between layers, damping nature of backing material, and the acoustic coupling of energy into the propagation medium. Therefore, careful consideration must be given to the choice of materials such that the transducer can withstand exposure to elevated temperature environments.

Protecting this stack from the outside environment is vital for transducers meant for leave-in-place applications. Typical commercial housings consist of thin aluminum shells and incorporate minimum amounts of wear protection through thin protective layers in front of a piezoelectric element. Although designed with some protection, they require careful handling.

Leave-in-place sensors for most industrial applications must withstand rugged conditions associated with installation, handling, and harsh environments. This can be achieved through the incorporation of a sturdy housing, along with wear protection, and an effective clamping mechanism.

All of these considerations went into the choice of materials and coupling techniques for this transducer. Materials were chosen according to their capability to withstand temperature and ability to facilitate maximum performance of the sensor. A housing and clamping design was implemented to best protect the transducer from the outside environment. The finished sensor was tested in an oven as part of an ultrasonic target positioning system. Characterizations of the transducer at and after exposure to elevated temperatures are shown.

Materials

A novel portion of this work lies in the choice of the backing material. Carbon/Carbon has numerous aerospace applications because of its stable mechanical properties up to temperatures greater than 2000^0C [6]. Its potential as a backing material relies on its energy scattering characteristics. Carbon/Carbon has several different forms. Generally, it consists of carbon fibers embedded in a carbon matrix whose properties vary depending on the nature of fabrication [6]. For this work, a bidirectional laminate was used because of its immediate availability in the laboratory. The highly anisotropic nature and multidirectional fiber matrix composition makes carbon/carbon a candidate for an energy scattering material.

Non-contact ultrasonic evaluation has given rise to some pertinent acoustic properties of this particular carbon/carbon composite [7, 8]. Its low longitudinal velocity (1.33mm/μsec) and low density (1.42gm/cm^3) gives this material a high acoustic attenuation factor. Therefore, acoustic energy that penetrates a considerable layer of carbon/carbon will be highly damped. Considering high frequency acoustic energy (10MHz), sound transfer into and back out of a carbon/carbon layer would be minimal. The low impedance (1.89MRayls) of this composite somewhat limits its capability for acoustic impedance matching with some typical piezoelectric elements used for high temperature applications. This could hinder its ability as a backing material to effectively damp the ringing of the active element. This problem can be overcome through innovative transducer design.

An additional benefit of carbon/carbon is its electrical conductivity. At 600S/cm^2, carbon/carbon provides potential electrical coupling to the element. This allows for more versatility in the overall design of the transducer and also eliminates some of the need for difficult wiring and connections directly on the element. It also eliminates the potential failure of these connections that may be caused by induced strains due to thermal expansions. This would also increase the rugged nature of the transducer by making it less sensitive to handling as a result of the more robust electrical connection.

Lithium Niobate ($LiNO_3$) has often been cited as the most beneficial piezoelectric material for elevated temperature applications [1-4]. This is mostly due to its high Curie temperature (T_c=1200^0C) and a coupling factor (k_t=0.49) comparable to other common piezoelectric elements [4]. At temperatures above 600^0C, a loss of oxygen occurs in the crystal lattice which will hinder the efficiency of the transducer considerably [1]. As mentioned before, the high acoustic impedance (Z=34 MRayls) causes difficulty in acoustic coupling with the backing material. However, this was overcome to achieve a fairly broadband transducer.

A quarter-wave matching layer plays a crucial role in maximizing the energy propagating out of the element along with the acoustic coupling of energy into the medium. Typically, coupling is achieved through viscous type fluids. This is less useful for elevated temperature applications. Considering the leave-in-place nature of this sensor, a method for dry coupling is more desirable. A layer of gold foil provides a simple solution to the aforementioned issues. By using an annealed gold foil shim, a quarter-wave matching layer can be achieved which will allow significant energy transfer into a material. The gold foil is also beneficial for an electrical lead contact to the element. As for elevated temperature environment, gold foil has been used up to 500^0C as a means for acoustic coupling [3].

Transducer Design

This design follows the general schematic of commercial transducers as shown in Fig. 1 with some variations in electrical coupling, housing, and clamping mechanism. The initial application for this transducer called for a 10 MHz centerline frequency. The thickness of the element was then determined according to:

$$\frac{\lambda}{2} = \frac{v}{2f} \qquad (1)$$

where λ is the wavelength, v is the velocity and f is the centerline frequency. A thickness of ½ wavelength ensures maximum energy propagation at the centerline frequency. With a longitudinal velocity of 7.34mm/μsec, a lithium niobate element thickness of 365μm is required. A lithium niobate wafer of 12.7mm diameter and thickness of 350μm was obtained from Boston Piezo-Optics, Inc. This thickness corresponds to a centerline frequency of 10.48MHz. This equation does not consider the resonance shift caused by mass loading of the entire stack. Considering a broadband transducer, this shift is minimal and does not affect the overall performance of the sensor. The wafer was also coated with chrome and gold on both surfaces to promote electrical contact. Finally, the wafer was polished for potential overtone use. This aspect was not explored.

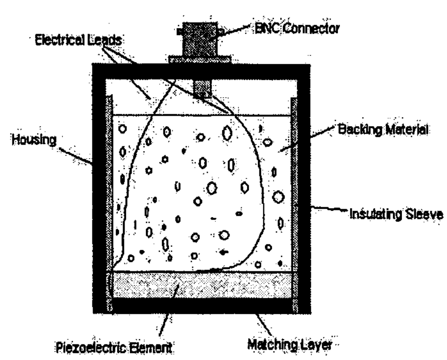

Fig. 1: General Schematic of an Ultrasonic Transducer

A cylindrical slug of Carbon/Carbon was cut out of an existing sample section. The faces of the sample were then machine polished to maximize the surface contact between the element and the backing layer. The slug was approximately 25 mm long with a diameter of 12.7mm. A general rule of thumb calls for a backing layer 10x that of the element thickness. Because of the unconventional use of Carbon/Carbon, a longer specimen was chosen to increase the attenuation and scattering effect of the backing layer.

In order to maximize energy transfer into the medium, a quarter-wave gold layer was implemented. For the particular application, the transfer medium was inconel. Knowing the impedance in inconel and lithium niobate, the optimum matching layer impedance can be determined according to:

$$Z_m = (Z_1 Z_2{}^2)^{\frac{1}{3}} \qquad (2)$$

where Z_1 is the impedance of the piezoelectric element (33 MRayl) and Z_2 is the impedance of the load medium (47.2 MRayl). This leaves an ideal impedance of 41.9MRayl. With an acoustic impedance of 61.4MRayl, annealed gold was not ideal for impedance matching.

Despite these drawbacks, gold foil proved to be an effective quarter wave matching layer. Since the wavelength is on the order of 700 μm, a gold layer thickness of $\lambda/4$ is not feasible considering its structural sensitivity and difficulty in adhesion. Therefore, a gold film on the order of 900 μm or $5\lambda/4$ was used since it has been shown that odd integer multiples of a quarter wavelength can be effective matching layers [5].

A nylon inner sleeve was machined to 12.7mm inner diameter and 16mm outer diameter. This provided both mechanical protection and electrical insulation between the center stack and the outer housing. The housing was machined from a stainless steel tube with approximately a 3mm thickness. The inner diameter was 16.1mm to comply with the nylon sleeve, leaving an outer diameter of approximately 19mm. The outer diameter was turned down approximately 1.5mm making a recessed section with a height of approximately 6 mm compared to the 26mm overall height of the housing itself. This recessed portion was used to adhere a thin section of copper tape to the housing, providing a material for the gold foil to be soldered to. Copper tape is often used as an electrical ground in association with Scanning Acoustic Microscopy and served a similar purpose for this design.

The final concern for the structural design of the transducer was the backing wear plates and insulation. Several small ceramic discs of 1mm thicknesses were machined to a 12.7mm diameter along with two stainless steel wear discs of similar dimensions. The two ceramic discs were used to electrically isolate the backing layer from the wear disc, ultimately isolating it from the housing. The wear discs were simply used to protect the center stack as well as act as strong surface for the pressure contact of the clamping mechanism to be discussed later.

A simple yet effective approach was taken to form the necessary electrical connections of the transducer. Because of the need for pressure coupling on the back surface of the transducer, the connector was side mounted. A small hole was drilled through the side of the stainless steel housing, the nylon sleeve, and approximately 3mm into the Carbon/Carbon backing. A copper slug was then fitted into the hole of the Carbon/Carbon. A small wire was soldered to the slug and encased in a miniature ceramic tube to keep the wire electrically insulated from the housing. The other end of the wire was then soldered to the center pin of a sub-miniature BNC connector that was threaded into the housing. The impedance across this electrical path shown in Fig. 2 of >1μF was measured with a Digital Multimeter confirming an electrical path to the Lithium Niobate element.

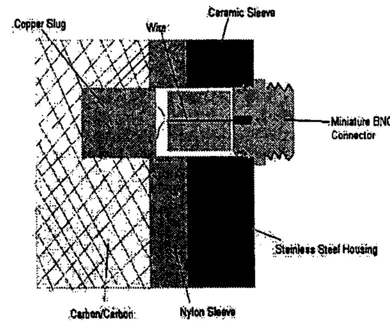

Fig. 2: Shows a close-up of the electrical connection between the BNC connector and the Carbon/Carbon backing.

As a result of the design, the housing was used as the electrical ground. The connection is made through the pressure contact between the element and the gold foil, which is soldered to the copper tape, which is adhered to the housing. The housing is in direct contact with the male threads of the BNC connector, a typical location for soldering a ground wire. This helps the overall rugged nature of the transducer of which a full schematic is shown in Fig 3.

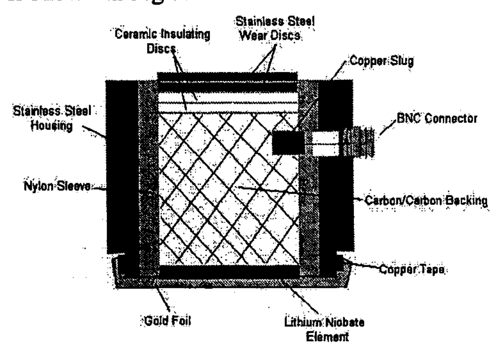

Fig. 3: Schematic Cross Section of the Novel Ultrasonic Transducer

To make this a leave-in-place sensor, a clamping mechanism was applied to attach the transducer to the inconel housing used in experimentation. Two thin threaded rods were screwed into the inconel housing. A plate was then screwed onto the two rods. Attached to the plate was a spring-loaded screwing mechanism with a small rubber disc to apply pressure onto the center stack. Care was taken to ensure that pressure was only applied to the center stack to avoid placing any shearing force on the element, gold foil, or the electrical connections. A picture of the transducer and the hold down mechanism are shown in figure 4.

Transducer Characterization

The experimental setup consisted of the transducer on a water-filled inconel chamber. A target reflector was located inside the water chamber. This system was placed in an oven with temperature readouts according to a thermocouple. Toneburst excitations were generated with a Matec Standalone TB1000. Signals were received, digitized, and analyzed with a Tektronix TDS 3012B oscilloscope. The setup is shown in Fig. 5.

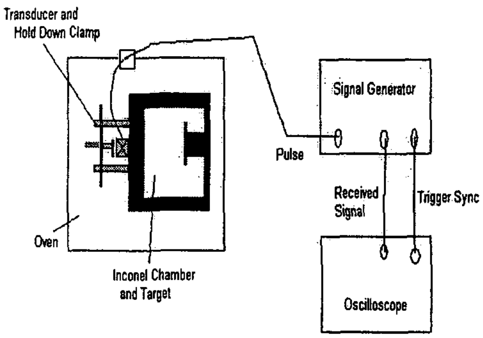

Fig. 5: Experimental Setup used to evaluate Transducer performance

The transducer was first evaluated at room temperature to setup some initial performance parameters. The impedance of the transducer as a function of excitation frequency was measured with a Network Analyzer. The frequency at which the impedance is a minimum represents the centerline frequency of the transducer. In this case, the centerline frequency was 9.57MHz. This value is slightly less than the desired 10MHz but is a result of the additional mass loading mentioned before.

The frequal content was also a concern. The first roundtrip reflection from the target surface was used for analysis. An initial bandwidth of 64% was measured leading to the qualification of this transducer as broadband. These measurements were then repeated after a period of 100+ hrs of exposure to 77^{0}C environments consisting of several transitions between room temperature and elevated temperature. The –6dB bandwidth and impedance were then measured for comparison. These measurements were then repeated at temperatures ranging from 25^{0}C to 77^{0}C to determine the temperature dependency of the transducer performance.

Finally, insertion loss was measured as a function of temperature after 100+ hrs of exposure to 77^{0}C environments. Typically, insertion loss is measured by comparing the received and transmitted amplitudes of signal passing through water and reflecting off of a target surface according to:

$$I_L = 20\log\left[\frac{V_1}{V_2}\right] \qquad (3)$$

where V_1 is the peak to peak amplitude of the emitted signal and V_2 is the peak to peak amplitude of the received signal. Because of the constraints of this application, the energy must first traverse through a layer of inconel. The low attenuation of fine grained inconel makes the loss due to this added layer negligible.

Results

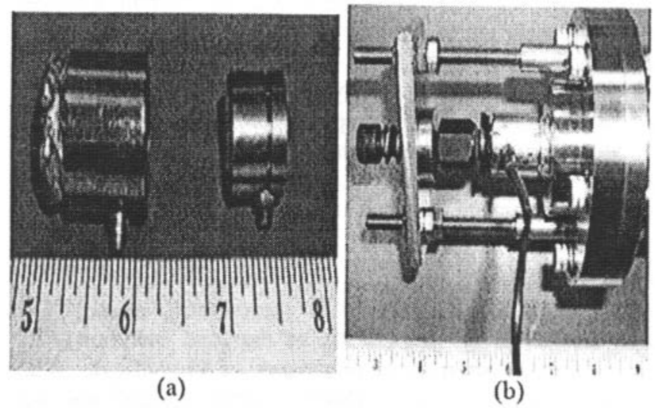

Fig. 6: (a) fabricated transducer (left) along with commercial transducer of the same size and frequency (right) for comparison (b) transducer and clamping mechanism

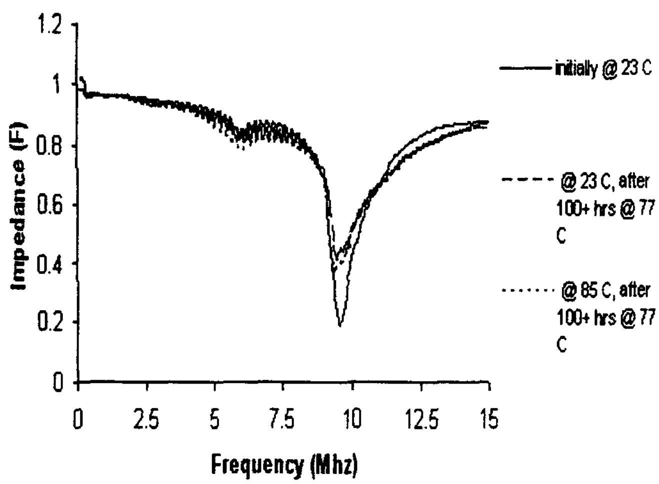

Fig. 7: Results from Network Analyzer showing Impedance vs. Frequency at different stages of temperature exposure

The results for bandwidth and insertion loss as functions of temperature are shown in Figs 8 and 9, respectively. A second order trendline was added to each curve to determine the transducer's potential capabilities beyond the temperature range tested. Both curves were extremely linear. Over this range, the bandwidth decreased 0.01% per ^{0}C and the insertion loss increased 0.03 dB per ^{0}C

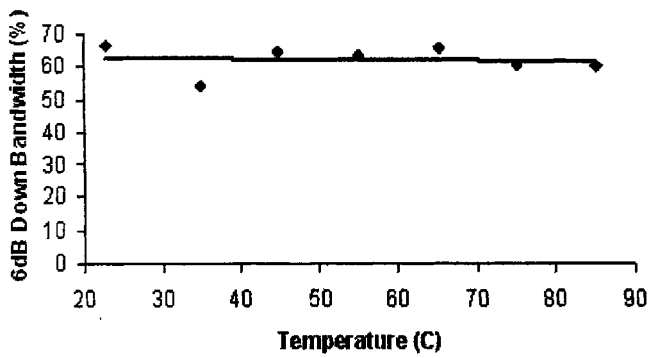

Fig. 8: -6dB bandwidth as a function of temperature ranging from 53% to 67%

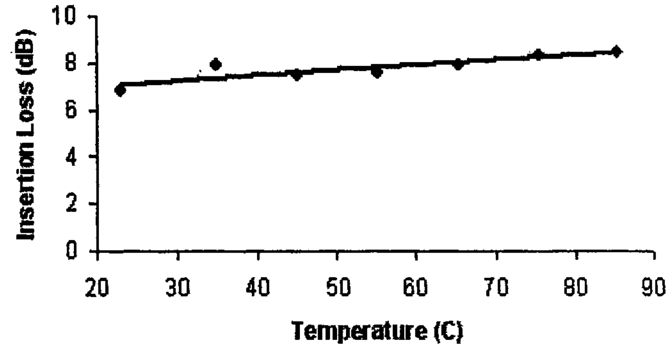

Fig. 9: Insertion loss as a function of temperature which ranges from 6.8 dB at room temperature up to 8.5 dB

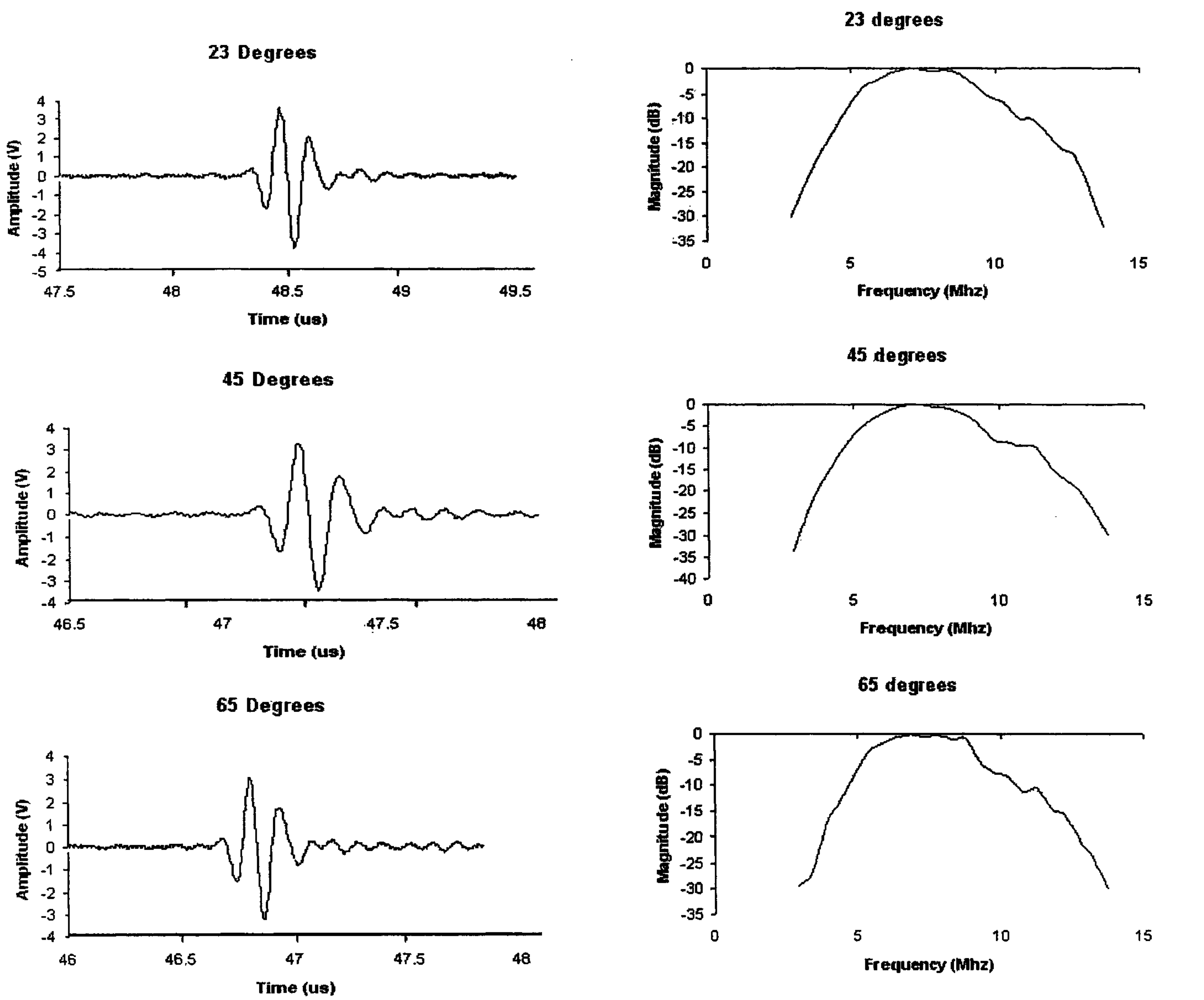

Fig. 8: (left column) Reflection from the target using the fabricated transducer at different temperatures (right column) The corresponding frequency spectrum used to analyze the bandwidth of the transducer

Conclusion and Discussion

Numerous evaluations at different stages of temperature exposure show that this transducer design is suited for operation at elevated temperatures. Small changes were found in the minimum impedance of the transducer but, there were no changes in the centerline frequency and the shape of the curve was maintained throughout testing. This caused a small shift in the coupling factor but little to no shift in the frequency/bandwidth characteristics of the transducer. These conclusions were supported by the measurements of bandwidth and insertion loss as a function of temperature as well as the qualitative analysis of the rf waveform at differing temperatures.

Although only tested up to 85^0C, the results show promise in transducer performance at even higher temperatures. The inability to control phase transition of water at higher temperatures prohibited experimentation at these higher temperatures. Work is currently being done to further model the performance of this transducer as well as, developing a testing apparatus for analysis at higher temperatures. The feasibility of transducer miniaturization is being examined to further increase the potential application for this technology.

References

[1] McNab, A; Kirk, K.J.; Cochran, A.; Ultrasonic Transducers for High Temperature Applications. IEEE Proceeds-Scient. Meas. Technology, vol 145, n5, September, 1998. p 229-236

[2] Tittmann, B.R.; Aslan, M.; Ultrasonic Sensors for High Temperature Applications. Jpn Journal of Applied Physics, vol 38, 1999, p 3011-3013

[3] Lynnworth, L.C. Ultrasonic Measurements for Process Control. Academic Press. 1989

[4] Cannata, J.M.; Ritter, T.A.; Chen, W.; Silverman, R.H.; Shung, K.K.; Design of Efficient Broadband Single-Element (20-80 MHz) Ultrasonic Transducer for Medical Imaging Applications. IEEE Trans. Ultrasonics, Ferroelectrics, and Frequency Control, vol 50, n11, November, 2003, p Imaging Applications. IEEE Trans.

[5] Nascimento, V.M.; Nantes Button, V.L.; Maia, J.; Costa, E; Oliviera, J.V.; Influence of Backing and Matching Layers in Ultrasound Transducer Performance. SPIE Medical Imaging: Ultrasonic Imaging and Signal Processing, vol 5035, 2003, p 86-96

[6] ASM Handbook. v 21. 2001. p865-866

[7] Tittmann, B.R.; Bhardwaj, M.; Vandervalk, L.; Neeson, I.; Non Contact Ultrasonic NDE of Carbon/Carbon Composite. Proc. of American Ceramics Society. January 1999.

[8] Tittmann, B.R. Acoustic Microscopy for the Characterization of High Temperature Composites