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FLEXIBLE ULTRASONIC TRANSDUCERS

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INDEX TERMS

flexible ultrasonic transducer, high temperature, structural health monitoring, non-destructive testing, sol-gel spray technique

ABSTRACT

Flexible ultrasonic transducers (UTs) consisting of a metal foil, a piezoelectric ceramic film and a top electrode have been developed. The flexibility is realized owing to the porosity of piezoelectric film and the thinness of metal foil. In this paper, the stainless steel, lead-zirconate-titanate (PZT)/PZT composite and silver paste were chosen as metal foil, piezoelectric film and top electrode materials, respectively. The stainless steel foil serves as both substrate and bottom electrode. The PZT/PZT piezoelectric composite film is made by the sol-gel spray technique. PZT/PZT films of thicknesses from 40 to 70 μm were fabricated onto SS foils. The capability of these flexible sensors operated in the pulse/echo mode for non-destructive testing on flat and curved surfaces of different materials at room temperature and 160°C has been demonstrated. Simulations of the effects of the metal foil thickness on the ultrasonic performance of flexible UTs were also carried out, and the results are in reasonable agreement with experimental data. In addition, the PZT/PZT piezoelectric film UTs deposited onto a long steel buffer rod delay line showed a signal strength comparable with that obtained by commercial room temperature narrow bandwidth UTs.

I. INTRODUCTION

In-situ structural health monitoring and on-line diagnosis and off-line nondestructive testing (NDT) are necessary to identify, characterize, assess the voids, defects and damages and qualify repairs in many industrial applications, such as aerospace, marine, nuclear structures, etc [1-4]. Ultrasonic techniques are frequently used for these purposes because of their subsurface inspection capabilities, fast inspection speed, simplicity and ease of operation. In these applications, ultrasonic transducers (UTs) may need to contact directly with the inspection object. However, many metal, polymer or composite material parts have curved surfaces or complex geometries such as pipes and conventional UTs show poor inspection performance [1,3]. Flexible UTs are suitable for these applications because they insure the self-alignment to the object surface even with curved or complex geometry so that the transmitted ultrasonic energy can be maximized to improve diagnoses [3].

The required characteristics of flexible UTs are capability to transfer ultrasonic energy into various materials, including polymer or carbon composite with moderately high attenuation characteristic, reliability and cost effectiveness. Furthermore, several industrial applications require high temperature (HT) operation of UTs to perform in-situ characterization of materials, real-time process monitoring, and NDT [5,6]. This leads to our research interest in developing flexible UTs, which may be operated at HT.

As for commercially available flexible UTs, piezoelectric polymers such as polyvinylidene fluoride (PVDF) [7] and piezoelectric ceramic/polymer composites [5,8] are mainly used as piezoelectric materials. Both materials include polymer which prevents the use of such flexible UTs at elevated temperature. For instance, PVDF shows significant piezoelectric deterioration above 65°C. Several copolymers have superior temperature stability compared to

PVDF, however, operation temperature is limited to around 90-100°C [7]. In addition, piezoelectric polymers have low electromechanical coupling constants [9,10]. Piezoelectric ceramic/polymer composites may have superior electromechanical coupling properties compared to bulk piezoelectric ceramics or piezoelectric polymers in addition to flexibility and low dielectric losses [11], since high temperature resin becomes soft because of its glass transition at 150°C, good ultrasonic performances were reported only up to 80°C in particular under thermal cycling environment [5]. Other flexible HTUTs in the literatures [12,13] have been also reported. Because of single crystal films used, in order to provide the flexibility, the thickness of the piezoelectric film is thin, from 0.2 to 10 μm . The operating frequency was normally higher than 30 MHz and it might not be suitable for NDT of thick and highly attenuating materials [14-16].

This study proposes a new concept for flexible UTs to meet these demands. They consist of a metal foil, a piezoelectric ceramic film and a top electrode. Onto these foils thick piezoelectric lead-zirconate-titanate (PZT)/PZT films are fabricated by the sol-gel spray technique [17,18]. The top electrode can be made of silver paste. The flexibility is achieved because of the porosity in the composite films and thin thickness of the foil. Since polymer is not used in the sensor configuration, this flexible UT enables the use at HT. In this paper, we focus on PZT/PZT composite because of its high piezoelectric strength and Curie temperature of 350°C. Ultrasonic performance in pulse-echo mode will be investigated for different materials with various geometries, such as steel pipe, and flat graphite/epoxy composite and high-density polyethylene (HDPE) plates. For steel pipe ultrasonic measurements at 160°C will be presented. Simulation results are to be compared with experimental data to examine the effects of the metal foil thickness on the ultrasonic performance. In order to demonstrate the good piezoelectric strength of PZT/PZT film, the film is also fabricated onto a steel buffer rod delay line and the

reflection echoes from the end of the buffer rod will be compared with those obtained by commercial UTs.

II. FABRICATION AND CHARACTERISTICS OF PIEZOELECTRIC CERAMICS

The piezoelectric PZT powders were purchased with a particle size distribution of 1-3 μm . The powders were dispersed into PZT sol-gel solution by the ball milling method to achieve the paint. The final PZT powders were estimated of sub-micron size. An airbrush was then used to spray the PZT/PZT sol-gel composite directly onto stainless steel (SS) foils. The thicknesses of SS foils were 38 and 75 μm to assure the flexibility. The foil served as both substrate and bottom electrode. The stainless steel was selected because of its high corrosion resistance. With the sol-gel spray technique, the PZT/PZT films can be produced at desired locations through a paper shadow mask onto the thin SS foils. After spray coating, thermal treatments such as drying, firing and annealing were carried out at temperatures of 90, 430 and 650°C, respectively with optimal time duration. Multiple layers were made in order to reach the desired thickness. The films were then electrically poled using the corona discharging technique. For corona poling, the temperature of the thin SS substrate was around 120°C and a high positive voltage supplied from a 28 kV DC power supply was fed into a thin and sharp needle located several centimeters above the PZT/PZT film coated on the SS foil, which serves as the ground electrode. The distance and voltage were optimized for different film thicknesses and geometries. The poling time was about 10 minutes. The corona poling method was chosen because it could pole the piezoelectric film over a large area with different curvatures and with ease. Finally, silver paste painting was used to form the top electrode at room temperature. This convenient approach

makes the selection of electrode size, i.e. the sensor size, simple. The silver paste had been tested and its operating temperature could be up to at least 220°C.

In this investigation, the thickness range of the PZT/PZT films fabricated by sol-gel spray technique was from 40 to 70 μm , and it provided operation frequency range from 2 to 15 MHz. This frequency range is commonly preferred for NDT applications because it provides sufficient time delay resolution and allows acceptable ultrasonic attenuation in metals, composites and polymers. It is noted that PZT sol-gel solution contributed as bonding material between the PZT powder and the metal foil substrate. The dielectric constant of the PZT/PZT films was around 140 measured by a Hewlett Packard 4192A LF Impedance Analyzer at 1 kHz. This value was lower than that of PZT/PZT on a bulk substrate, that was around 320 [19]. It was probably due to the different temperature profiles during the thermal treatments. A porosity of more than 20 volume % was estimated from the relatively low dielectric constant of the PZT/PZT films. The electromechanical constant of the composite film was measured to be 0.07 [20].

III. ULTRASONIC PERFORMANCE

A. Steel pipe at room and elevated temperature

Developed flexible UTs can operate in pulse-echo, pitch-catch and transmission configurations. Here only measurements obtained in the pulse-echo mode are presented. At first, a section of a steel pipe was chosen as the test object and Figure 1 shows an experimental setup. The flexible UT, composed of a 40 μm thick PZT/PZT film, a 75 μm thick SS foil and a silver paste top electrode, was attached by a mechanical holder onto the steel pipe with outer diameter of 102 mm, inner diameter of 46 mm, and a length of 205 mm. A viscous oil ultrasonic couplant was placed between the SS foil and the outer surface of the pipe.

The steel pipe was heated up by a hot plate while measuring ultrasonic signals and the surface temperature of the pipe. The ultrasonic performances in the time and frequency domains at room temperature are shown in Figure 2 (a) and (b), respectively. In Figure 2(a) L_2 , L_4 and L_6 are respectively the 1st, 2nd and 3rd round-trip reflected echoes through the thin SS foil, couplant and the wall thickness of the steel pipe. The ultrasonic signal L_2 at room temperature shows a signal-to-noise ratio (SNR) of about 36 dB. In this paper, SNR is defined as the ratio of the amplitude of the first echo L_2 traveling one round trip throughout the thickness over that of the noise between the echoes. The center frequency and 6 dB bandwidth of L_2 were about 9.7 MHz and 5.6 MHz, respectively. Figure 3 shows the ultrasonic performance in time domain at 160°C. The SNR of L_2 remains almost the same as that at room temperature, although signal strength at 160°C was reduced to 28 dB. The reduction of 8 dB in signal strength and limitation to 160°C were due to the high temperature liquid couplant, which was gradually evaporated at elevated temperature. The PZT/PZT composite film has been used up to 220°C [19]. The test results show that this particular flexible UT can be bended into a curvature of a radius of 15 mm without damaging the ultrasonic performance. It is expected that lower metal foil and PZT/PZT composite film thicknesses will enhance the flexibility.

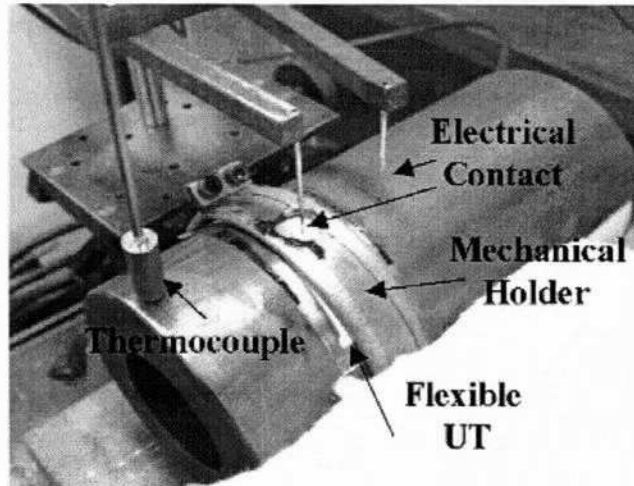


Fig. 1. A PZT/PZT flexible HTUT attached onto a steel pipe by a mechanical holder.

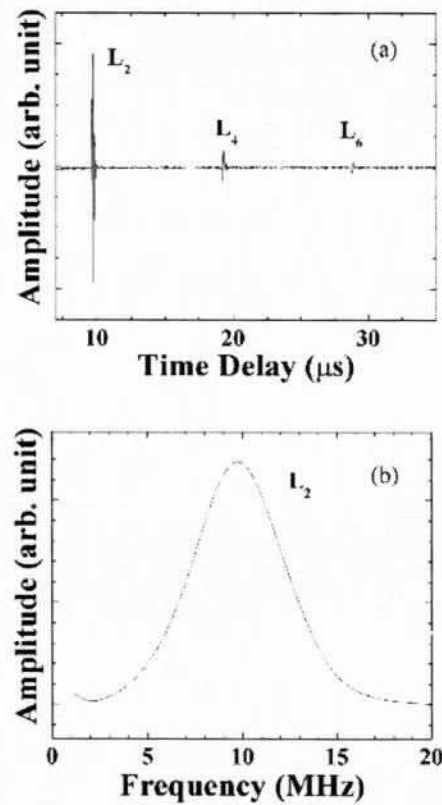


Fig. 2. Ultrasonic performance of PZT/PZT flexible UT in the pulse-echo measurement configuration shown in Fig. 1 in the (a) time domain and (b) frequency domain at room temperature.

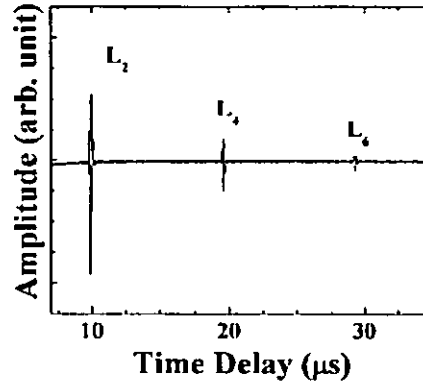


Fig. 3. Ultrasonic performance of PZT/PZT flexible UT in the pulse-echo measurement setup shown in Fig. 1 in the time domain at 160°C.

B. Graphite-epoxy composite and HDPE plate at room temperature

In this section, a flat graphite/epoxy composite plate was chosen as the test object to show the capability of the flexible UT. Graphite/epoxy composites are widely used in the aerospace industry because of their high strength over weight ratio. They can be subjected to harsh environments during service and internal damages may occur, and inspection is necessary [14,15]. Figure 4 shows a measurement configuration. The flexible UT, composed of a 70 μm thick PZT/PZT film, a 75 μm thick SS foil and a silver paste top electrode was attached onto a 30 mm thick, 213 mm by 22.9 mm graphite/epoxy composite plate using aluminum tape. An oil ultrasonic couplant was placed between the SS foil and the graphite/epoxy composite flat plate. The ultrasonic performance at room temperature of the first round trip echo L_2 through the thickness in time and frequency domains are shown in Figures 5 (a) and (b), respectively. As we can see, the ultrasonic signal shows a SNR of about 5 dB. The center frequency and 6 dB bandwidth were about 750 kHz and 880 kHz, respectively. The low center frequency and bandwidth were caused by the high ultrasonic attenuation within the thick composite. In

principle, the ultrasonic attenuation is proportional to the operation frequency squared. The higher frequency components suffer significant ultrasonic loss. It is expected that the L_2 with improved SNR can be obtained if the thickness of the PZT/PZT film increases and the center frequency of the flexible UT decreases. It is noted that the flexible UT also can be glued to the graphite/epoxy composite plate for ultrasonic measurements.

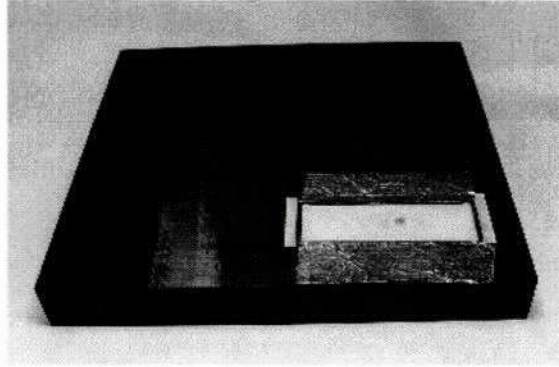


Fig. 4. A PZT/PZT flexible UT attached onto a carbon composite plate by aluminum tapes.

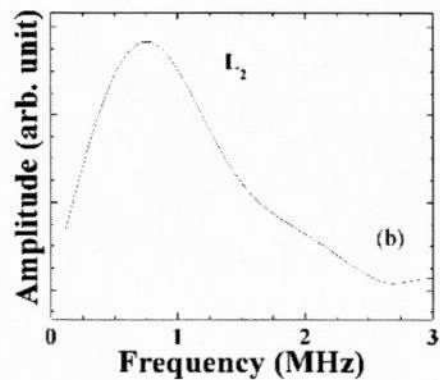
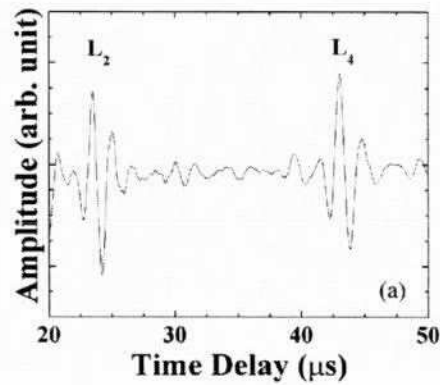


Fig. 5. Ultrasonic performance of PZT/PZT in the pulse-echo measurement configuration shown in Fig. 4 in the (a) time domain and (b) frequency domain at room temperature.

A HDPE plate was also chosen as another test sample to demonstrate measurement ability of flexible UT for polymers. HDPE is commonly used as the material for gasoline tanks used in automotive industry [16]. Figure 6 shows the measurement configuration. Part of the flexible UT showed in the last section was cut into a 10 mm square and glued onto a 7 mm thick, 56 mm by 75 mm HDPE plate. This glue also served as the ultrasonic couplant between the flexible UT and HDPE plate. The ultrasonic performance at room temperature in time and frequency domains are shown in Figures 7 (a) and (b), respectively. The 1st, L₂, and 2nd, L₄, round-trip reflected echoes through the thickness can be observed. The center frequency and 6 dB bandwidth were about 6.5 MHz and 6.0 MHz, respectively.

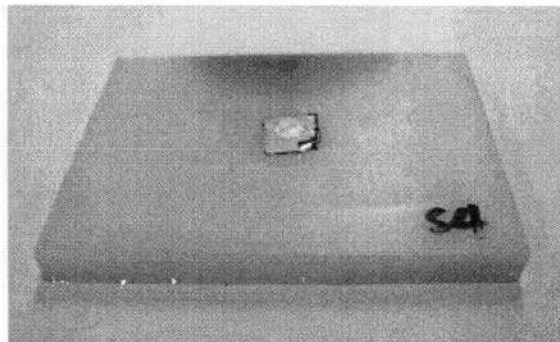


Fig. 6. A PZT/PZT flexible UT glued onto a HDPE plate.

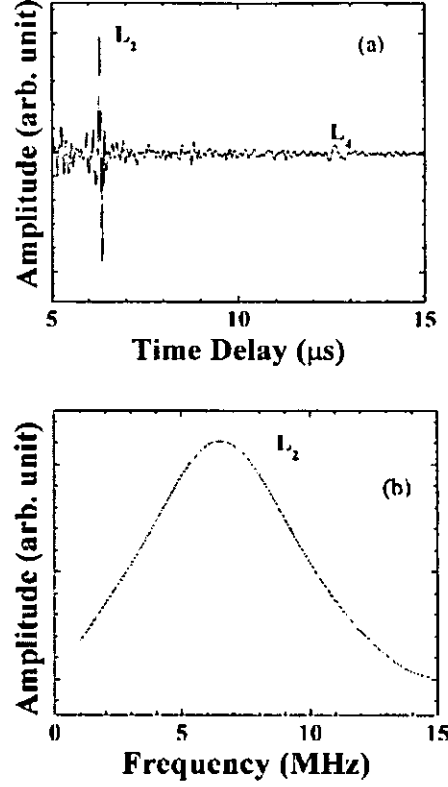


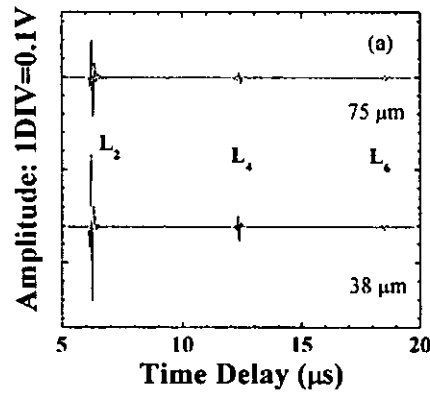
Fig. 7. Ultrasonic performance of PZT/PZT flexible UT in the pulse-echo measurement configuration shown in Fig. 6 in the (a) time domain and (b) frequency domain at room temperature.

C. Substrate thickness dependence for ultrasonic performance

In order to assure the flexibility, the thickness of the SS foil must be thin enough. However, foil thickness has influences on the ultrasonic performance of the flexible UT such as frequency and coupling mechanism from this metal foil to a test sample. Therefore, experiments with different foil thicknesses were performed. First, PZT/PZT films about 70 μm thick were deposited onto 38 and 75 μm thick SS foils. Both samples were fabricated under the same process. Each samples had a silver paste top electrode with diameter of 6 mm. The test object was a 19.0 mm thick aluminum plate. The results at room temperature of the 1st round-trip echo

L_2 in time and frequency domains are shown in Figures 8 (a) and (b), respectively. It is found that the flexible UT coated onto a 38 μm thick SS foil shows a higher signal strength by 5 dB and a higher center frequency than that coated onto a 75 μm thick foil.

In order to verify this tendency, theoretical calculations were carried out for the comparison to experimental results. The transfer matrix formalism [21] was used to evaluate the ultrasonic wave interaction with a multilayered structure composed of a silver paste top electrode, a PZT/PZT piezoelectric film, a SS foil, a silicone oil layer as couplant, and a 19.0 mm thick aluminum plate. Information on each layer, such as thickness, density, longitudinal wave velocity was required for the calculations. The data for PZT/PZT was taken from Ref. [22]. The results of the first echo L_2 in time and frequency domains are shown in Figures 9 (a) and (b), respectively. A fairly good agreement of the tendency, i.e. relative signal strength and center frequency of L_2 for different SS foil thicknesses, is found between the experimental and calculated results. Our calculations also show that even thinner foil can be used while not disturbing the ultrasonic performance of the flexible UT. It is noted that the detailed pulse shape and duration between experiment and calculation are different. It is mainly due to the ignorance of the loss factor in the PZT/PZT film.



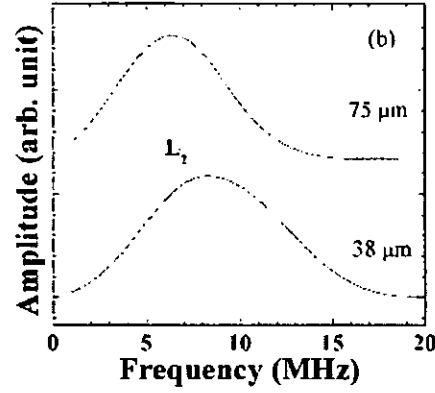


Fig. 8. Experimental results of PZT/PZT flexible UTs with 38 and 75 μm thick SS foils onto a 19 mm aluminum plate in the (a) time domain and (b) frequency domain at room temperature.

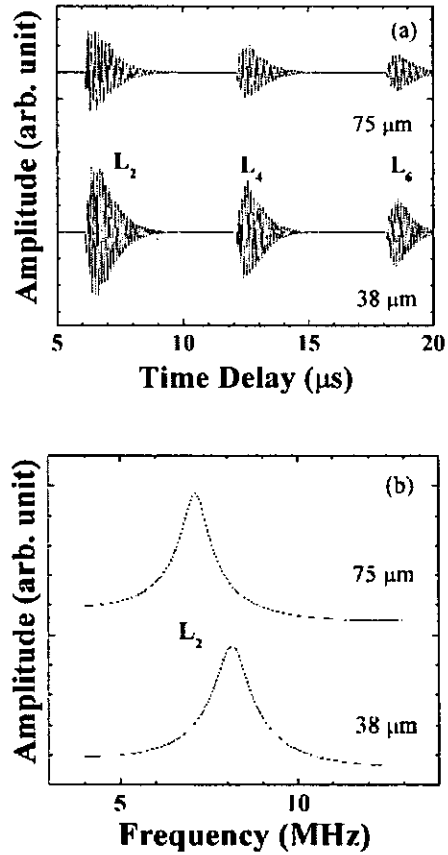


Fig. 9. Calculated results of PZT/PZT flexible UTs with 38 and 75 μm thick SS foils onto a 19 mm aluminum plate in the (a) time domain and (b) frequency domain at room temperature.

D. Comparison with commercial ultrasonic transducers

High piezoelectric strength is one of the desired characteristics of flexible UTs. Ultrasonic performances of our flexible UTs were demonstrated with various materials and geometries. Here we would like to directly compare the ultrasonic signal strength of the flexible UT with that of commercially available UTs. For such a comparison, instead of depositing PZT/PZT film on a SS foil, it was directly fabricated onto a 61 mm long steel clad buffer rod ultrasonic delay line [23]. After poling, the silver paste top electrode was fabricated. The sample is shown in Fig. 10. The ultrasonic performance at room temperature of the first round-trip echo L_2 in time and frequency domains are shown in Figures 11 (a) and (b), respectively. The SNR was about 35 dB. The center frequency and 6 dB bandwidth were about 8.2 MHz and 6.2 MHz, respectively. Then, a commercial narrow bandwidth (high penetration) UT was attached with a couplant onto the other side of the buffer rod. The ultrasonic performance at room temperature of L_2 in time and frequency domains are shown in Figures 12 (a) and (b), respectively. It is seen that the signal strength of L_2 produced by PZT/PZT UT is comparable with that received by the commercial UT. In fact, the signal frequency bandwidth is broader if a PZT/PZT UT is used instead of the commercial UT.

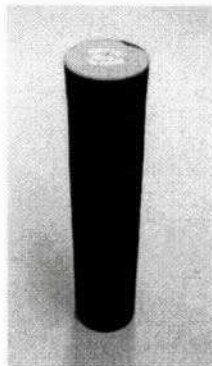


Fig. 10. PZT/PZT UT coated onto a 61 mm long steel clad buffer rod.

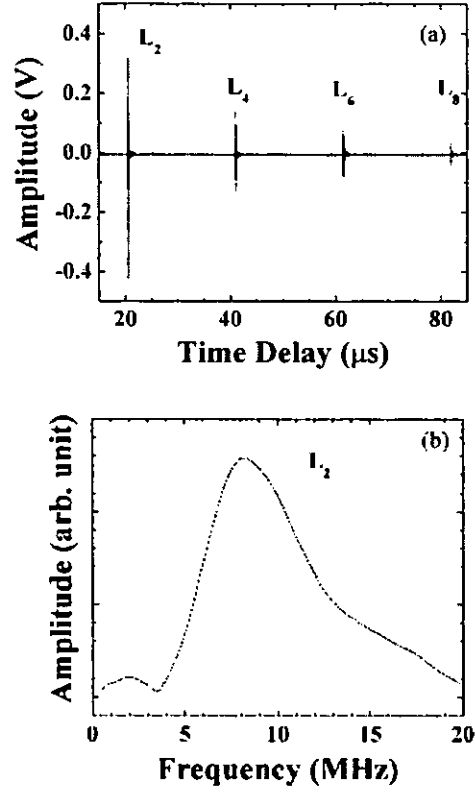
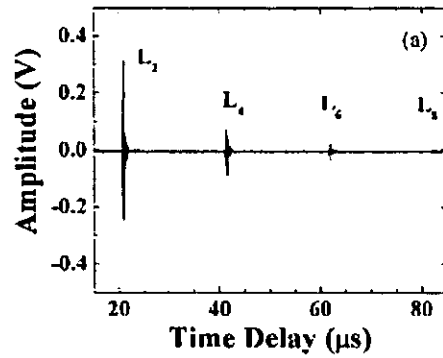


Fig. 11. Ultrasonic performance of PZT/PZT UT in the pulse-echo measurement configuration shown in Fig. 10 in the (a) time domain and (b) frequency domain at room temperature.



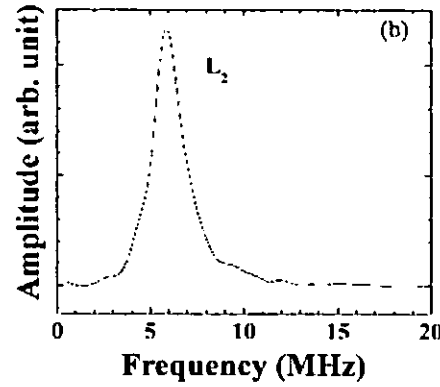


Fig. 12. Ultrasonic performance of a commercial narrowband UT with a similar setup in the (a) time domain (b) frequency domain at room temperature.

IV. CONCLUSION

Flexible ultrasonic transducers (UTs) consisting of a metal foil, a piezoelectric ceramic film and a top electrode were developed. Ball-milled PZT sub micrometer powders were dispersed into a PZT solution to achieve the paint that was then sprayed onto metallic foils at room temperature. Thermal treatments up to 650°C were required. Films with desired thicknesses have been obtained through multilayer coating approach. Piezoelectricity was achieved using the corona discharge poling method. The flexibility is realized owing to the porosity of piezoelectric film and the thinness of metal foil. In this study, SS, PZT/PZT composite and silver paste was chosen as metal foil, piezoelectric film and top electrode materials, respectively. The SS foil serves as substrate and bottom electrode simultaneously. PZT/PZT films of thicknesses from 40 to 70 μm were coated onto SS foils. In [24], PZT/PZT film thickness up to 200 μm was produced.

A flexible UT, composed of a 40 μm thick PZT/PZT film, a 75 μm thick SS foil and a silver paste top electrode, was attached by a mechanical holder onto the steel pipe with an outer diameter of 102 mm, an inner diameter of 46 mm, and a length of 205 mm. A viscous oil

couplant was placed between the SS foil and the outer surface of the pipe. The measurement results showed that this transducer together with the couplant could operate up to 160°C at 9.7 MHz with a SNR of 36 dB. The test results show that this particular flexible UT can be bended into a curvature of a radius of 15 mm without damaging the ultrasonic performance. It is expected that lower metal foil and PZT/PZT composite film thicknesses will enhance the flexibility. A similar flexible UT, but with a PZT/PZT film thickness of 70 μm , was also attached to a 30 mm thick graphite/epoxy composite and a 7 mm thick HDPE plate. The measurement results prove that this type of UT can be used to perform NDT on these materials. Also, the ultrasonic signal strengths generated by a PZT/PZT composite UT and a narrow bandwidth (high penetration) commercially available transducer are shown to be comparable. It is noted that if bismuth titanate powders are used instead of PZT powders, then the operation temperature can be up to more than 440°C, but the strength of the UT may be reduced by 15-20 dB [18,19].

In order to investigate the influence of the metal foil thickness on the ultrasonic performance of the flexible UTs, 70 μm PZT/PZT films were fabricated onto 38 and 75 μm thick SS foils and their ultrasonic performances were compared with our theoretical calculated results. The flexible UT with 38 μm SS foil showed a higher signal strength and higher center frequency than that with 75 μm SS foil and calculation results were in agreement with this tendency.

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