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Flexible Metallic Ultrasonic Transducers for Structural Health Monitoring of Pipes at High Temperatures

Jeanne-Louise Shih, Makiko Kobayashi, *Member, IEEE*, and Cheng-Kuei Jen, *Senior Member, IEEE*

Abstract—Piezoelectric films have been deposited by a sol-gel spray technique onto 75- μm -thick titanium and stainless steel (SS) membranes and have been fabricated into flexible ultrasonic transducers (FUTs). FUTs using titanium membranes were glued and those using SS membranes brazed onto steel pipes, procedures that serve as on-site installation techniques for the purpose of offering continuous thickness monitoring capabilities at up to 490°C. At 150°C, the thickness measurement accuracy of a pipe with an outer diameter of 26.6 mm and a wall thickness of 2.5 mm was estimated to be 26 μm and the center frequency of the FUT was 10.8 MHz. It is demonstrated that the frequency bandwidth of the FUTs and SNR of signals using glue or brazing materials as high-temperature couplant for FUTs are sufficient to inspect the steel pipes even with a 2.5 mm wall thickness.

I. INTRODUCTION

THE non-destructive evaluation (NDE) of pipes in nuclear and fossil fuel power plants [1]–[3], chemical and petroleum plants [1], [2], and other structures [4] has become an increasingly important element in the improvement of safety and in the extension of a structure's life span. Structural health monitoring (SHM) [5], [6], which may provide continuous NDE of pipes or their health conditions, has also drawn much attention recently. Ultrasonic techniques are frequently used for these NDE and SHM purposes because of their subsurface inspection capabilities, fast inspection speeds, simplicity, and ease of operation. In these applications, ultrasonic transducers (UTs) may need to be made directly in contact with structures that have surfaces with different curvatures and must also be able to operate at elevated temperatures. However, conventional UTs having rigid flat end surfaces may, in general, show poor performance and therefore may not be readily suitable for the inspection of pipes at elevated temperatures. The poor SNR is in part due to the fact that the contacting area is a narrow line allowing only a small portion of the available ultrasonic energy to be transmitted into the pipe. Different thicknesses in gel couplant that are present in the gap area between the UT flat end surface and the curved

surface of the pipe cause the areas other than this narrow contact line of the UT to induce a spatial spread of the UT excitation, generating unwanted noise. Flexible UTs (FUTs) are therefore more suitable under such conditions because they ensure their own self-alignment to the object's surface even in the case of a curved or complex geometry so that the transmitted ultrasonic energy may be maximized and noise may be minimized to improve SNR for NDE or SHM purposes [7]–[11].

For commercially available FUTs, piezoelectric polymers such as polyvinylidene fluoride (PVDF) [8] and piezoelectric ceramic/polymer composites [5], [9]–[11] are mainly used as the piezoelectric materials. Both materials include polymer, which prevents the use of such flexible UTs at elevated temperatures. Other flexible, high-temperature ultrasonic transducers (HTUTs) have also been reported [6]. To provide flexibility for the single-crystal films used, the thicknesses of the piezoelectric films were made small, from 0.2 to 10 μm . Operating frequencies were thus normally higher than 30 MHz and such high frequencies may not be suitable for NDE and SHM of thick and highly attenuating materials.

The objective of this investigation is to develop FUTs characterized by a high level of flexibility similar to PVDF FUTs [8], that can operate at up to at least 500°C and that have a high ultrasonic performance comparable to commercial broadband UTs. To improve the ultrasonic properties of the FUTs reported in [7], [12], a rapid thermal annealing-like process [13]–[15] was used for the thermal treatment. The rapid thermal annealing has the merit of limiting the degradation of the piezoelectric film-substrate interface and to improve the crystallization behavior of the piezoelectric film. In addition to stainless steel (SS), titanium (Ti) membranes are introduced to reduce the level of oxidation during the thermal treatment steps and thus enhance the electrical conductivity of the bottom electrode and the ultrasonic performance of the FUT. The 75- μm -thick Ti membrane is also more flexible than the SS membrane of the same thickness. In addition to the use of a high-temperature couplant for momentary contact NDE, on-site bonding techniques including gluing and brazing methods compatible with the fabricated FUTs are mentioned in this study and will be developed further for permanent NDE or SHM purposes over curved surfaces such as on steel pipes. In these cases, the glue or brazing material between the FUT and the external surface of the pipe serves as a permanent high-temperature couplant.

II. FABRICATION AND PERFORMANCE OF FUTS

A. Fabrication Procedures

FUTs to be presented use thick-film fabrication technology and Ti or SS membrane substrates that are 75 μm

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thick. Thick piezoelectric films may be fabricated by jet printing [16], dip coating [17], tape casting [18], or sol-gel processing [7], [12], [19]–[22] methods. In this study, the fabrication of the FUT based on a sol-gel spray technique consists of six main steps [7], [12], [22]: 1) preparing a high dielectric constant lead-zirconate-titanate (PZT) solution; 2) ball milling the piezoelectric PZT or bismuth titanate (BIT) powders in a PZT solution to submicron sizes; 3) sensor spraying using slurries from steps 1 and 2 to produce a film with thicknesses of between 5 and 20 μm ; 4) heat treating to produce a solid PZT composite (PZT-c) or BIT composite (BIT-c) thick film; 5) Corona poling to obtain piezoelectricity; and 6) silver paste painting for depositing electrical connections. Steps 3 and 4 are performed multiple times to produce optimal film thicknesses for specified ultrasonic operating frequencies. In this investigation, step 4 is significantly different from the FUT fabrication process presented in [7]. Here a rapid thermal annealing-like process [13]–[15] was used for the thermal treatment. The main advantage of rapid thermal annealing is to limit the eventual degradation of the film-substrate interface such as through inter-diffusion of lead, and also to improve the crystallization behavior of the piezoelectric film. The short annealing time also helps to reduce the growth of an oxidation layer between the SS or Ti membrane and the PZT-c or BIT-c film. Oxidation layers reduce the electrical conductivity of SS or Ti, thereby decreasing the ultrasonic performance. In step 5 the Corona poling temperature, the voltage, and the poling time length were 125°C, 25 kV, and 10 min for PZT-c film and 300°C, 25 kV, and 10 min for BIT-c film. The flexibility of the FUTs comes from the thinness of the membrane substrate, the piezoelectric film, and the top electrode, as well as from the porosity of the piezoelectric film. The porosity of the piezoelectric PZT-c and BIT-c films, which are controlled during film fabrication, achieves the frequency bandwidth of the FUTs to be presented.

B. Performance of a FUT Made on a 75- μm -Thick SS Membrane

A FUT was made with a 114- μm -thick PZT-c film that was deposited onto a 75- μm -thick SS membrane. The FUT was attached to the flat surface of a 15.1-mm-thick aluminum (Al) plate using a gel couplant and the pulse-echo measurement was carried out by a hand-held EPOCH model LT pulser/receiver (from Olympus-Panametrics, Waltham, MA) at room temperature as shown in Fig. 1(a). This particular type of hand-held device is used on a daily basis for NDE in industrial settings. It also does not have the functionality of signal averaging and filtering and only displays the raw ultrasonic measurement data. Performance levels achieved and demonstrated on this hand-held device with the fabricated FUTs on flat and curved surfaces help to demonstrate the applicability of such FUTs under current industrial SHM and NDE settings. The diameter of the top silver paste electrode of the FUT in Fig. 1(a) was 5 mm, which was the size required

Fig. 1. (a) Measurement setup for a flexible ultrasound transducer made of PZT-c film attached to the flat surface of an Al plate using an EPOCH LT in pulse-echo mode; (b) measured ultrasonic signals at room temperature.

to match the electrical impedance of the PZT-c film with that of the Epoch LT and to achieve maximum signal strength in pulse-echo mode at room temperature. The measured ultrasonic data in pulse-echo mode is shown in Fig. 1(b), where L^n is the n th trip of the longitudinal echo (L) through the plate thickness. The center frequency and the 6-dB bandwidth of the L^2 echo were 8.0 MHz and 2.2 MHz, respectively. In Fig. 1(b), the pulse energy used was a 100 V negative pulse with a pulse width of 35 ns, which was the lowest setting available on the EPOCH LT; 0 dB gain (i.e., no amplification) out of the available 100 dB receiver gain was used. The SNR of the L^2 echo was 39 dB. The SNR is defined as the ratio of the amplitude of the first echo (here L^2) over that of the surrounding noise. The rapid decay of the echo signals L^n shown in Fig. 1(b) may mainly come from the impedance mismatch of the gel couplant and the attenuation of the steel plate because of grain scattering.

A typical value of d_{33} measured for the PZT-c film on steel substrates is 30×10^{-12} m/V, the K_t is 0.2, the relative dielectric constant is 320, the density is 4400 kg/m³ and the L wave velocity 2200 m/s. For comparison purposes, Figs. 2(a) and 2(b) show measured results obtained when commercial broadband UTs with center frequencies of 5 and 10 MHz respectively, were used at the other side of the Al plate that was shown in Fig. 1(a) together with the same gel couplant. The receiver gains used by the

Fig. 2. Measured ultrasonic signals from commercial ultrasonic transducers with a center frequency of (a) 5 MHz and (b) 10 MHz operated in pulse-echo mode at the opposite surface and through the thickness of the Al plate.

EPOCH LT were 4 dB and 2 dB, respectively. These show that while using the EPOCH LT, the signal strength of the FUT on flat plates was at least as good as those of the two commercially purchased broadband UTs. The center frequency and the 6-dB bandwidth of L^2 echo in Fig. 2(a) are 5.5 MHz and 5.4 MHz and those in Fig. 2(b) are 8.5 MHz and 8.4 MHz, respectively. Fig. 2 indicates that the bandwidth of the commercial broadband UTs is higher than that of the FUT shown in Fig. 1. Further comments on the sufficiency of the bandwidth of the FUTs will be given in the next sections.

C. Performance of a FUT Made on a 75- μ m-Thick Ti Membrane

Another FUT consisting of a 75- μ m-thick Ti membrane, a 70- μ m-thick PZT-c film, and a 5- μ m-thick silver paste electrode with a 3.6 mm diameter was also fabricated. It was glued onto a steel pipe and is shown in Fig. 3. Ti membranes are chosen to reduce the oxidation during the thermal treatment and they are more flexible than SS membranes of the same thickness. Room temperature curable glue was used in this experiment. The outer diameter (OD) and the wall thickness of the pipe were 89 mm and 6.5 mm, respectively. In Fig. 3, there are five top electrodes and each of them serves as a single FUT. Using one of the five FUTs, the ultrasonic measurement was also taken by the EPOCH LT together with two spring electrical contacts, one of which connects to the top silver paste

Fig. 3. A flexible ultrasound transducer fabricated on a 75- μ m-thick Ti membrane and glued onto a steel pipe with the ultrasonic measurements displayed using a hand-held EPOCH LT pulser/receiver.

electrode and the other to the bottom electrode, which was the metal substrate, in this case Ti. The pulse energy used was the lowest available on the EPOCH LT and the gain used was again, 0 dB out of the available 100 dB. This result indicates that the FUT made on the 75- μ m thick Ti membrane together with the glue serving as ultrasonic couplant achieve good ultrasonic performance. It is noted that because of lower oxidation on Ti during the heat treatments, the ultrasonic performance of the FUT made on Ti membrane is a few dBs stronger than that made on SS membrane.

Fig. 4 shows a performance comparison between the pulse-echo measurement results obtained by the glued FUT shown in Fig. 3 (upper trace), a commercial broadband UT centered at 10 MHz (middle trace) and another one centered at 5 MHz (lower trace). L^n is the n th trip of the L wave echo through the pipe wall thickness. Both commercial UTs had a diameter of 3.2 mm and were used with commercially available couplant on the same pipe. The center frequency and 6 dB bandwidth of the L^2 echo of the upper trace were 13.1 MHz and 6.6 MHz, respectively. The decay of the echo signals L^n shown in Fig. 4 may mainly come from the impedance mismatch of the glue and the attenuation of the steel pipe due to grain scattering. It is clear that the ultrasonic performance in terms of signal strength of the glued FUT on this curved pipe surface was much better than those obtained by the commercial broadband UTs and therefore the conformability of the FUT creates a clear advantage. However, if the commercial UT has only a narrow line active area along the pipe axis instead of one of 3.2 mm in diameter, the difference in the three traces shown in Fig. 3 may be reduced in terms of the signal strength. Because of the well-separated echoes in the time domain, Fig. 3 also indicates that the bandwidth of this FUT is sufficient to inspect such a pipe with a 6.5 mm wall thickness. In principle, for NDE and SHM of pipes with smaller ODs and at high temperatures, the advantages of the FUT over

Fig. 4. Pulse-echo measurement results obtained by the glued flexible ultrasound transducer shown in Fig. 3 (upper trace), a commercial broadband ultrasound transducer centered at 10 MHz (middle trace), and one centered at 5 MHz (lower trace).

conventional UTs will become more evident. Furthermore, such FUTs made of PZT-c films and glued to the pipe have survived thermal cycles between -80°C and 100°C . At 100°C , the reduction in signal strength of the FUTs was about 5 dB. They are therefore highly suitable for the SHM of pipes within this temperature range. It is to be noted that in this particular case, the 100°C limitation came from the glue. Glues, which are able to function at up to 300°C , may be also used [12], but they may not be curable at room temperature.

III. ULTRASONIC MEASUREMENTS OF PIPES AT ELEVATED TEMPERATURES

A. Momentary NDE with a FUT Fabricated on a $75\text{-}\mu\text{m}$ -Thick SS Membrane

For NDE, momentary contact inspection is often used to monitor pipe thicknesses at elevated temperatures and is performed at different locations of the structure to be inspected. Fig. 5(a) shows a mechanical holder that was used to attach a FUT fabricated on a $75\text{-}\mu\text{m}$ -thick SS membrane to an Al pipe with an OD of 42.5 mm and a wall thickness of 5 mm. The pipe was heated to 150°C by a hot plate and the temperature was controlled and monitored via a thermocouple in contact with the pipe. Oil was used as the ultrasonic couplant between the FUT and the external surface of the pipe. This FUT had a $152\text{-}\mu\text{m}$ -thick PZT-c film and the diameter of the top silver paste top electrode was 3 mm. Fig. 5(b) shows the measured ultrasonic signal where L^n is the n th trip of the L wave echo through the pipe wall thickness. It is noted that in [22], because of the electrical impedance matching between the

(a)

(b)

Fig. 5. (a) A flexible ultrasound transducer is attached onto an Al pipe by a mechanical holder and operated at 150°C and (b) its measured ultrasonic signals in pulse-echo mode.

active FUT size, which is determined by the size of the top electrode, and the pulser/receiver used, there is an optimum diameter (5.1 mm in this case) to achieve the maximum signal strength of this FUT. However, if the top electrode is larger than a size under which the ultrasonic couplant can be pressed onto the surface uniformly, as mentioned in the introduction, unwanted noise will be induced by the spatial spread of the UT excitation due to the non-uniformity of the ultrasonic couplant under the FUT and will induce large spurious noises and thus reduce SNR. Here, the electrode size of 3 mm was chosen not to achieve maximum signal strength, but rather to ensure sufficient SNR of the L^2 for thickness measurement

Fig. 6. Braided flexible ultrasound transducer stainless steel membrane substrate on the external surface of a steel pipe where the outer diameter and the wall thickness of the steel pipe are shown.

because the ultrasonic couplant under this 3 mm diameter area is more likely to be pressed onto the surface uniformly at 150°C. The center frequency and the 6-dB bandwidth of the L^2 echo in Fig. 5(b) are 8.3 MHz and 2.4 MHz, respectively. For this measurement, a gain of 32 dB was used out of the available 100 dB gain provided by the EPOCH LT. The high amplification required and the relatively small bandwidth of the FUT may be explained by the effects due to the presence of the oil couplant, the 150°C high temperature, the non-optimized top electrode diameter and the insufficient contacting pressure applied to the FUT with the holder. The SNR of L^2 in Fig. 5(b) is 18 dB. Due to the separated echoes in the time domain, Fig. 5 also indicates that the bandwidth of this FUT is sufficient to inspect such an Al pipe with a 5 mm wall thickness. Despite some drawbacks in terms of ultrasonic performance with the momentary contact method, the measurement confirms that such a FUT is useful for momentary thickness measurements of an Al pipe with a 5 mm wall thickness at up to at least 150°C. Separation between echoes at such high temperatures means that if there is a defect existing within the thickness of the pipe under the top electrode, NDE of the said defect may be achieved. If the thickness of the pipe is thin enough compared with the wavelength, such a FUT may be able to generate and receive guided ultrasonic waves along the pipe.

B. Permanent NDE with a Braided PZT-c Film FUT Fabricated on a 75- μ m-Thick SS Membrane

In certain situations, NDE of pipes must be carried out continuously. The momentary contact approach may not be appropriate; therefore a bonding technique such as gluing which was mentioned above was implemented. However, continuous monitoring may need to be performed on pipes at temperatures higher than 100°C. An alternative permanent brazing technique using induction heating is considered here. Fig. 6 shows a 15-mm-wide, 23-mm-long, and 75- μ m thick SS membrane, which is one of the types

TABLE I. ULTRASONIC COUPLING EFFICIENCY OF THE BRAZING MATERIAL TOGETHER WITH THE SS MEMBRANE.

Position of brazed SS	Coupling efficiency (dB)
1	4
2	6
3	4
4	3
5	5
6	3
7	6
8	6
9	6

of substrates used for FUTs fabricated in this study, that was brazed onto a steel pipe with an OD of 26.6 mm and a wall thickness of 2.5 mm. The developed approach in brazing the SS membrane is simple and easy to follow. The pipe was first washed with water, soap, and ethanol. A brazing paste was then deposited on the backside of the SS membrane. The SS membrane was then clamped onto the cleaned pipe using a metallic worm clamp with a SS plate of 1-mm thickness that was conformed over the FUT and onto the curvature of the pipe. The induction system was calibrated to maximize the power and frequency of the system and it was controlled by a two-color pyrometer. The induction lasted three minutes and the temperature required was 825°C for this SS membrane to be brazed onto the steel pipe. In the case of a brazed FUT, after the induction, Corona poling was used to make the film piezoelectric. The developed Corona poling technique is a convenient method to pole FUTs that have been brazed onto curved pipes. After poling, a silver paste was used to deposit the top electrode of necessary size.

The evaluation of the ultrasonic coupling efficiency of the brazing material together with the 75- μ m-thick SS membrane, which is used as the brazed FUT substrate, and the steel pipe was carried out after the induction brazing process. A commercial broadband UT centered at 10 MHz and with a diameter of 3.2 mm together with the gel couplant was used. The signal strength measured by this commercial UT in direct contact to the steel pipe's external surface with the gel couplant, under manual pressure and at room temperature was recorded as the reference and designated as 0 dB. Nine locations of direct contact made between the UT and the surface of the SS membrane brazed onto the steel pipe and made with the same gel couplant under the same pressure are indicated in Fig. 6. The signal strength reduction in decibels between the measured signal amplitude on the bare external steel pipe surface and that of each of the nine locations is recorded in Table I. The reduction of the signal strength in decibels accounts for the loss caused by the brazing material and SS membrane. The results in Table I show that the average loss was about 5 dB and that the maximum difference between the nine locations was 3 dB.

Fig. 7(a) shows a FUT brazed onto the same pipe, which was heated and the measurement results taken at 150°C are presented in Fig. 7(b). L^n is the n th trip of the

$$\sigma(\Delta t - \Delta t') \geq \sqrt{\frac{3}{2f_0^3 \pi^2 T(B^3 + 12B)} \left(\frac{1}{\rho^2} \left(1 + \frac{1}{\text{SNR}_1^2} \right) \left(1 + \frac{1}{\text{SNR}_2^2} \right) - 1 \right)} \quad (1)$$

(a)

(b)

Fig. 7. (a) Measurement setup of a PZT-c film flexible ultrasound transducer brazed onto a steel pipe and (b) the ultrasonic measurement through the 2.5 mm wall thickness at 150°C.

L wave echo through the pipe wall thickness. The gain used with the EPOCH LT was 20 dB out of the available 100 dB. This FUT had a 113- μm -thick PZT-c film and the diameter of the silver paste top electrode was 2.5 mm. The 2.5 mm diameter was chosen not to achieve maximum signal strength, but rather to achieve maximum SNR of the L^2 for thickness measurement. Spring-loaded pins, one of which was connected to the top electrode and the other, connected to the grounded steel pipe, served as the electrical contact. The center frequency and the 6-dB bandwidth of the L^2 echo in Fig. 7(b) are 10.8 MHz and 3.4 MHz, respectively. The SNR of L^2 is 26 dB. The decay of the echo signals L^n shown in Fig. 7(b) may mainly come from the attenuation of the steel pipe due to grain scattering. It

can be seen that for a high-curvature steel pipe comprising of a 26.6 mm OD and a wall thickness as thin as 2.5 mm and heated to 150°C, the echoes L^n are well separated in the time domain. This demonstrates that the bandwidth of this FUT is sufficient to inspect such steel pipes with a 2.5 mm wall thickness. In general, for power and chemical plants, the wall thicknesses of the pipes that require NDE and SHM at high temperatures are much larger than 2.5 mm. Fig. 7(b) clearly indicates that the brazing technique uniquely used for such a FUT fabricated with a SS substrate is a good bonding approach to steel pipes for NDE or SHM measurements performed at up to 150°C.

C. Thickness Measurement Accuracy of a Braided PZT-c Film FUT Onto a Pipe at 150°C

Eq. (1) [23, Eq. (19)], see above, is used here for the estimation of the accuracy in time delay measurement and by extension, in the thickness measurement of the steel pipe shown in Fig. 7(a) and tested under the conditions presented in Fig. 7. The equation takes into account jitter and false-peak errors that may arise in delay time estimations that are commonly caused by noise, finite window lengths, and signal decorrelations resulting from the experimental setup and/or the imperfections in the transducers. In (1), f_0 is the center frequency, T is the time window length for the selection of L^2 and L^4 in Fig. 7(b) that is required for the cross-correlation measurement, B is the fractional bandwidth of the signal, which is the ratio of the signal bandwidth over f_0 , ρ is the correlation coefficient, SNR_1 and SNR_2 are the SNR of the L^2 and L^4 echo respectively, and $\sigma(\Delta t - \Delta t')$ is the standard deviation of the measured time delay (Δt being the true time delay and $\Delta t'$, the measured time delay). Using (1) and the parameters tabulated in Table II, which characterize this particular braided FUT, the calculated $\sigma(\Delta t - \Delta t')$ was 2.66 ns.

Because a sampling rate of 100 MHz was used in the experiment, with the use of the cross correlation method and taking into account interpolation [24], the time measurement error, which may be additionally introduced, was estimated to be at an upper limit of 2 ns. The total uncertainty in time delay measurement was therefore estimated at 4.66 ns. Because the measured longitudinal velocity V_L in the steel pipe using the pulse-echo technique at 150°C was 5682 m/s, the best possible thickness measurement accuracy achievable on a 2.5-mm thick pipe was 26 μm in pulse-echo mode at 150°C. If the sampling rate is increased to more than 100 MS/s, improved thickness measurement accuracy may be obtained; however this result established according to (1) demonstrates that at such a sampling rate, the fabricated FUTs centered at

TABLE II. PARAMETERS FOR (1) AND DIGITIZATION RESOLUTION.

Parameter	Value for the brazed FUT on steel pipe
f_0	10.8 MHz
T	0.88 μ s
B	0.32
ρ	0.91
SNR ₁	26 dB
SNR ₂	20 dB
$\sigma(\Delta t - \Delta \hat{t})$	2.66 ns
Digitization resolution (100 MHz) including interpolation	2 ns
Total time delay uncertainty	4.66 ns
V_L	5682 m/s
Thickness measurement accuracy	26 μ m

10.8 MHz have a SNR and a bandwidth that are suitable for thickness measurements of thin pipes at 150°C.

D. Permanent NDE With Brazed BIT-c Film FUT Made on a 75- μ m-Thick SS Membrane

To perform SHM or NDE at a temperature higher than 150°C, a different film is required. A FUT made of a 75- μ m-thick SS membrane, a 95- μ m-thick BIT-c film [12], [22], and a 5- μ m-thick silver paste top electrode was fabricated. BIT was chosen because of its maximum operable temperature of 520°C [3], [12], [22] even though it is known to have a lower piezoelectric coefficient than PZT. This FUT was brazed onto a steel pipe, which had an OD and a wall thickness of 25 mm and 3.5 mm, respectively, as shown in Fig. 8. The same brazing material mentioned earlier was used. Again the Corona poling and the top electrode deposition were carried out on-site after the brazing. In Fig. 8, each of the five top electrodes serve as a single FUT. Fig. 9 shows the pulse-echo measurements performed by one of these five FUTs at room temperature and at up to 490°C using the same spring electrical contacts that were shown in Fig. 3. L^n is the n th trip of the L wave echo through the pipe wall thickness. The traces in Fig. 9 were taken with the same pulser/receiver settings, the exception being the bottom trace. The bottom trace, which was obtained at 490°C, had an additional 15 dB gain added to compare it to the adjacent trace, which was obtained also at 490°C, as well as to the trace taken at room temperature. At 490°C, the center frequency and 6 dB bandwidth of the L^2 echo achieved with this FUT were 12.8 MHz and 6.1 MHz, respectively. The decay of the echo signals L^n shown in Fig. 9 may mainly come from the attenuation of the steel pipe because of grain scattering. This brazed FUT achieved a SNR on its L^2 echo of more than 18 dB within the room temperature to 490°C range. Brazing may thus be a suitable on-site installation technique for bonding such FUTs onto pipes for the purposes of SHM and NDE at such high temperatures. Because of the well-separated echoes in the time domain, Fig. 9 also indicates that the bandwidth achieved by the FUT in combination with the use of the brazing material as a permanent couplant is sufficient to

Fig. 8. A BIT-c film on a stainless steel membrane, brazed onto a steel pipe and fabricated into 5 flexible ultrasound transducers.

Fig. 9. Pulse-echo measurements of a flexible ultrasound transducer shown in Fig. 8 taken at room temperature and at up to 490°C with the same pulser/receiver settings, except for the bottom curve, which was taken with an additional signal amplification gain of 15 dB for comparison.

inspect such a steel pipe with a 3.5 mm wall thickness at up to 490°C.

IV. CONCLUSION

FUTs consisting of metal membranes, piezoelectric films, and thin silver paste top electrodes were fabricated. The piezoelectric films were made by a sol-gel spray technique together with rapid thermal annealing. The main advantage of rapid thermal annealing is to limit the eventual degradation of the film-substrate interface and also to improve the crystallization behavior of the PZT-c film. The short annealing time also prevents oxidation between

the SS and PZT-c film of the FUT. In this study, the ultrasonic performances, in terms of signal strength of a PZT-c film FUT made on a 75- μm -thick SS membrane, were at least as good as commercially available 5-MHz and 10-MHz broadband UTs for measurements on flat surfaces at room temperature. This type of FUT was used for pipe-thickness measurements at 150°C using a momentary contact method with a high-temperature ultrasonic couplant. In addition, a FUT consisting of a 75- μm -thick Ti membrane and a 70- μm -thick PZT-c film was bonded onto a steel pipe with an 89 mm OD using glue. Ti membranes were chosen to reduce the oxidation during the thermal treatment and thus enhance the electrical conductivity of the bottom electrode and the ultrasonic performance of the FUT. The Ti membrane of 75 μm thickness is also more flexible than the SS membrane of the same thickness. The glue for the bonding served as the ultrasonic couplant. It was found that the ultrasonic performances of FUTs, in terms of signal strength at room temperature on the curved surface, was better than those obtained by commercial broadband UTs. Such FUTs and glues have had consistent and high performances in the temperature range between -80°C and 100°C .

PZT-c film FUT and one BIT-c film FUT were fabricated on 75- μm -thick SS membranes and these were brazed onto steel pipes by an induction method to allow for operation at up to 150°C and 490°C , respectively. The brazing material served as a high-temperature ultrasonic couplant. The SNR of the first round trip echo was 26 dB for the PZT-c FUT at up to 150°C and 18 dB for the BIT-c FUT at up to 490°C . At 150°C , the best possible thickness measurement accuracy achievable by the brazed PZT-c film FUT was estimated to be 26 μm for a steel pipe with a 26.6 mm OD and a wall thickness of 2.5 mm where the center frequency of the FUT was 10.8 MHz. These FUTs together with the gluing and brazing methods serve as promising solutions for SHM and NDE at room and/or high temperatures because of their performance in terms of signal strength and bandwidth, their conformability, and their capability for on-site installation.

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