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Publisher's version / Version de l'éditeur:

Proceedings of 12th CANSMART International Workshop on Smart Materials and Structures, pp. 217-226, 2009-01-01

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SMART MATERIALS AND STRUCTURES

22 - 23 October 2009, Montreal, Quebec, Canada

**HIGH TEMPERATURE FLEXIBLE ULTRASONIC TRANSDUCERS
FOR STRUCTURAL HEALTH MONITORING AND NDT**

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ABSTRACT

Flexible ultrasonic transducers (FUTs) consisting of a 75 μm thick metal membrane, a piezoelectric composite with a thickness larger than 85 μm and a top electrode were developed for structural health monitoring (SHM) and non-destructive testing (NDT) applications. The piezoelectric films were made by a sol-gel spray technique. Its ultrasonic performance in terms of signal strength is at least as good as commercially available broadband ultrasonic transducers at room temperature. Onsite gluing and brazing installation techniques which bond the FUTs onto steel pipes for SHM and NDT purposes up to 100°C and 150°C are developed, respectively. The best thickness measurement accuracy of FUT at 150°C was estimated to be 26 μm .

Keywords: Flexible ultrasonic transducer, High temperature, Thick piezoelectric film, Non-destructive testing, Structural health monitoring, Brazing.

INTRODUCTION

The non-destructive testing (NDT) 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] is a furtherance of the NDT approach. Ultrasonic techniques are frequently used for these NDT 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 signal-to-noise ratio (SNR) may in part come from 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 generate many unwanted noises. Flexible UTs (FUTs) are therefore more suitable under such conditions because they ensure their 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 noises may be minimized to improve SNR for NDT or SHM purposes [7 - 9].

In commercially available FUTs, piezoelectric polymers such as polyvinylidene fluoride (PVDF) [8] and piezoelectric ceramic/polymer composites [8, 10] are mainly used as 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 [11]. In order to provide flexibility for the single crystal films used, the thickness of the piezoelectric films were thin, from 0.2 to 10 μm . Thus operating frequencies were normally higher than 30 MHz and these may not be suitable for NDT and SHM of thick and highly attenuating materials.

The objective of this investigation was to develop FUTs that have high flexibility similar to PVDF FUTs [7], but can operate at up to at least 150°C and have a high ultrasonic performance comparable to commercial broadband UTs. In addition to the use of a high temperature couplant for momentary contact NDT, a gluing and a brazing onsite installation technique will be investigated for permanent NDT or SHM over curved surfaces such as on steel pipes and at temperature up to 150°C. The glue and the brazing material between the FUT and the external surface of the pipe serves as a permanent high temperature couplant.

FABRICATION AND PERFORMANCE OF FUT

Fabrication procedures

The fabrication of the FUT consists of a sol-gel based sensor fabrication process [12]. The substrate can be a 75 μm thick titanium (Ti) or stainless steel (SS) membrane. Such an approach consists of six main steps [9, 13]: (1) preparing a high dielectric constant lead-zirconate-titanate (PZT) solution, (2) ball milling the piezoelectric PZT powders in a PZT solution to submicron

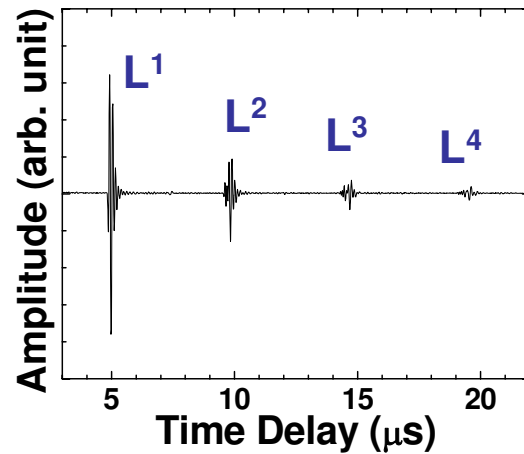
sizes. In this case, PZT powders were selected because of their high piezoelectric strength and Curie temperature of 350°C. (3) sensor spraying using slurries from steps (1) and (2) to produce a film with thicknesses of between 5 and 20 μm , (4) heat treating to produce a solid PZT composite (PZT-c) 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, steps (4) and (5) are significantly different from the FUT processes presented in [9]. Here a rapid thermal annealing like process [14 - 16] 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 PZT film. The short annealing time also avoids the growth of an oxidation layer between the Ti or SS and PZT-c film. An oxidation layer would reduce the electrical conductivity of Ti and SS, thereby decreasing the ultrasonic performance. In this study longitudinal (L) ultrasonic wave transducers are described. The relative dielectric constant was calculated using the capacitance measured by an impedance analyzer.

Performance of FUT

Firstly, an FUT was made with a $\sim 120\ \mu\text{m}$ thick PZT-c film that was deposited onto a $75\ \mu\text{m}$ thick Ti membrane. It is noted that the ultrasonic performance of such FUTs on Ti membranes showed in general a 5 dB stronger signal strength than those reported in [9], whereby FUTs were made onto SS membranes. The improved signal strength comes from the reduced oxidation of the membrane substrates (Ti over SS) during heat treatments and improvement of the sol gel spray technique. The FUT was attached to a 15.1 mm thick aluminum (Al) plate using a gel couplant as shown in Fig. 1a. The pulse-echo measurement was carried out by a handheld EPOCH model LT pulser/receiver (from Olympus-Panametrics, USA) at room temperature. The EPOCH LT is commonly used for NDT in industrial environments. The diameter of the top silver paste electrode of this FUT was 7 mm, which was the size required to match the electrical impedance of the PZT-c film with that of the pulser/receiver 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. 1b, where L^n is the n^{th} trip L echo through the plate thickness. The center frequency and the 6 dB bandwidth of L^1 echo are 8.1 MHz and 5.3 MHz respectively. In Fig. 1b, 0 dB gain out of the available 100 dB receiver gain of EPOCH was used. The SNR of the L^1 echo is $\sim 38\text{dB}$. The SNR is defined as the ratio of the amplitude of the first echo (here L^1) over that of the surrounding noise. For comparison, Figs 2a and 2b show measured results obtained when commercial broadband UTs with a center frequency of 5 MHz and 10 MHz, respectively, were used at the other side of the Al plate shown in Fig. 1a together with the same gel couplant. The receiver gains used by the EPOCH pulser/receiver were 2 dB and 2 dB, respectively. These results show that while using the EPOCH, the signal strength of the FUT was at least as good as those of the two commercially purchased broadband UTs.

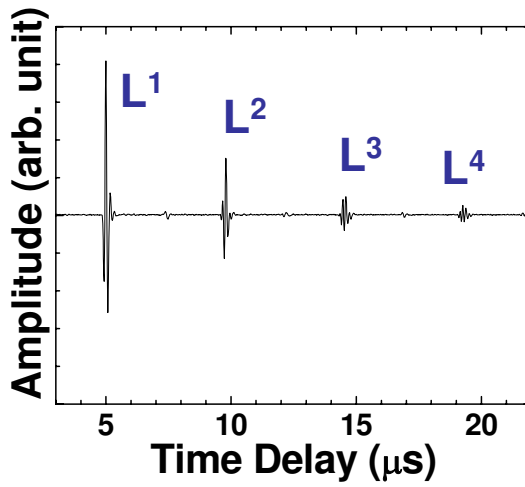


(a)

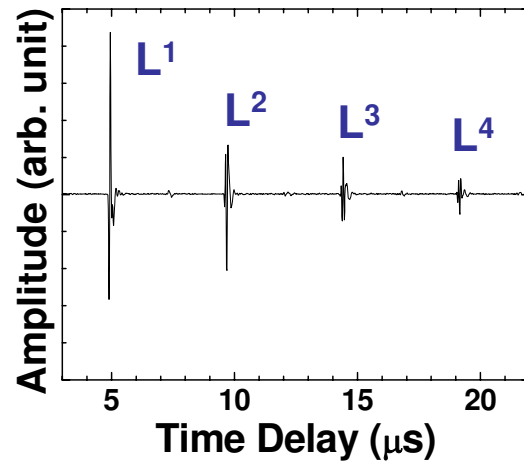


(b)

Fig. 1: (a) Measurement setup for a FUT made of PZT-c film attached to an Al plate using an EPOCH LT in pulse-echo mode; (b) Measured ultrasonic signals at room temperature.



(a)



(b)

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

ULTRASONIC THICKNESS MEASUREMENTS OF PIPES AT ELEVATED TEMPERATURES

Momentary NDT with FUT

Developed FUTs can be operated in pulse-echo, pitch-catch and transmission configurations. Fig. 3a shows a magnet holder that was used to attach a FUT to a steel pipe with an outer diameter (OD) of 76 mm and an inner diameter (ID) of 50 mm at 150°C. The thickness of the pipe was 13 mm. The temperature was achieved with a hot plate and was controlled by the monitoring of a thermocouple in contact with the pipe. Oil was used as the ultrasonic couplant between the FUT and the external surface of the pipe. A momentary contact method such as the example given here is often used during NDT applications. The same FUT together

with the holder can be used at different locations. The FUT had a 95 μm thick PZT-c film and the diameter of the top silver paste top electrode was 5 mm. Fig. 3b shows the measured ultrasonic signal, where L^n is the signal traveling through the thickness for the n^{th} time. The 5 mm top electrode diameter was chosen not to achieve maximum signal strength, but rather to achieve maximum SNR of the L^1 for thickness measurement. The center frequency and the 6 dB bandwidth of the L^1 echo were 10.9 MHz and 2.9 MHz, respectively. For this measurement, the holding of the FUT onto the steel pipe was using a magnet as shown in Fig.3a. A gain of 52 dB was used out of the available 100 dB gain provided by the EPOCH LT. The high 52 dB gain may be explained by the presence of the oil couplant, the 150°C high temperature, not optimized top electrode diameter, the insufficient contact force applied to the FUT and the ultrasonic attenuation within the thickness of the pipe wall. The SNR of L^1 is ~ 24 dB. The measurement confirms that such a FUT is useful for thickness measurements of a pipe at up to at least 150°C. Certainly if there is a defect existing within the 13 mm thickness of the pipe under the top electrode, NDT of the said defect may be achieved. If the thickness of the pipe is thin enough compared to the wavelength, such a FUT may be able to generate and receive guided waves along the pipe.

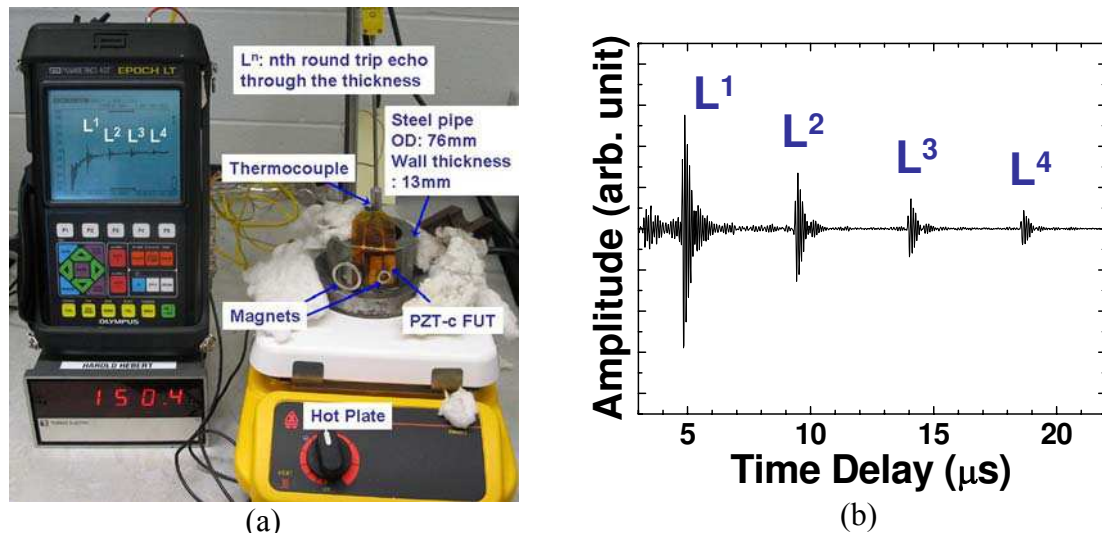


Fig. 3: (a) A FUT is attached onto a steel pipe by a magnet holder and operated at 150°C and (b) shown is its measured ultrasonic signals in pulse-echo mode.

Permanent NDT with glued FUT

In certain situations, NDT of pipes must be carried out continuously. The momentary contact approach presented in the previous section may not be appropriate; therefore a onsite gluing technique is performed. Let FUT consisting of a 75 μm thick Ti membrane, a 85 μm thick PZT-c film, a 5 μm thick silver paste was made, glued onto a steel pipe, and heated by a hot plate up to $\sim 100^\circ\text{C}$ as shown in Fig. 4a using a glue which can be cured at room temperature. The pipe was first washed with water, soap and methanol. A thin layer of glue was then deposited on the backside of the FUT. It is then clamped onto the cleaned pipe using a metallic worm clamp and a SS plate that is conformed over the FUT and onto the curvature of the pipe. The OD and the wall thickness of the pipe are 89 mm and 6.5 mm, respectively. In Fig. 4a, there are two top electrodes and each of them serves as one FUT. Using one of the two FUTs the ultrasonic measurement was performed by a handheld EPOCH LT pulser/receiver

together with two spring electrical contacts of which one connects to the top silver paste electrode and one to the bottom electrode which is the Ti membrane. L^n is the n^{th} round trip ultrasonic echoes within the wall thickness of the pipe. The pulse energy used was the lowest available and the gain was 5 dB out of the available 100 dB at 100°C.

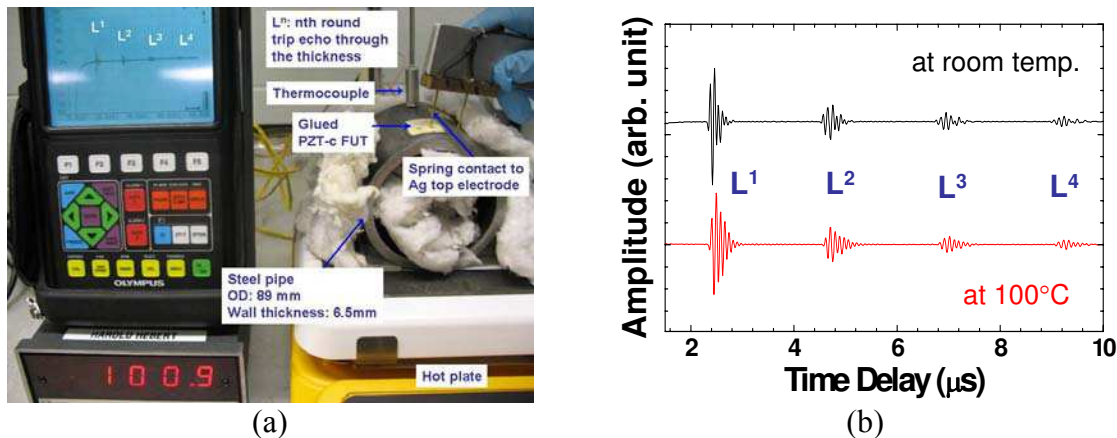


Fig. 4: (a) A FUT fabricated on a 75 μm thick Ti membrane and glued onto a steel pipe with the ultrasonic measurements displayed using a handheld EPOCH LT pulser/receiver (b) Measurement results obtained at room temperature (upper trace) and 100°C (lower trace).

Fig. 4b shows the pulse/echo measurement results obtained at room temperature (upper trace) and 100°C (lower trace). The center frequency and 6 dB bandwidth of the L^1 echo of the lower trace were 11.9 MHz and 4.1 MHz, respectively. The signal strength of the L^1 echo obtained at 100°C (lower trace) reduces only about 1 dB comparing to that obtained at room temperature. The onsite installation of FUTs using glue cured at room temperature is therefore suitable for SHM of pipes within this temperature range.

Permanent NDT with brazing FUT

Also for permanent NDT and SHM another onsite installation technique using brazing was also performed. Fig. 5 shows a 15 mm wide and 23 mm long 75 μm thick SS membrane which is brazed onto a steel pipe with an OD of 26.6 mm and pipe wall thickness of 2.5 mm. For brazing 75 μm SS rather than Ti membrane was selected for FUT due to its ability to be brazed onto steel pipes with a small compromise to be made with respect to the minor level of oxidation that develops on the SS membrane during heat treatments. The developed onsite installation approach for brazing the FUT onto steel pipes is also simple and easy to follow. Similar to the gluing technique the pipe was first washed with water, soap and ethanol and a thin layer of brazing paste was then deposited on the backside of the FUT as evenly as possible. The FUT is then clamped onto the cleaned pipe using a metallic worm clamp and a SS plate that is conformed over the FUT and onto the curvature of the pipe. The induction heating 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 substrate FUT to be brazed onto the steel pipe. After the induction, Corona poling was used to make the film piezoelectric. The developed Corona poling method is a convenient method to pole the FUT that has been brazed onto curved pipes. After poling, a silver paste was used to deposit the top electrode of necessary size.

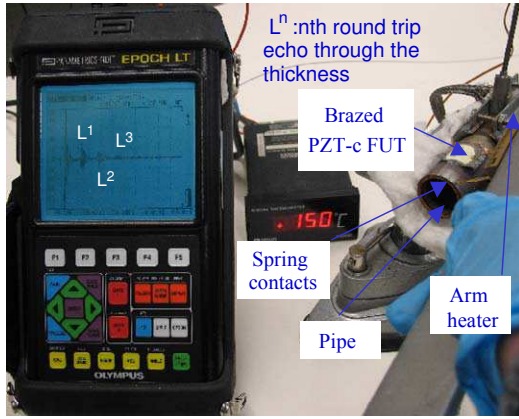


Fig. 5: Brazed FUT SS membrane substrate on the external surface of a steel pipe where the ID and the OD of the steel pipe are shown.

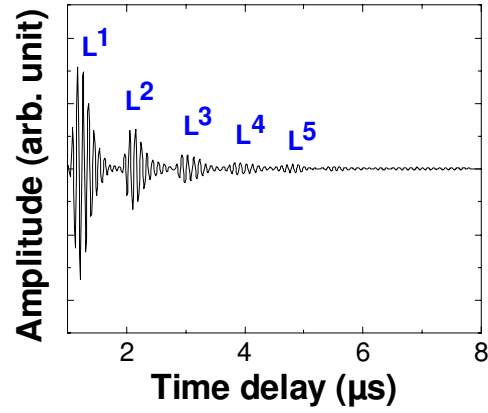
Table 1 demonstrates the coupling efficiency of the brazing material existing between the SS membrane and the external surface of the pipe under the SS membrane. It was measured with a commercial broad bandwidth UT centered at 10 MHz. Let us assume that 0 dB is the coupling efficiency of a commonly used gel couplant between a UT and the pipe. The amount of dBs appearing in nine measurement points on the pipe proves that the brazing material between the SS membrane and the external surface of the pipe was uniform and that the average loss was about 5 dB. Fig. 6a shows a FUT brazed onto this pipe and the measurement results taken at 150°C are presented in Fig. 6b. The gain used with the EPOCH was 20 dB out of the available 100 dB. This FUT had a 113 μm thick PZT-c film and the diameter of the top silver paste top electrode was 2.5 mm. The 2.5 mm was chosen not to achieve maximum signal strength, but rather to achieve maximum SNR of the L^1 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 20 dB gain may be explained by the presence of the brazing material, the 150°C high temperature, not optimized top electrode diameter and the ultrasonic attenuation within the thickness of the pipe wall. Fig. 5b indicates that the brazing technique uniquely used for such a FUT is an excellent approach to bond a FUT to a pipe with an OD of 26.6 mm for NDT or SHM measurements performed at up to at least 150°C.

Table 1: Ultrasonic coupling efficiency of brazing material.

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



(a)



(b)

Fig. 6: (a) A FUT brazed onto a steel pipe and (b) ultrasonic measurement through thickness at 150°C.

Thickness measurement accuracy

Equation (1) (Equation 19 in [17]) is used here for the estimation of the measurement accuracy for time delay and then that for thickness of the steel pipe shown in Fig. 6a.

$$\sigma(\Delta t - \Delta t') \geq \sqrt{\frac{3}{2f_0^3 \pi^2 T (B^3 + 12B)} \left(\frac{1}{\rho^2} \left(1 + \frac{1}{SNR_1^2} \right) \left(1 + \frac{1}{SNR_2^2} \right) - 1 \right)} \quad (1)$$

Table 2: Parameters for Equation 1 and digitization resolution

Parameters	Values for the brazed FUT on steel pipe
f_0	10.8 MHz
T	0.88 μs
B	0.32
ρ	0.91
SNR_1	26 dB
SNR_2	20 dB
$\sigma(\Delta t - \Delta t')$	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 μm

In this equation, f_0 is the center frequency, T is the time window length for the selection of L^1 and L^2 in Fig. 6b 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 1st echo and 2nd 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 estimated time delay). Using Equation 1, the calculated $\sigma(\Delta t - \Delta t')$ was 2.66 ns. Since a sampling rate of 100 MHz was used in the experiment, with the use of the cross correlation

method including interpolation [18], the time measurement error, which may be additionally introduced, was estimated to be 2 ns. The total uncertainty in time delay measurement was therefore 4.66 ns. Since the measured longitudinal velocity V_L in the steel substrate using the pulse-echo technique at 150°C was 5682 m/s, the best possible thickness measurement accuracy achievable using the above parameters given in Table 2 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.

CONCLUSIONS

Flexible ultrasonic transducers (FUTs) consisting of a 75 μm thick metal membrane, a piezoelectric PZT composite with a thickness larger than 85 μm and a top electrode were developed for NDT and/or SHM applications. 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 such as through inter-diffusion of lead and also to improve the crystallization behavior of the PZT film. The short annealing time also prevents oxidation between the Ti or SS and PZT-c film of the FUT. An oxidation layer would reduce the electrical conductivity of Ti and SS, which would decrease the ultrasonic performance. In this study, the ultrasonic performances in terms of signal strength of a FUT were at least as good as commercially available 5 MHz and 10 MHz broadband ultrasonic transducers at room temperature. One FUT developed was used for pipe thickness measurements at 150°C using momentary contact with a high temperature ultrasonic couplant. The onsite installation gluing and brazing techniques were used to glue or braze a FUT to a steel pipe to serve NDT and/or SHM applications such as the monitoring of erosion and corrosion of the inner pipe surfaces. The Corona poling method was conveniently applied to the FUT after the brazing technique. At 150°C the best possible thickness measurement accuracy was estimated to be 26 μm for a steel pipe with a 26.6 mm outer diameter and a thickness of 2.5 mm.

ACKNOWLEDGMENT

Financial support of J.-L. Shih from the Natural Sciences and Engineering Research Council of Canada and the technical assistance of J.-F. Moisan are acknowledged.

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