Flexible ultrasonic transducers for structural health monitoring of pipes at high temperature

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Publisher's version / Version de l'éditeur:

IEEE International Ultrasonics Symposium Proceedings, 2009, 2009-09-01

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

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***Abstract*—Piezoelectric films have been deposited by a sol-gel spray technique onto 75 µm thick metal membranes and have been fabricated into flexible ultrasonic transducers (FUTs). Such FUTs were glued and brazed onto steel pipes providing as on-site installation techniques for continuous thickness monitoring purposes 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. Ultrasonic 4 by 16 element arrays were also fabricated and single element performance was measured.**

Keywords- flexible ultrasonic transducer; array; high temperature; structural health monitoring; NDE

I. INTRODUCTION

Structural health monitoring (SHM) and non-destructive evaluation (NDE) of pipes in electrical power plants including nuclear, fossil fuel and gas, chemical and petroleum plants and in other structures have become increasingly important in the improvement of safety and in the extension of these structures' life span [1, 2]. In these applications, ultrasonic transducers (UTs) may need to be operable at high temperatures and may need to be conformed to surfaces with different curvatures in order to obtain high signal to noise ratios (SNR) for precision thickness measurements. Conventional piezoelectric UTs with rigid flat end surfaces may not be convenient for such inspections, especially at elevated temperatures due to poor SNR in pulse-echo mode and due to the difficulty in their bonding to curved surfaces. The main goal of this research is to improve the ultrasonic performance of flexible ultrasonic transducers (FUTs) fabricated in the laboratory and to develop simple and economical on-site sensor installation approaches which use gluing and brazing techniques to bond FUTs onto pipes. These techniques were developed in order to achieve an excellent form of permanent bonding for SHM and NDE purposes. The fabricated FUTs may be operated in pulse-echo, pitch-catch and transmission configurations.

The fabrication method is based on a sol-gel spray technique [3, 4]. It consists of six main steps [4]: (1) preparing a high dielectric constant lead-zirconate-titanate (PZT) solution, (2) ball milling of piezoelectric PZT or bismuth titanate (BIT) [4, 5] powders to a submicron size while mixing them in with the solution (3) sensor spraying using slurries from steps (1) and (2) to produce a layer of ceramic film onto thin metal membrane substrates, (4) heat treatment to produce a solid composite ceramic film on these metal membranes, (5) corona poling to obtain piezoelectricity of the composite ceramic film and (6) electrode painting of electrical connections. Steps (3) and (4) are performed multiple times to produce the proper film thickness for optimal FUT ultrasonic operating frequencies. Special silver paste was used to fabricate top electrodes for their operation at elevated temperatures. In this investigation, the PZT composite (PZT-c; PZT powder and PZT sol gel) and BIT composite (BIT-c; BIT powder and PZT sol gel) were fabricated onto 75 µm thick titanium and stainless steel (SS) membranes respectively as FUTs. These powders were chosen due to their high piezoelectricity in the case of PZT and high Curie temperature in the case of BIT.

II. EXPERIMENTAL RESULTS

In certain situations, NDE of pipes must be carried out continuously. The momentary contact approach, which was presented in [6], may not be appropriate; thus gluing and brazing as on-site installation techniques were developed as a more permanent solution to SHM and NDE.

A. *FUTs Glued onto a Pipe for Operation at up to 150°C*

A FUT consisting of a 75 µm thick titanium membrane, a 70 µm thick PZT-c film and a 5 µm thick silver paste was fabricated and glued onto a steel pipe and is shown in Fig. 1. Room temperature curable glue was used in this case. A typical value of d_{33} measured for this PZT-c film on steel substrates is about 30 x 10^{-12} m/V, the K_t about 0.2, the relative dielectric constant 320, the density 4400 kg/m^3 and the L wave velocity about 2200 m/s. The outer diameter (OD) and the wall thickness of the pipe were 89 mm and 6.5 mm, respectively. In Fig. 1, there are five top electrodes and each of them serves as a single FUT. Using one of the five FUTs, the ultrasonic measurement was performed by a handheld EPOCH LT pulser/receiver together with two spring electrical contacts, one of which connects to the top silver paste electrode and the other to the bottom electrode. The bottom electrode is the titanium membrane in this case. L^n is the n^{th} round trip ultrasonic echo within the wall thickness of the pipe. The pulse energy used was the lowest available and the gain used was zero dB out of the available 100 dB.

Fig. 2 shows the comparison between the pulse/echo measurement results obtained by the glued FUT shown in Fig.

1 (upper trace), a commercial broadband UT centered at 10 MHz (middle trace) and another one centered at 5 MHz (lower trace). The center frequency and 6 dB bandwidth of the L^1 echo of the upper trace, which was obtained by the FUT, were 13.3 MHz and 6.6 MHz, respectively. It is clear that for this pipe, the ultrasonic performance of the FUT on the curved surface was better than those obtained by the commercial broadband UTs. In principle, for the SHM of pipes with smaller ODs at high temperatures, the advantages of FUT over conventional UTs will become more evident. Such FUTs made of PZT-c films and glued to the pipe have survived thermal cycles between -80°C and 150°C. At 150°C, the signal strength of the FUTs reduced by about 5 dB. These are therefore highly suitable for the SHM of pipes within this temperature range. It is noted that the ultrasonic performance of such FUTs on titanium membranes showed in general a 5 to 10 dB stronger signal strength than those reported in [6], whereby FUTs were made onto SS membranes. The improved signal strength likely comes from the reduced oxidation of the membrane substrates (titanium over SS) during heat treatments and improvement of the sol gel spray technique.

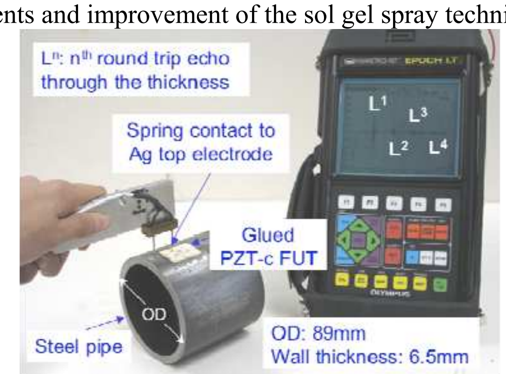


Figure 1. A FUT fabricated on a 75 µm thick titanium membrane and glued onto a steel pipe with the ultrasonic measurements displayed using a handheld EPOCH LT pulser/receiver.

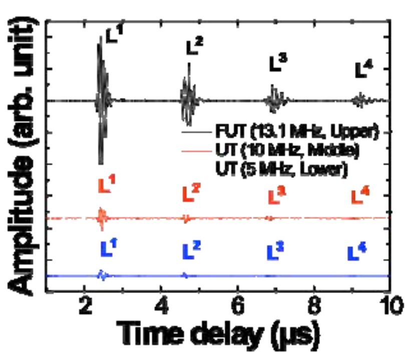
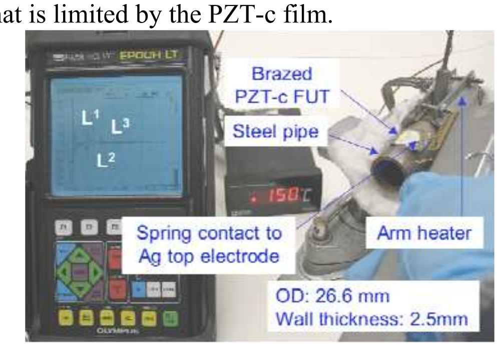


Figure 2. Pulse/echo measurement results obtained by the glued FUT shown in Fig. 1 (upper trace), a commercial broadband UT centered at 10 MHz (middle trace) and one centered at 5 MHz (lower trace).

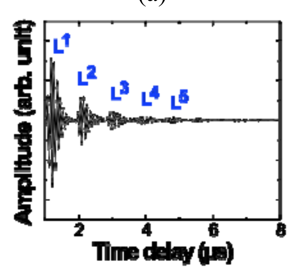
B. FUTs Brazed onto a Pipe for Operation at up to 150°C

Another on-site installation technique for FUTs is brazing. The developed approach is simple and easy to follow. For brazing, SS membrane rather than titanium was selected as the FUT substrate due to its ability to be brazed onto steel pipes with the small compromise of having a minor level of oxidation that develops on the SS membrane during heat treatments. The structure or part, in this case a steel pipe, was first washed with water, soap and methanol. A brazing paste was then deposited on the backside of the FUT SS membrane as evenly as possible. It was then clamped onto the cleaned pipe using a metallic worm clamp and a SS plate 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 substrate FUT to be brazed onto the steel pipe. After the induction, Corona poling was used to make the film piezoelectric. The developed room temperature Corona poling under UV illumination method was a convenient method to pole the FUTs that had been brazed onto curved pipes. After poling, a silver paste was used to deposit the top electrode of necessary size.

Fig. 3(a) shows a FUT brazed onto a pipe with an OD of 26.6 mm and a wall thickness of 2.5 mm. The measurement results taken at 150°C are presented in Fig. 3(b). L^n is the n^{th} round trip ultrasonic echo within the wall thickness of the pipe. 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 was chosen not to achieve maximum signal strength, but rather to achieve maximum SNR of the L^1 echo for thickness measurement. Fig. 3(b) indicates that the brazing technique uniquely used for such a FUT is an excellent approach to bonding a FUT to a pipe for NDE or SHM measurements performed at up to at least 150°C, a temperature level that is limited by the PZT-c film.



(a)



(b)

Figure 3. (a) A FUT brazed onto a steel pipe and (b) the ultrasonic measurement through the thickness at 150°C.

Equation (1) (Equation 19 in [7]) was used for the estimation of the measurement accuracy for the time delay and then for the thickness of the steel pipe shown in Fig. 3(a).

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

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. 3(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, 〉 is the correlation coefficient, SNR_1 and SNR_2 are the SNR of the 1st echo and 2nd echo, respectively and ⌠ (Δt - Δt') is the standard deviation of the measured time delay (Δt being the true time delay and Δt', the estimated time delay). Using Equation 1, the calculated ⌠ (Δt - Δt') 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 [8], the time measurement error, which may be additionally introduced, was estimated to be 2 ns. The total uncertainty in the 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 parameters shown in Table 1 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

TABLE 1
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
〉	0.91
SNR_1	26 dB
SNR_2	20 dB
σ(Δt-Δt')	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

C. FUTs Brazed onto a Pipe for Operation at up to 490°C

In order to perform SHM or NDE at a temperature higher than 150°C, a different film is required. A FUT made of a 75 µm thick SS membrane, a 95 µm thick BIT-c film and a 5 µm thick silver paste top electrode was fabricated. BIT was chosen due to its operable temperature being at up to more than 520°C [4, 6], although it has lower piezoelectricity 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. 4. 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. 4 there are also five top electrodes and each of them serve as a single FUT. Fig. 5 shows the pulse/echo measurements performed by one of these five FUTs at room temperature and at up to 490°C using the spring electrical contacts shown in Fig. 1 and the same pulser/receiver settings, the exception being the results shown in 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 obtained also at 490°C as well as to the trace taken at room temperature or 23°C. L^n is the n^{th} round trip ultrasonic echo within the wall thickness of the pipe. At 490°C, the center frequency and 6 dB bandwidth of the L^1 echo achieved with this FUT were 12.8 MHz and 6.1 MHz, respectively. This brazed FUT achieved a SNR on its L^1 echo of more than 18 dB within the room temperature to 490°C range and may thus be an excellent on-site installation technique for SHM and NDE of pipes at such high temperatures.

Figure 4. A FUT brazed onto a steel pipe.

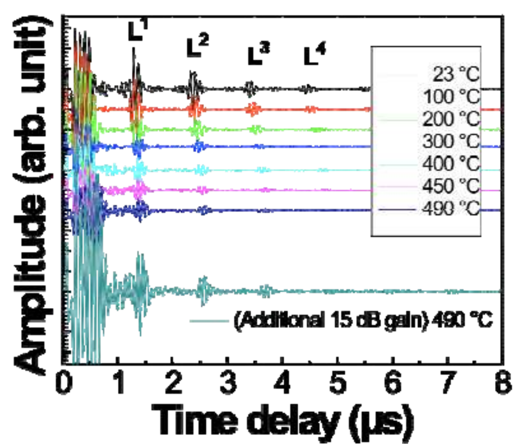


Figure 5. Pulse/echo measurements taken at room temperature and at up to 490°C with the same pulser/receiver settings, except for the bottom curve which was taken with an additional signal amplification gain of 15 dB to compare.

D. 4 by 16 FUT Array

In some cases, a need for a higher level of diagnostic evaluation is required in NDE and SHM. UT arrays are attractive for the purposes of offering spatial resolution or full volumetric coverage and/or complex beam steering capabilities in the case of phased array applications. The sol gel spray technique is a highly flexible method of fabrication and array configurations with dimensions in the cm or mm range are easily sprayed onto appropriate substrates. No form of sawing is required through the ceramic and therefore the final production yield does not depend on post-piezoelectric film fabrication steps. This capability is particularly attractive from a mass production standpoint. The spraying of the sol gel film into an array configuration, as the one shown in Fig. 6(b), required the use of a shadow mask, which in this case was a 76 µm thick brass sheet that was processed using photolithography techniques to form an array. A 4 by 16 element FUT was fabricated using the same steps as those mentioned in the introduction section and onto a 75 µm thick titanium sheet. The PZT-c film thickness was 120 mm and each element size was 3 mm x 3 mm with a center-to-center kerf separation of 5 mm. The Ag paste electrode size was about 2.5 mm x 2.5 mm. Ultrasonic measurements were taken for individual elements with the EPOCH LT pulser/receiver together with the two spring electrical contacts, the set up of which is shown in Fig. 6(a). Gel couplant was used between the FUT array and the 15.1 mm thick Al block and the gain used was 10 dB out of the available 100 dB. The performance of each element of the array may be adjusted by using different viscosities of the PZT-c slurry and by the number of layers sprayed during the film building process as well as by the size of each element. Fig. 6(c) shows the measured ultrasonic signals on one of the elements. The center frequency and 6 dB bandwidth of the L^1 echo were 12.5 MHz and 3.1 MHz, respectively. It is noted that laser-machining techniques may also be applied for patterning the array configurations of PZT-c film.

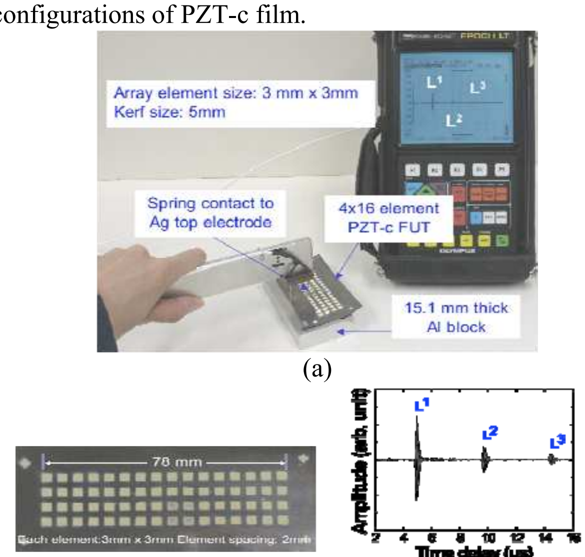


Figure 6. (a) Ultrasonic measurement of a 4 by 16 element array FUT on an Al block with gel couplant, (b) the FUT array and (c) the ultrasonic measurement through the thickness of the Al block.

III. Conclusions

In conclusion, FUTs consisting of metal membranes, piezoelectric films made by a sol-gel spray method and thin silver paste top electrodes were fabricated. A FUT consisting of a 75 µm thick titanium membrane and a 70 µm thick PZT-c film was bonded onto a steel pipe with a 89 mm OD using glue. This glue served as the ultrasonic couplant and it was found that the ultrasonic performance at room temperature on the curved surface was better than those obtained by commercially broadband UTs. Such FUTs have had consistent and high performance at up to 150 °C. Two other FUTs fabricated on 75 µm thick SS membranes with a PZT-c film and a BIT-c film were brazed onto steel pipes by the induction method. 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. These FUTs together with the gluing and brazing methods serve as excellent solutions for SHM and NDE at room and/or high temperatures due to their performance, conformability as well as their capability for on-site installation. A 4 by 16 element FUT array was also made by spraying through a shadow mask. Individual ultrasonic performance of single elements on the 4 by 16 FUT array has demonstrated excellent signal quality.

Acknowledgment

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

References

[1] R.H. M.V. Gandhi and B.S. Thompson, B.S.: ‘Smart Materials and Structures’ (Chapman & Hall, New York, 1992)

[2] S.P. Kelly, I. Atkinson, C. Gregory and K.J. Kirk, ‘On-line ultrasonic inspection at elevated temperatures’, Proc. IEEE Ultrasonics Symp., 2007, pp.904-908

[3] D. A. Barrow, T. E. Petroff, R. P. Tandon, and M. Sayer, ‘Characterization of thick lead zirconate titanate films fabricated using a new sol gel based process’, J. Appl. Phys., 1997, vol.81, no.2, pp. 876-881

[4] M. Kobayashi and C.-K. Jen: ‘Piezoelectric thick bismuth titanate/PZT composite film transducers for smart NDE of metals’, Smart Materials and Structures, 2004, vol.13, pp.951-956

[5] P. Kazys, A. Voleisis, R. Sliteris, B. Voleisiene, L. Mazeika and H.A. Abderrahim, ‘Research and development of radiation resistant ultrasonic sensors for quasi-image forming systems in a liquid lead-bismuth’, Ultragarsas (Ultrasound), 2008, vol.62, pp.7-15

[6] M. Kobayashi, C.-K. Jen and D. Lévesque, ‘Flexible ultrasonic transducers’, IEEE Trans. UFFC, 2006, vol.53, pp.1478-1485.

[7] W.F. Walker and G.E. Trahey, “A fundamental limit on delay estimation using partially correlated speckle signals,” *IEEE Trans. Ultrason. Ferroelect. Freq. Control*, vol.42, pp.301-8, 1995.

[8] J.-D. Aussel and J.-P. Monchalin, “Precision laser-ultrasonic velocity measurement and elastic constant determination,” *Ultrasonics*, vol.27, pp.165-177, 1989.