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CanSmart 2006: International Workshop on Smart Materials and Structures [Proceedings], 2006-10-12

Cansmart 2006

International Workshop

SMART MATERIALS AND STRUCTURES

12 - 13 October 2006, Toronto, Ontario, Canada

FLEXIBLE ULTRASONIC HIGH TEMPERATURE TRANSDUCERS FOR NDT APPLICATIONS

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ABSTRACT

Flexible ultrasonic transducers (UTs) consisting of a thin substrate, a piezoelectric ceramic film and electrodes have been developed. The flexibility is realized owing to the porosity of piezoelectric film and the thinness of the substrate and electrodes. In this paper, lead-zirconate-titanate composite piezoelectric film with thickness varying from 40 to 120µm is fabricated by a spray technique. The thin substrates used are stainless steel foils and polyimide films. Electrode materials are silver paste or silver paint. The UT array is configured by the selected top electrodes. The flexible UT array has been successfully tested at 150°C. The array of UT has also been successfully employed as water submerged ultrasonic probe operating in the pulse-echo mode. The UTs have been used for non-destructive testing of different materials with good signal to noise ratio.

***Keywords**:* flexible transducer, film piezoelectric sensor, high temperature, non-destructive testing, health monitoring

INTRODUCTION

Non-destructive testing (NDT) of materials are commonly performed to identify, characterize, assess voids, defects and damage in metals, metal alloys, composites and other materials [1-4]. Ultrasonic techniques are routinely used for such NDT purposes because of their subsurface inspection capabilities, fast inspection speed, simplicity and ease of operation. In many applications, ultrasonic inspections may need to be applied to curved surfaces or complex geometries. It is known that conventional planar UTs show poor inspection performance on curved surfaces [1,3]. Flexible UTs are deemed suitable for such NDT applications. This new capability insures the self-alignment of the UTs to the curved and complex geometry so that the transmitted ultrasonic energy can be maximized for improved diagnoses [3]. Furthermore, several industrial applications require high temperature (HT) operation of UTs to perform in-situ characterization of materials, real-time process monitoring, and NDT [4,5]. Thus, the research interest here is to develop flexible UTs for potential implementation in normal and HT applications and in simple and on complex geometries.

In commercially available flexible transducers, piezoelectric polymers such as polyvinylidene fluoride (PVDF) [6] and piezoelectric ceramic/polymer composites [7-10] are mainly used as piezoelectric materials. Both materials include polymer which prevents the use of such flexible transducers 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 [6]. In addition, piezoelectric polymers have low electromechanical coupling coefficients [6]. Compared to bulk piezoelectric ceramics or piezoelectric polymers, piezoelectric ceramic/polymer composites may have superior electromechanical coupling properties in addition to flexibility and low dielectric losses. However, at high temperatures good ultrasonic performances were reported only up to 80°C in particular under thermal cycling environment [4] due to the soft state of the resin as it reaches its glass transition temperature of 150°C. Other flexible high temperature ultrasonic transducers (HTUTs) have been also reported [11,12]. Because of single crystal films used, to provide the flexibility, the thickness of the piezoelectric film ranged from 0.2 to 10µm. These films provide an operating frequency normally higher than 30 MHz that may not be suitable for NDT of thick and highly attenuating materials.

This study proposes a new concept for flexible transducers to meet these stringent demands. These transducers consist of a conducting metal foil or a non-conducting polyimide film with a bottom electrode as substrate, a piezoelectric ceramic film and a top electrode. The fabrication process of the piezoelectric film is based on sol-gel technique [13-17]. The flexibility is achieved because of the porosity in the composite films and thinness of the substrate and electrodes. The operation temperature will be demonstrated up to 150°C.

FLEXIBLE TRANSDUCER FABRICATION

In this study, a 75µm thick stainless steel (SS) foil and a 60µm polyimide film have been selected for substrates. The SS foil is an electrical conductor which can be used as the bottom electrode for the UT and can sustain operation temperature above 700°C. The polyimide film is an electrical insulator and it can sustain the operation temperature above 350°C. This polyimide film firstly was coated with a conducting layer to form the bottom electrode of the UTs. Two methods were used to form this electrode; one is electroless nickel alloy plating and another is colloidal silver spray method. Care has been taken to ensure good adhesion between the film and electrode during thermal cycling as part of the manufacturing process.

The fabrication processes of the piezoelectric composite film based on sol-gel spray technique are the same as those reported in [13-16]. The ball-milled sub-micron piezoelectric lead-zirconate-titanate (PZT) powders were dispersed into PZT sol-gel solution. The PZT was chosen because of its high piezoelectric strength and acceptable Curie temperature (350° C). The final PZT/PZT mixture (paint) was then sprayed directly onto SS foil or the electrode coated polyimide substrates through an airbrush to produce a film (coating) of desired thickness. With this sol-gel spray technique, the film can be produced with specified thicknesses at desired locations using a paper shadow mask. After spraying the coating, thermal treatments such as drying, firing or annealing were carried out using a heat gun. Multiple layers were made in order to reach desired film thickness. The piezoelectric PZT/PZT film was then electrically poled using the corona discharging technique. The corona poling method was chosen because it could pole the piezoelectric film over a large area with complex geometries. Finally, top electrode can be made by silver paste pen or colloidal silver spray method. The simplicity of top electrodes fabrication provides added flexibility and convenience in the UT array configuration.

It is noted that the relative dielectric constant of the PZT/PZT composite film was about 60 measured by a Hewlett Packard 4192A LF Impedance Analyzer at 1 kHz. The measured piezoelectric constants d_{33} for PZT/PZT was about 30×10^{-12} m/V on the SS substrate.

PERFORMANCE OF FlEXIBLE UT USING SS FOIL AS THE SUBSTRATE

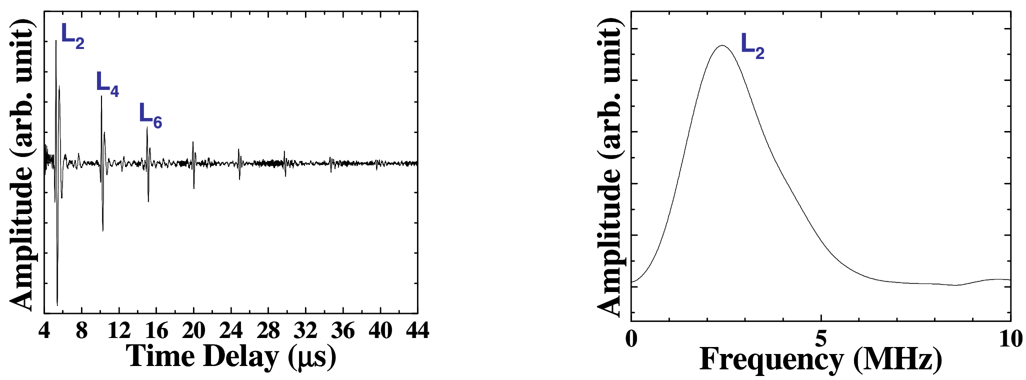
Since SS substrate can sustain operation temperature more than several hundred degrees Celsius (> 700°C), it may be brazed or welded onto metallic structures for HT operation. It may be also glued onto metallic, polymer or graphite/epoxy (Gr/Ep) composite materials for NDT applications. Figure 1 illustrates two views of a PZT/PZT 120µm thick composite film five UTs array directly fabricated onto a 75µm thick SS foil with this particular merit. Thinner SS foils may also be used as reported in [18]. The entire transducer array structure was sandwiched by polyimide films excluding the probing side of the membrane (the side opposite to thick film) so that it may be protected from the moisture in the environment and can operate at temperatures up to 150°C which is currently limited by the operating temperature of PZT/PZT composite. Copper strips were used for electrical connections.

Flexible UT array for NDT of steel plate at 150°C

When this flexible UT array was pressed onto a steel plate of 13.8mm together with HT coupling oil and fixed by a mechanical clamp, the measured ultrasonic response of UT3, shown in Figure 1, in time and frequency domains at 150°C, is obtained and presented in Figure 2. L_2, L_4 and L_6 represent the first, second and third round trip echoes through thickness of the steel plate. The center frequency, 6dB band width and signal to noise ratio (SNR) of the L_2 echo are determined to be 2.6MHz, 2.6MHz and 22dB, respectively. We have also used steel, titanium, nickel and copper membranes for the fabrication of flexible UTs [14]. These flexible UTs with the SS membranes may be also glued, soldered or brazed or mechanically fastened onto curved surfaces for ultrasonic measurements at elevated temperatures. This type of flexible UTs has been also employed to inspect metallic tubes, Gr/Ep composite and polymer materials [16]. The 150°C temperature limitation is also caused by the quick evaporation of the coupling oil at HT and the mechanical fastening approach of the flexible transducer adopted in our experiment.

(a) (b)

Figure 1: A flexible PZT/PZT 120µm thick composite film five UT array using a 75µm thick SS membrane.

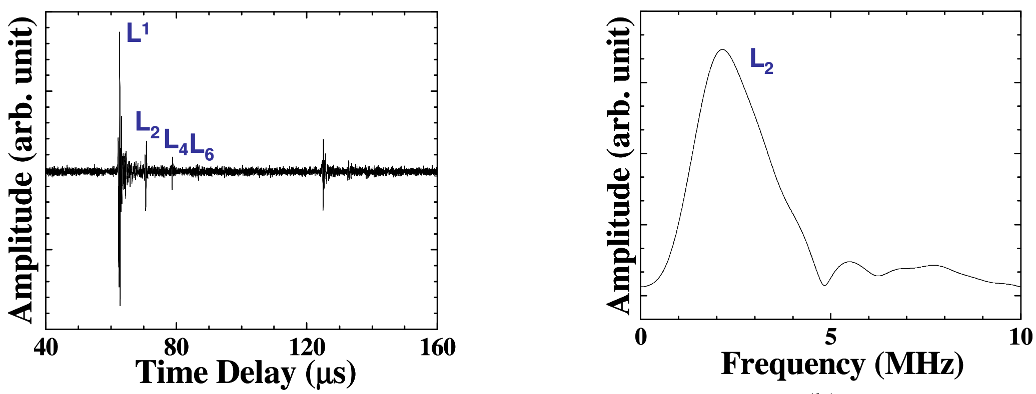


(a) (b)

Figure 2: Ultrasonic performance of the flexible ultrasonic transducer (UT3) in (a) time and (b) frequency domains for NDT of a 13.8mm thick steel plate at 150°C.

<u>Flexible UT array operated as an immersion probe for NDT of Aluminum plate</u>

The flexible UT array was completely immersed in water for three days and operated as immersion ultrasonic probes. Figure 3 shows the ultrasonic performance of the UT3 as shown in Figure 1 when placed 46mm away from a 25.5mm thick aluminum (Al) plate in a water tank. The center frequency, 6dB band width and SNR of the L_2 echo, reflected from the back side of the Al plate, are determined to be 2.4MHz, 2.1MHz and 10dB, respectively. Due to the flexibility of these flexible probes it is our expectation that the inspection of curved objects may be easier than those planar commercially available UTs. The proper curvature of the SS membrane may lead the flexible UT to become a cylindrically or spherically focused ultrasonic probe as well.



(a) (b)

Figure 3: Ultrasonic performance of the flexible ultrasonic transducer (UT3) in (a) time and (b) frequency domains at 22°C immersed in water for NDT of a 25.5mm thick Al plate.

PERFORMANCE OF FLEXIBLE UT USING POLYIMIDE FILM AS THE SUBSTRATE

In order to increase the flexibility of the flexible UT polyimide films are used for this investigation because polyimide films can sustain 350°C and the sol-gel PZT/PZT multilayer fabrication process. Its acoustic impedance is also different than that of the SS substrate. Because the polyimide film is an insulator, a colloidal silver spray and nickel alloy electroless plating methods were developed to coat a conductive layer onto the piezoelectric composite film side of the film as the bottom electrode. However, in this particular sample, colloidal silver spray method was used and two microns thick silver paint was deposited between the top polyimide film and the PZT/PZT composite. Care has been taken to strengthen the adhesion between this electrode layer and the polyimide. Figure 4 shows the flexible UT with the 60μm polyimide film substrate with a PZT/PZT composite film of 60μm thickness. This PZT/PZT film thickness is obtained using ten layers of coating process. Such fabrication process implies that the polyimide film has sustained ten thermal cycles during the drying and firing of the PZT/PZT composite film and also the corona poling heating process. As shown in Figure 4, the current process produces less than perfect flat UT surfaces (presence of wrinkles) due to the applied processing heat. Efforts are being devoted to reduce or eliminate such wrinkles and imperfections.

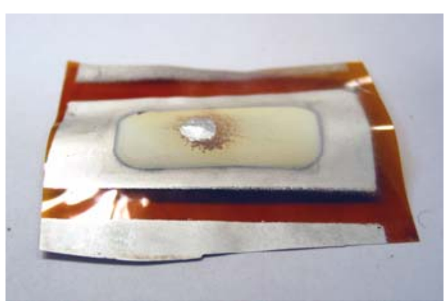
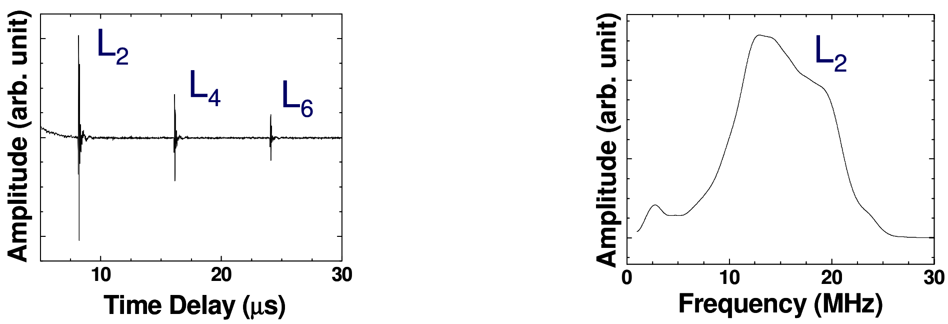


Figure 4: A flexible UT using polyimide film as the substrate.

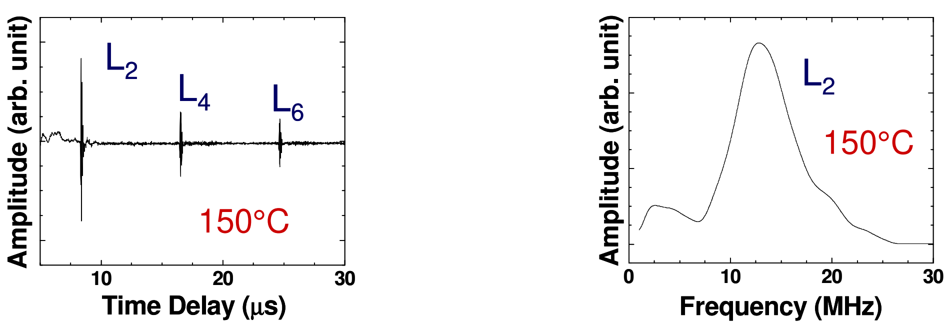
Flexible UT for NDT of Aluminum plate at 150°C

In order to demonstrate the performance of the flexible UT using polyimide film as the substrate at elevated temperature, the transducer was pressed onto an Al plate heated to 150°C. HT oil couplant was placed between the probing side of the polyimide film and Al plate. Figures 5a and 5b show the transducer response, in time and frequency domains respectively, in pulse-echo mode at room temperature. L_2 and L_4 are the first and second round trip echoes through the thickness of the Al plate. The center frequency, the 6dB band width and SNR of the L_2 echo are determined to be 15.4MHz, 10.8MHz and 25dB, respectively. The ultrasonic response of the transducer at 150°C is shown in Figure 6. The center frequency, the 6dB band width and SNR of the L_2 echo at this operating temperature is 13.4MHz, 6.7MHz and 20dB, respectively. It is observed that the signal strength of the L_2 echo is decreased by about 3dB and the frequency bandwidth reduced by 4.1MHz. At 150°C, the time delay of the L_2 echo travelling in Al substrate has 0.2μs more delay than that measured at room temperature.



(a) (b)

Figure 5: Room temperature flexible UT response in (a) time and (b) frequency domain for a 25.2mm thick Al plate.

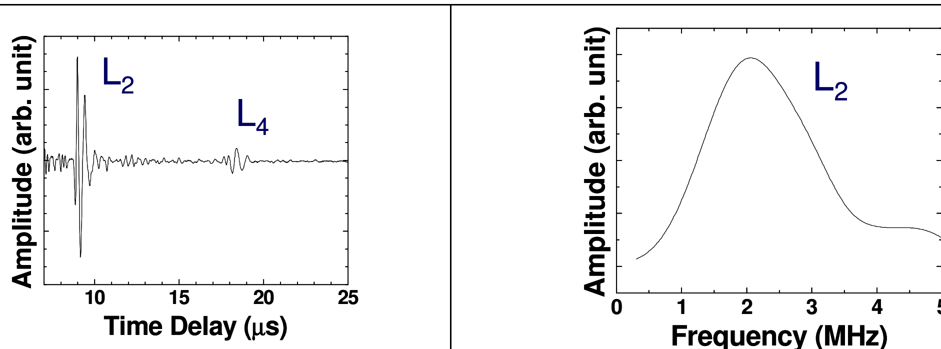


(a) (b)

Figure 6: HT (150°C) flexible UT response in (a) time and (b) frequency domain for a 25.2mm thick Al plate.

Flexible UT for NDT of Gr/Ep composite

A Gr/Ep composite plate was also chosen as the test object to illustrate the performance of the flexible UT using polyimide film for NDT application. Gr/Ep composites are widely used in the aerospace industry because of their high strength to weight ratio. They can be subjected to harsh operational environments and may experience impact or fatigue damage. The developed flexible UT can provide an attractive tool for damage assessment. The flexible UT was attached onto a 13.1mm thick Gr/Ep composite plate and an ultrasonic couplant was also placed between the polyimide film probing side and the Gr/Ep composite plate. The UT response in the pulse-echo mode at room temperature, in time and frequency domains, is shown in Figure 7. L_2 and L_4 are the first and second round trip echoes through the thickness of the composite component. The center frequency, the 6dB band width and SNR of the L_2 echo are found to be 2.2MHz, 1.8MHz and 15dB, respectively. The experienced low center frequency and bandwidth are caused by the high ultrasonic attenuation within the thick composite plate. Generally, the ultrasonic attenuation is proportional to the operation frequency squared and the higher frequency components suffer larger ultrasonic loss. It is noted that the flexible UT can be also glued to the Gr/Ep composite plate for ultrasonic measurements.



(a) (b)

Figure 7: Room Temperature flexible UT response, in the (a) time domain and (b) frequency domain, attached to a 13.1mm thick Gr/Ep composite plate.

CONCLUSIONS

Flexible ultrasonic transducers (UTs) consisting of a 75µm thick stainless steel (SS) foil or a 60µm thick polyimide film, a piezoelectric PZT/PZT composite film and electrodes were developed. The flexibility was realized owing to the porosity of piezoelectric film and the thinness of substrate and electrodes. In this paper, PZT/PZT composite was chosen as piezoelectric film because of its high piezoelectric strength. Thicknesses of 40 to 120µm were obtained by a spray technique. Electrode materials are painted or sprayed silver. SS foil itself serves as the bottom electrode; however, polyimide film required a coating of a conducting layer before the deposition of PZT/PZT composite film. The UT array can be conveniently configured by making several top electrodes. The flexible UT array with the SS foil has been successfully tested at 150°C for NDT of a 13.8mm thick steel plate and also immersed into water as immersion ultrasonic probe operated in the pulse-echo mode to inspect a 25.5mm thick Al plate. The flexible UT with the polyimide film was also used for NDT of a 25.2mm thick Al plate at room temperature and 150°C and of a 13.1mm thick Gr/Ep composite. Such flexible UTs are expected to be applicable for health monitoring of humans and structures with complex shapes and geometries.

ACKNOWLEDGMENT

The authors are grateful to H. Hébert and J. Tatibouët for their technical assistance. Financial support from the Natural Sciences and Engineering Research Council of Canada is acknowledged.

REFERENCES

1. Roy, O., Mahaut, S. and Casula, O., "Development of a smart flexible transducer to inspect component of complex geometry: modeling and experiment", Review of Progress in Quantitative Nondestructive Evaluation, vol. 21, pp. 908-914, 2002.
2. Wang, D. H. and Huang, S. L., "Health monitoring and diagnosis for flexible structures with PVDF piezoelectric film sensor array", Journal of Intelligent Material Systems and Structures, vol. 11, pp. 482-491, 2000.
3. Frankle, R. S. and Rose, D. N., "Flexible ultrasonic array system for inspecting thick composite structures", Proc. SPIE, vol. 2459, pp. 51-59, 1995.
4. Devallencourt, C., Michau, S., Bantignies, C. and Felix, N., "A 5 MHz piezocomposite ultrasound array for operations in high temperature and harsh environment", Proc. IEEE Ultrason. Symp., 2004, pp. 1294-1297.
5. Karasawa, H., Izumi, M., Suzuki, T., Nagai, S., Tamura, M. and Fujimori, S., "Development of under-sodium three-dimensional visual inspection technique using matrix-arrayed ultrasonic transducer", Journal of Nuclear Science and Technology, vol. 37, pp. 769-779, 2000.
6. Brown, L. F. and Fowler, A. M., "High vinylidene-fluoride content P(VDF-TrFE) films for ultrasound transducers", Proc. IEEE Ultrason. Symp., 1998, pp. 607-609.
7. Bowen, L. J., Gentilman, R. L., Pham, H. T., Fiore, D. F. and French, K. W., "Injection molded fine-scale piezoelectric composite transducers", Proc. IEEE Ultrason. Symp., 1993, pp. 499-503.
8. Park, J.-M., Kong, J.-W., Kim, D.-S. and Yoon, D.-J. "Nondestructive damage detection and interfacial evaluation of single-fibers/epoxy composites using PZT, PVDF and P(VDF-TrFE) copolymer sensors", Composites Science and Technology, vol. 65, pp. 241-256, 2005.
9. Gachagan, A., Reynolds, P., Hayward, G. and Mcnab, A. "Construction and evaluation of a new generation of flexible ultrasonic transducers", *Proc*. IEEE Ultrason. Symp., 1996, pp. 853-856.
10. McNulty, T. F., Janas, V. F., Safari, A., Loh R. L. and Cass, R. B., "Novel processing of 1-3 piezoelectric ceramic/polymer composites for transducer applications", J. Am. Ceram. Soc., vol. 78, pp. 2913-2916, 1995.
11. Akiyama, M., Ueno, N., Ikeda, K., Nonaka, K. and Tateyama, H., "High-sensitivity flexible ceramic sensor", U.S. Patent, 6 608 427 B2, Aug. 19, 2003.
12. Akiyama, M., Kamohara, T., Nishikubo, K., Ueno, N., Nagai, H. and Okutani, T., "Ultrahigh temperature vibration sensors using aluminum nitride thin films and W/Ru multilayer electrodes", Appl. Phys. Lett., vol. 86, 022106 (3 pages), 2005.
13. Sayer, M., Lukas, M., Olding, T., Pang, G., Zou, L. and Chen, Y., "Piezoelectric films and coatings for device purposes", Proc. Mat. Res. Soc. Symp., 1999, vol. 541, pp. 599-608.

14. Kobayashi, M. and Jen, C.-K., "Piezoelectric thick bismuth titanate/PZT composite film transducers for smart NDE of metals", Smart Materials and Structures, vol. 13, pp. 951-956, 2004.
15. Kobayashi, M., Jen, C.-K., Ono, Y. and Moisan, J.-F., "Integratable high temperature ultrasonic transducers for NDT of metals and industrial process monitoring", CINDE Journal, vol.26, pp.5-10, March/April 2005.
16. Kobayashi, M., Jen, C.-K. and Lévesque, D., "Flexible ultrasonic transducers", IEEE Trans. UFFC, vol.53, pp.1478-1484, 2006.
17. Sayer, M., Lockwood, G.R., Olding, T.R., Pang, G., Cohen, L.M., Ren, W. and Mukherjee, B.K., "Macroscopic actuators using thick piezoelectric coatings", Mat. Res. Soc. Symp. Proc. Vol.655, pp.cc13.6.1-11, 2001.
18. Jen, C.-K., Wu, K.-T., Kobayashi, M., Ono, Y., Song L. and Shih, I., "Integrated high temperature plate and surface acoustic wave transducers", to appear in this CanSmart Workshop Proceeding.