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Publisher's version / Version de l'éditeur:
https://doi.org/10.1117/12.715290
Proceedings of the SPIE Smart Structures and Materials 2007, 2007-03-22

Integrated surface and plate acoustic wave sensors for health monitoring

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ABSTRACT

Piezoelectric films sprayed onto metal substrates together with interdigital transducer electrodes form the integrated Rayleigh surface acoustic wave (RAW) transducers to excite and detect RAW. Using integrated longitudinal (L) wave ultrasonic transducers (UTs) and mode conversion from L waves to shear waves symmetrical, anti-symmetrical and shear horizontal types of guided plate acoustic waves have been generated and received in aluminum alloy plates. These transducers can be operated in pulse-echo mode for in-situ non-destructive testing (NDT) and/or health monitoring purposes in a distance of hundreds of mini-meters at 150°C. Examples of using such waves for NDT of defects are also demonstrated.

Keywords: High temperature ultrasonic measurement, Rayleigh wave, plate wave, interdigital transducer, integrated ultrasonic transducer, nondestructive testing, and mode conversion

1. INTRODUCTION

For the applications of nondestructive testing (NDT) and health monitoring of materials and structures there is a critical need for integrated in-situ sensors for local and global damage detection and assessment[1-6]. It is known that Rayleigh surface (RAW) and plate acoustic wave (PAW) transducers[7,8] can be used for NDT of metals such as steel and aluminum (Al) alloys in the range of hundreds of mini-meters depending on the attenuation characteristics of the materials. In the common practice the longitudinal (L) or shear (S) wave ultrasonic transducers (UTs) and a wedge are used to generate and receive the desired RAW and PAW with the proper mode conversion inside and through the wedge[3,4]. There is a requirement of an ultrasonic couplant between the wedge and the sample under test. It is difficult to apply these UTs and wedges on curved surfaces and at high temperature. The purpose of this investigation is to develop integrated transducers directly coated onto desired planar and curved metallic structures to generate and receive RAW and PAW for NDT and/or health monitoring applications, including high temperatures without the need of couplant.

In this study, sol-gel fabrication processes of thick piezoelectric films used are the same as those reported[5,6]. The ball-milled sub-micron piezoelectric lead-zirconate-titanate (PZT) powders were dispersed into PZT sol-gel solution. The PZT powders were chosen because of their high piezoelectric coupling constant. The final PZT/PZT mixture (paint) was then sprayed directly onto selected substrates, such as steel and Al, through an airbrush. With this sol-gel spray technique, the films 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 or an oven. Multiple layers were made in order to reach desired film thicknesses. Piezoelectric films were 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. For RAW a newly developed silver paint spray method was used to form interdigital transducer (IDT) electrodes at room temperature. Bulk L wave UTs will be used to generate PAW. Our transducer fabrication technique using hand held devices presented here is developed for the use of on-site fabrication. Samples with large size and/or heavy weight are not required to be brought at the sensor fabrication site; instead the fabrication tool kit is moved to the desired sample site. Since a pulse-echo mode is of interest here for NDT and health monitoring applications, most measurement data will be shown in this mode although measurements can be carried out in a transmission mode as well.

2. IDT AND PIEZOELECTRIC FILM CHARACTERISTICS

The IDT masks (negative) shown in Fig.1 were made by an electrical discharge machining (EDM) method. The top and bottom connection electrodes are called bus-bars, the other thin electrodes perpendicular to the wave propagation direction are called fingers. The colloidal silver paint was sprayed onto the piezoelectric film through these IDT masks to form the IDT. Since in this study the RAW and PAW operation frequency range of interest is between 0.5 and 2.0MHz, the finger widths of the IDT mask were made to be 0.5mm. The gaps between the adjacent fingers were also 0.5mm wide. The aperture of the IDT was 13.0mm. The mask was made of a 0.57mm-thick SS plate. The thickness is chosen so that the mask is flat, has negligible shadow effect during the colloidal silver spray and is reusable. This IDT fabrication technique using the colloidal silver paint spray makes the selection of the finger size and sensor size simple and convenient, and enables on-site fabrication of RAW and PAW transducers possible.

The measured relative dielectric constant of the PZT/PZT film was about 320. The d_{33} measured by an optical interferometer was 30 (10^{-12}m/V) and the thickness mode electromechanical coupling constant measured was 0.2.

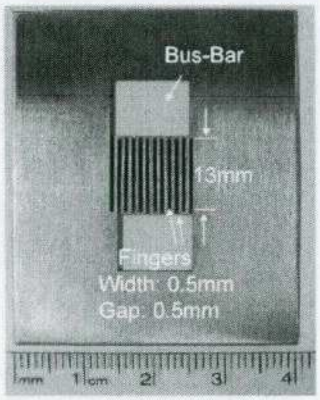


Fig. 1. A SS mask of IDT pattern.

3. RAYLEIGH ACOUSTIC WAVE (RAW) MEASUREMENTS

3.1 RAW on steel cylinder

In order to demonstrate the ability of the sol-gel spray technology to fabricate RAW transducer onto curved surfaces a steel tube with 102mm outer and 46mm inner diameter was used as a sample as shown in Fig.2. An 89µm thick PZT/PZT film and IDT were deposited onto the right side of this tube's cylindrical surface by using the technique described in the Introduction. The IDT together with PZT/PZT piezoelectric film serves as both the RAW generator and receiver. In Fig.2 there are two L wave UTs deposited onto the tube surface. Their performance is not discussed in this investigation. Figures 3a and 3b show the RAW measurements at 150°C in the time and frequency domain (of the first echo R_1), respectively in the pulse-echo mode. The center frequency, 6dB bandwidth and SNR were 1.5MHz, 0.3MHz and 24dB, respectively, where R_1, R_2 ... R_n are the nth round trip echo around the cylindrical surface of the tube. Each round trip travels in a distance of 320.4mm. In Fig.3 the R_6 echo has travelled a distance of 1,922mm.

At room temperature the measured L wave velocity V_L and S wave velocity V_S of this steel tube along the axial direction are 5904m/s and 3227m/s, respectively. Using these data and Eqn (1)[7,8],

$$\left(\frac{V_R}{V_S}\right)^6 - 8\left(\frac{V_R}{V_S}\right)^4 + 8\left\{3 - 2\left(\frac{V_S}{V_L}\right)^2\right\}\left(\frac{V_R}{V_S}\right)^2 - 16\left\{1 - \left(\frac{V_S}{V_L}\right)^2\right\} = 0 \quad (1)$$

The calculated RAW group and phase velocity V_R was 2986m/s. It is noted that for isotropic substrates the phase velocity is equal to the group velocity[7,8]. At room temperature the measured V_R was 2980m/s which agreed well with the theoretically calculated value. At 150°C, as shown in Fig.3, the measured (RAW) velocity was 2853m/s and the signal strength at 150°C was 3dB stronger than that at room temperature.

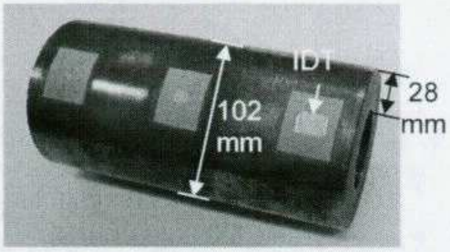
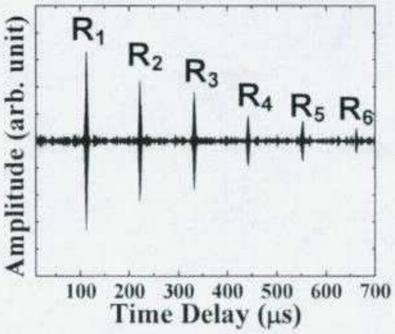
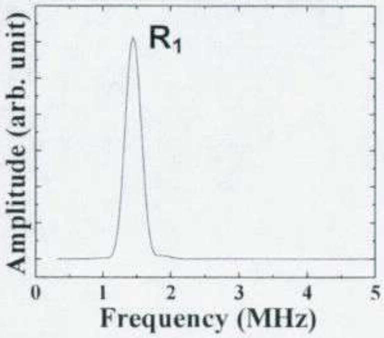


Fig. 2. A steel tube with 102 mm external diameter and 46 mm inner diameter and IDT for RAW generation and detection in pulse-echo mode.



(a)



(b)

Fig. 3. Ultrasonic performance of the integrated RAW transducer at 150°C in (a) time and (b) frequency (for echo R_1) domain. R_1, R_2, ... R_n are the nth round trip echoes around the tube external cylindrical surface.

3.2 RAW on planar stainless steel plate for NDT illustration

A 26.1mm-thick stainless steel (SS) plate was selected in this study for NDT demonstration using integrated RAW transducer. Two IDTs were made on top of the 99μm-thick PZT/PZT film by the colloidal sliver paint spray. The thickness of IDT was about several microns. Fig.4 shows the integrated PZT/PZT composite film transducer with the IDT near edge "A" operated in the pulse-echo mode at 150°C. The aperture of the IDT shown in Fig.1 was 13mm. Two line grooves with a width of 1mm and a depth of 0.3mm were made to simulate the defects (D1 and D2) perpendicular to the RAW path. The lengths of D1 and D2 partially blocking the RAW path were 5.5mm and 9.2mm, respectively which were 42% and 71% of the aperture (13mm) of the IDT as shown in Fig.4. The measured RAW signals in time domain with a band pass filter between 1.3MHz and 1.7MHz is given in Fig.5. In Fig.5 R_A, R_B , R_{D1}, R_{D2} and R_{A+B} were the reflected echoes from the edge "A", the edge "B", the artificial line defect D1 and D2, and the edge A (or B) and then edge B (or A) through the corresponding RAW travel paths (distances) of 2A, 2B, 2D1, 2D2 and 2A+2B, respectively. The distance was measured from the center of the IDT to the edge or the center of the line defect. The echoes in Fig.5 clearly show that at 150°C the defects D1 and D2 can be identified. It is noted that at 1.5MHz the Rayleigh wave length at 150°C was 1.9mm. The noises in Fig.5 came from the scattered bulk waves from the lower corners of the two edges of the SS substrate. It is noted that when both IDTs shown in Fig.4; one as the RAW transmitter and another as the receiver, are used, transmitted RAW can be obtained. The IDT near edge "B" can be operated in the pulse-echo mode as well. It was observed that the signal strength at 150°C was 5dB weaker than that at room temperature.

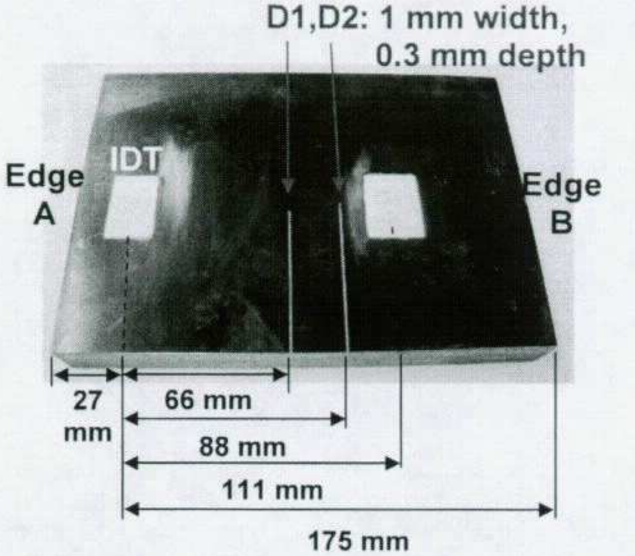


Fig. 4. A 26.1 mm thick SS plate with IDTs for RAW generation and detection in pulse-echo mode.

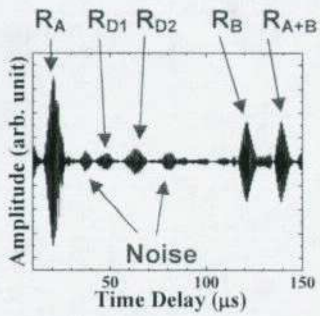


Fig. 5. Ultrasonic performance of an integrated RAW transducer near the edge A shown in Fig.4, operated in pulse-echo mode at 150°C in time domain with a band pass filter between 1.3MHz and 1.7MHz. D1 and D2 are line grooves simulating the defects.

3.3 RAW on planar Al alloy plate

Al alloys are common materials for aircraft structures and other transportation systems, such as automobiles. It is crucial to develop a NDT and health monitoring technology to inspect large area of structure integrity. A 25mm-thick Al alloy plate is chosen here for RAW demonstrations. Similar to the SS plate mentioned above two IDTs were made on top of the 86μm-thick PZT/PZT film by the colloidal sliver paint spray. Fig.6 shows the integrated PZT/PZT composite film transducer with the IDT near edge "A" operated in the pulse-echo mode at 150°C. The measured RAW signals in time domain with a band pass filter between 0.5MHz and 2.0MHz is given in Fig.3. In Fig.7 R_A, R_B and R_{A+B} are the reflected echoes either from the edge "A" or the edge "B" through the corresponding RAW travel paths (distances) of 2A, 2B, 2(A+B), respectively. The longest travel distance in this figure was 306mm (for R_{A+B}). The noises in Fig.7 were caused by the scattered bulk waves from the lower corners of the two edges of the Al alloy substrate.

At room temperature the measured L wave velocity V_L and S wave velocity V_S of this Al alloy substrate are 6343m/s and 3044m/s, respectively. Using these data and Eqn (1) the calculated RAW group and phase velocity V_R was 2846m/s. At room temperature the measured V_R was 2840m/s which agrees well with the theoretically calculated value. At 150°C, as shown in Fig.7, the measured (RAW) velocity was 2700m/s and the signal strength at 150°C was 13dB weaker than that at room temperature.

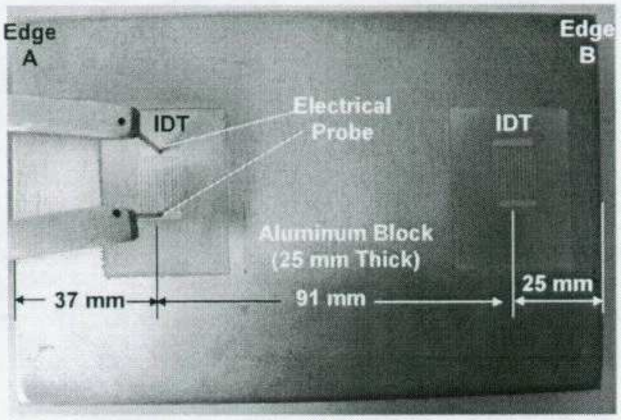


Fig. 6. A 25mm-thick Al alloy plate with IDTs for RAW generation and detection in pulse-echo mode.

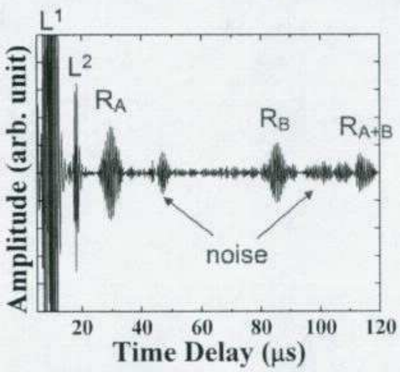


Fig. 7. Ultrasonic performance of an integrated RAW transducer near the edge A shown in Fig.6, operated in pulse-echo mode at 150°C in time domain with a band pass filter between 0.5MHz and 2.0MHz.

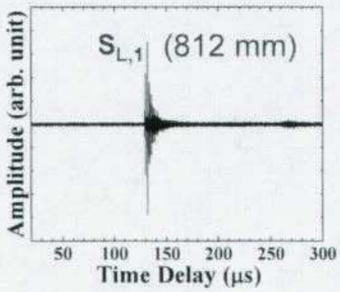
Fig.7 also shows the existence of L waves represented by L^1 and L^2 through the thickness direction of the Al alloy substrate. They were generated and detected by the same IDT transducer in Fig.6. The L^1 and L^2 were the first and second round-trip echoes through the thickness of the 25mm-thick Al alloy substrate. These films were excellent bulk wave ultrasonic transducers as illustrated in Refs.[5,6]. In Fig.7 the L^1 signal was saturated. The strength of the L wave could be adjusted by the electrode size of the upper and lower bus-bars and finger width of the IDT. By comparing the IDT shown in Fig.1 with that shown in Fig.6 we can see that the 2mm width of the bus-bars of the IDT pattern in Fig.7 is narrower than 9.5mm shown in Fig.1. The narrower is the width of these bus-bars, the weaker is the L wave and the stronger the strength of RAW. This indicates that NDT or health monitoring can be carried out not only by the RAW along the surface of the Al alloy substrate but also by the L wave along the thickness direction. Since the center frequency of the bulk L wave with this PZT/PZT composite film was around 7MHz, if the pass band was extended to higher frequency than 2MHz used for RAW, the L wave signal strength became stronger. The pass band of the band pass filtering could be also adjusted and carried out by software in real-time. Because the RAW transducer shown in Fig.7 is of layer structure which consists of the PZT/PZT composite film and Al alloy substrate, the excitation efficiency[9] of the RAW device with respect to the PZT/PZT film thickness and the finger width of the IDT which affect operating frequency will be further investigated in order to strengthen the RAW signals. It is noted that the measured L wave velocity in PZT/PZT composite film was 2200m/s which was slower than that 6343m/s in Al alloy, the V_R along the surface of PZT/PZT composite film on Al alloy shown in Fig.7 should be slower than that on the surface of Al alloy surface without the film[7-9]. For the integrated composite PZT/PZT transducer deposited on the SS substrate mentioned in the last Section the L wave could be observed if the pass band of the filter was increased to the PZT/PZT film thickness mode frequency around 3.2MHz.

4. PLATE ACOUSTIC WAVE MEASUREMENTS ON AL ALLY PLATES

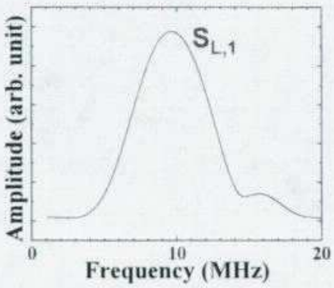
The integrated transducer shown in Fig.4 for the excitation and detecting of RAW can be used to excite PAW as well if the substrate thickness is thin enough comparing to the wavelength. A recent report[10] showed that an IDT deposited onto bismuth titanium /PZT thick piezoelectric composite film coated onto a 0.7mm thick steel plate and operated in pulse-echo mode could excite and receive PAW at 350°C in a distance more than 594mm with good SNR. In this investigation an alternative approach to excite and detect PAW is presented. Mainly integrated L wave PZT/PZT composite transducer[5,6] together with mode conversion[10,11] to generate and receive PAW. Such approach takes the advantage of simple fabrication of integrated L wave UTs, high electromechanical coupling and broad bandwidth of these UTs. Experimental results showed that the integrated L wave UT had the same performance as that of a commercial available broadband UT at center frequencies ranging from 2 to 20 MHz. However, at present the thickness of sol-gel sprayed L wave UTs is limited to 200μm or less, therefore the operation frequency is higher than 1MHz[5,6]. The higher is the frequency of PAW, the shorter is its propagation distance due to increased acoustic wave attenuation.

Figure 8 shows a 6.35mm thick, 50.8mm wide and 406.4mm long Al plate coated with one integrated L wave UT at one edge. From theoretical calculations such plate supports multimode PAW[7,8]. This L wave UT excites symmetrical types (S_L) of PAW. The measured reflected symmetrical PAW mode echoes at 150°C in time and frequency domain (for $S_{L,1}$ echo) from the edge opposite to the L wave UT are presented, respectively, in Figs.9a and 9b. After traveling a distance of 812mm the frequency of the $S_{L,1}$ echo was 9.7MHz. The subscript 1 denotes the 1st round-trip echo. It is expected that if the frequency of the UT were lower, larger distance than 812mm could be obtained. It is noted that the signal strength at 150°C was the same as that at room temperature. If the signals near $S_{L,1}$ echo are expanded in time domain, many trailing echoes[12] which represent different higher order symmetrical modes can be clearly seen.

Fig. 8. Integrated L wave UT for the generation and detection of symmetrical (S_L) PAW.



(a)



(b)

Fig. 9. Measured reflected symmetrical PAW mode echoes at 150°C from the edge opposite to the L wave UT in (a) time and (b) frequency domain.

Recently using mode conversion L wave can be converted into shear waves for NDT applications[10,11]. It is known that there exist shear vertical (S_V) and shear horizontal (S_H) waves in the bulk materials[8]. Here novel integrated PAW transducers using mode conversion from L wave to S_V and S_H concepts are developed. In Fig.10 an integrated L wave 102μm thick PZT/PZT composite film UT transducer was coated on top of the Al plate at the edge of L wave UT side.

The calculated optimal mode conversion angle for this configuration was 64.6°. At this angle the energy conversion rate from the L wave to the S wave is 75.1 %, which is only 0.06% smaller than the maximum conversion rate[13]. Due to this mode conversion configuration the anti-symmetrical modes (A_{SV}) will be excited. Again the Al plate supports multimode A_{SV} propagation. The measured reflected anti-symmetrical A_{SV} PAW mode echoes at 150°C in time and frequency domain (for the first echo) from the edge opposite to the L wave UT are given, respectively, in Figs.11a and 11b. After traveling nearly a distance of 770mm the frequency of the $A_{SV,1}$ echo was 3.9MHz. The subscript 1 denotes the 1st round-trip echo. In Fig.11a the 2nd echo $A_{SV,2}$ traveled in a distance of about 1,540mm could be still observed. For this configuration L wave traveled nearly half of the plate thickness and converted to PAW and vice versa. It was observed that the signal strength at 150°C was 5dB weaker than that at room temperature. It indicates that PAW generated and received by such mode conversion approach is feasible for large distance NDT and health monitoring purposes.

Fig. 10. Integrated L wave UT for the generation and detection of anti-symmetrical A_{SV} PAW using mode conversion.

(a) (b)

Fig. 11. Measured reflected anti-symmetrical PAW mode echoes at 150°C from the edge opposite to the L wave UT in (a) time and (b) frequency domain.

Fig. 12. Integrated L wave UT for the generation and detection of shear horizontal S_H PAW using mode conversion.

(a) (b)

Fig. 13.Measured reflected shear horizontal PAW modes echoes at 150°C from the edge opposite to the L wave UT in (a) time and (b) frequency domain.

If the L wave UT is located at the edge indicated in Fig.12, shear horizontal types[7,8] of guided PAW can be excited and received using mode conversion. The thickness of this PZT/PZT composite film was 105μm. Also for this configuration the calculated optimal mode conversion angle was 64.6°. The measured reflected shear horizontal guided SH PAW mode echoes at 150°C in time and frequency domain (for the first echo) from the edge opposite to the L wave UT are given, respectively, in Figs.13a and 13b. After traveling nearly a distance of 812mm the frequency of the $A_{SV,1}$ echo was 2.8MHz. The subscript 1 denotes the 1st round-trip echo. For this configuration L wave traveled nearly 25.4mm and then converted to shear horizontal PAW modes and vice versa. It is noted that the signal strength at 150°C was 8.5dB weaker than that at room temperature. The results showed that the signals for shear horizontal S_H PAW modes were noisier than those of anti-symmetrical A_{SV} PAW modes. The detail investigation will be performed.

5. CONCLUSIONS

Thick (>60μm) PZT/PZT composite piezoelectric films sprayed onto steel, SS and Al substrates together with interdigital transducer electrodes form the integrated RAW transducers to excite and detect RAW. They were operated in the frequency range between 1.5 and 9.3 MHz. It has been demonstrated that RAW can be used to detect line defects perpendicular to the RAW propagation path at 150°C in the pulse-echo mode. The width and the depth of the lines were 1mm and 0.3 mm, respectively and the RAW wavelength was 1.9 mm. Using integrated longitudinal (L) wave ultrasonic transducers (UTs) and mode conversion from L waves to shear waves symmetrical, anti-symmetrical and shear horizontal types of guided plate acoustic waves have been generated and received up to 150°C. The RAW and PAW presented here showed that they can be excited and received in pulse-echo mode for in-situ non-destructive testing (NDT) and health monitoring purposes in a distance of hundreds of mini-meters.

ACKNOWLEDGMENT

The authors are grateful to Y. Ono, H. Hébert and J.-F. Moisan for their technical assistance. Financial support from the Natural Sciences and Engineering Research Council of Canada is acknowledged.

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