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Integrated Plate Acoustic Wave Sensors for In-situ NDT Applications

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ABSTRACT

For in-situ NDT applications, two different types of miniature and light-weight plate acoustic wave (PAW) transducers have been developed. In the first type, thick films (>40μm) piezoelectric ultrasonic films were directly deposited onto the end edges of aluminum and stainless steel plates using a sol-gel spray technique as integrated ultrasonic transducers. They were used to generate and receive symmetrical, anti-symmetric and shear horizontal types of PAWs in pulse/echo mode. The propagation length reached more than one meter in frequencies of several MHz. In 2 mm thick plates line defects of 1 mm width and 1 mm depth were clearly detected at room temperature and 150°C. This type of PAW transducers does not need couplant. In the second type the piezoelectric films were coated onto 50μm thick polyimide membranes as flexible ultrasonic transducers. These flexible thick film piezoelectric transducers made off-line were glued to the edges of the above mentioned plates as PAW transducers and to excite and detect the above mentioned three types of PAWs in pulse/echo mode as well. Measurements results at room temperature and/or 150°C are presented and discussions of advantages and disadvantages of these two approaches are provided.

Keywords: Integrated ultrasonic sensor, flexible ultrasonic sensor, nondestructive testing, structural health monitoring, and plate acoustic waves.

1. INTRODUCTION

Many commercial and military airplanes are employed beyond their designed life time necessitating life extension programs. In addition, emerging new airplanes are increasingly required to be equipped with intelligence for improved flight control, increased fuel efficiency and reduced weight. Therefore, there is urgent need for miniaturized light weight integrated in-situ sensors and sensor systems for local and global damage detection and assessment in aerospace structures [1-3]. The ultimate goal is to use structurally integrated sensors to enable condition-based maintenance, estimate the remaining useful life on a continuous basis, inspect in-flight aircraft critical components, thus increasing platform availability and reducing associated maintenance costs.

It is known that plate acoustic waves (PAW) [4, 5] can propagate in a distance of more than tens or hundreds of cm in metal plates. PAWs can be excited and received by bulk wave transducers with a wedge [3,6] and interdigital transducers [7]. In this investigation, two types of PAW transducers are developed for the studying of different PAWs excitation and receiving as well as the capability for in-situ monitoring of the cracks in the plate. They are piezoelectric film based transducers which have been fabricated by a sol-gel spray technique [8-10]. In one sensor type, piezoelectric films of thickness greater than 40μm are deposited directly onto the edge of around 2mm thick aliminum (Al) alloy and stainless (SS) plate as integrated ultrasonic transducers (IUTs). In the other sensor type, piezoelectric films are coated onto a 50µm thick polyimide membrane as flexible ultrasonic transducers (FUTs). These FUTs will subsequently be glued onto similar locations at the edge of the metallic plates. The IUTs and FUTs are longitudinal (L) acoustic waves type, however, when they are coated or glued onto the edges of plates, they generate and receive PAWs. In this study three different configurations involving mode conversions [11-13] will be used and they can excite and detect symmetrical, anti-symmetrical and shear horizontal types of PAWs [4,5].

2. ULTRASONIC TRANSDUCERS

The sol-gel based sensor fabrication process consists of six main steps [9,10]: (1) preparing high dielectric constant lead-zirconate-titanate (PZT) solution, (2) ball milling of piezoelectric PZT powders to submicron size, (3) sensor spraying using slurries from steps (1) and (2) to produce the thin film, (4) heat treating to produce a solid composite (PZT/PZT) thin film, (5) corona poling to obtain piezoelectricity, and (6) electrode painting or spraying for electrical connections. Steps (3) and (4) are used multiple times to produce optimal film thickness for specified ultrasonic operating frequencies. Silver paste was used to fabricate top electrodes. Such electrode fabrication approach enables to achieve desired sensor array configurations easily and economically. In this study L acoustic wave transducers are used.

For the developed PZT/PZT composite film the measured relative dielectric constant was about 320. The d_{33} measured by an optical interferometer was near 30 (10^{-12} m/V) and the thickness mode electromechanical coupling constant measured was about 0.2 [10]. The scanning electron microscopic images of the film indicate grain size less than 1µm and 20% porosity. It is believed that the film porosity contributes to the low values of the dielectric constant, d_{33} and the low thickness mode electromechanical coupling constant.

Figure 1 illustrates the thick film IUT that was directly deposited onto the edge of a 2.0mm thick Al plate with a length of 406.4mm and a width of 50.8mm. The thickness of the PZT/PZT composite film was 88µm. The top rectangular electrode has a length of 46mm and width of 1.2mm, define the IUT active area. The advantage of such IUT is that it can be directly deposited or coated onto planar or curved surfaces without the need of couplant. The maximum fabrication temperature of these IUTs can be lower than 175°C [9, 10]; however, the lower the fabrication temperature the lower is the ultrasonic signal strength. These IUTs can be employed in operational temperatures, ranging from -100°C to 150°C. The L wave performance including strength and frequency bandwidth of the developed IUTs is close to those of the commercially available broad bandwidth UTs [9, 10].

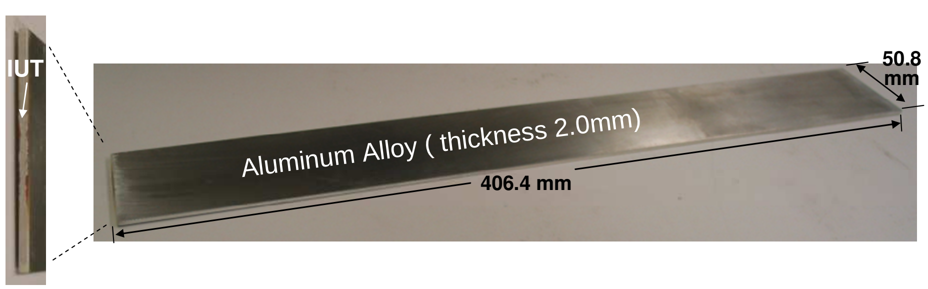
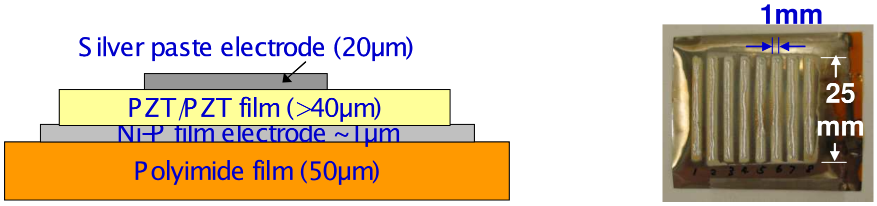


Figure 1. One IUT coated directly onto the edge of an Al plate.

The other type of sensor developed is the FUT. These FUTs were reported using poly (vinylidene fluoride) [14], polymer composites [15, 16] and metal foils [17]. Since polyimide film of 50µm thickness is very flexible and can sustain operational and fabrication temperatures of 350°C, it is used as the substrate for the FUT. Firstly, electroless nickel plating was carried out to produce a

~1µm thick nickel film as the bottom electrode. Then PZT/PZT composite films of >40µm were coated onto the nickel electrode. After corona poling, the top electrodes were made by silver paste of about 20µm thick. The schematic diagram and an actual flexible UT used for this study are shown in Figure 2(a) and 2(b), respectively. The thickness of the PZT/PZT composite film for the flexible UT shown in Figure 2(b) was 66µm. Since top electrode was fabricated using silver paste, array configuration can be achieved with ease. In Figure 2b each top electrode had a length of 24mm and a width of 1.2mm. Then each FUT is cut and glued onto the edge of the plates to be studied. Such simple FUT fabrication process is an excellent alternative to those reported in [14-17]. In general, the signal strength of the FUT using polyimide film substrate is about 10 dB weaker than the IUT due to the lower fabrication temperature associated with polyimide film substrate [10]. Such FUT can have operation temperature at least up to 150°C [10].



(a) (b)

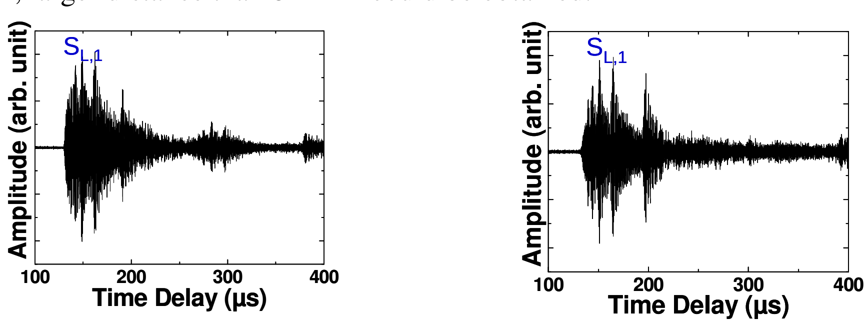
Figure 2. (a) Schematic and (b) actual FUTs using 50µm thick polyimide film as the substrate.

3. PAW TRANSDUCERS AND NDT MEASUREMENTS

There are many different types of PAWs which can be propagated in metallic plates [3-5]. In this investigation three types of PAWs; namely symmetrical, anti-symmetrical and shear horizontal PAWs, will be studied using IUTs and FUTs to generate and receive at the edges of the plates.

3-1. Symmetrical PAW

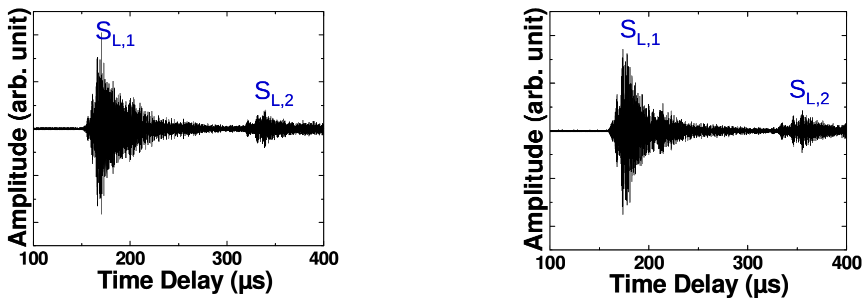
When IUT is deposited onto the edge of the Al plate as shown in Figure 1, it can generate and receive symmetrical (S_L) PAW. Figures 3(a) and 3(b) show the PAW signal obtained in pulse-echo mode in time domain at room temperature and 150°C, respectively. $S_{L,1}$ is the 1st round trip echo reflected from the edge opposite to the IUT. The Al plate was 2.0mm thick, 50.8mm wide and 406.4mm long. After traveling a distance of 812mm the center frequency of the $S_{L,1}$ echo was 4MHz. It is noted that the signal strength at 150°C was 8dB less than that at room temperature, but the arrival time of $S_{L,1}$ echo at 150°C was longer than that at room temperature due to the lower PAW velocity at higher temperature. If the signals near $S_{L,1}$ echo are expanded in time domain, many trailing echoes which represent different PAW modes can be clearly seen. It is expected that if the frequency of the IUT were lower, larger distance than 812mm could be obtained.



(a) (b)

Figure 3. Measured reflected symmetrical PAW mode echoes in a 2.0 mm thick Al plate at (a) room temperature and (b) 150°C from the edge opposite to the IUT in time domain.

In this study a 1.9mm thick SS plate with a length of 406.4mm and a width of 50.8mm was also used for PAW measurements. The length and the width of this SS plate was the same as those of the Al plate shown in Figure 1. An IUT having a 90μm thick PZT/PZT composite film was deposited onto the edge similar to that shown in Figure 1. Figures 4(a) and 4(b) show the PAW signal obtained in pulse-echo mode in time domain at room temperature and 150°C, respectively in this SS plate. $S_{L,n}$ is the nth round trip echo reflected from the edge opposite to the IUT. It is noted that the signal strength at 150°C was 4dB less than that at room temperature and $S_{L,2}$ echo traveled a distance of 1.625m.



(a) (b)

Figure 4. Measured reflected symmetrical PAW mode echoes in a 1.9 mm thick SS plate at (a) room temperature and (b) 150°C from the edge opposite to the IUT in time domain.

In order to demonstrate the long distance (global) non-destructive testing (NDT) capability of the PAW two artificial line defects, D1 and D2 with 1mm depth and 1mm width were made onto the Al plate shown in Figure 1. D1 and D2 had width of 25.4 mm and 50.8mm, respectively as shown in Figure 5. At 150°C the measured PAW signals in the Al plate shown in Figure 5 are given in Figure 6. Figure 3(b) in which no line defects exist and Figure 6 in which two line defects present cleanly confirm that PAW can be used to perform NDT of defects in long distance at 150°C. In the present case the defects were 146.3mm and 223.5mm away from the IUT.

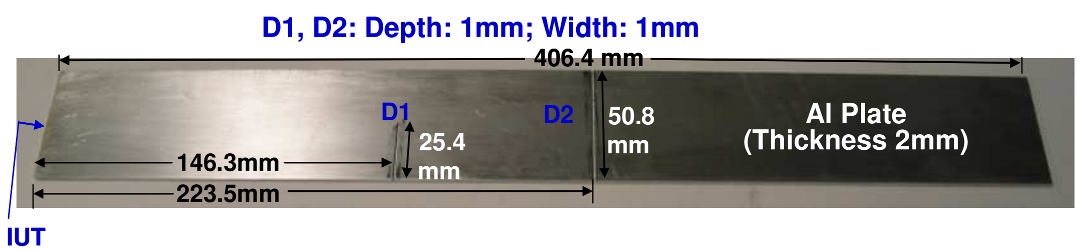


Figure 5. Two artificial line defects, D1 and D2 were made onto the Al plate shown in Figure 1.

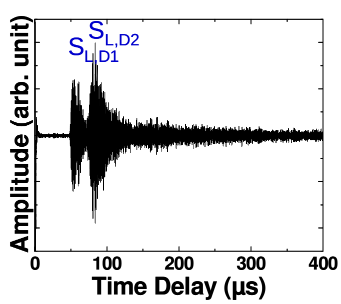


Figure 6. Symmetrical PAW signals detecting two artificial line defects, D1 and D2 in Figure 5.

In certain situations, accessibility to desired locations of aircraft components is limited for the fabrication of the IUTs, thus an alternative approach using FUT may be used. The fabrication of flexible UTs can be made off-line in a laboratory environment. Thereafter, they can be attached to desired sensor locations using adhesives such as glues that can sustain operational temperatures. Such adhesives can further be used as ultrasonic couplant. Figure 7 shows that one FUT which was obtained from the multiple FUTs shown in Figure 2(b) was attached to the edge of the Al plate identical to the one shown in Figure 1. Figure 8 shows the symmetrical PAW signal obtained in pulse-echo mode in time domain at room temperature in this Al plate. The PAW waveform in Figure 8 is quite similar to that in Figure 3(a). It is noted that because of the optimization of the glue between the FUT and the edge of the Al plate has not been carried out and the flatness of the edge was not optimal, the signal strength of $S_{L,1}$ echo in Figure 8 was 36dB less than that in Figure 3(a). It is noted that $S_{L,2}$ echo traveled a distance of 1.625m

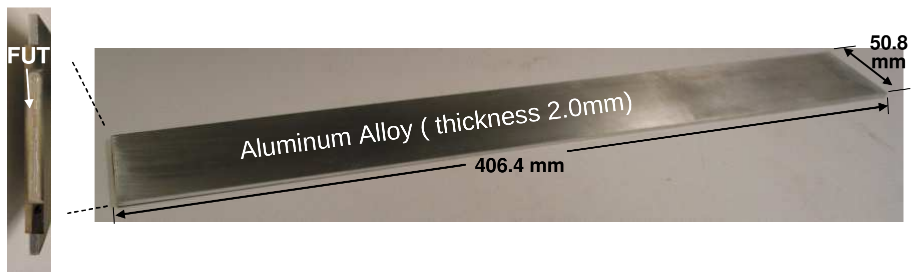


Figure 7. One FUT coated directly onto the edge of an Al plate to generate and receive symmetrical PAW.

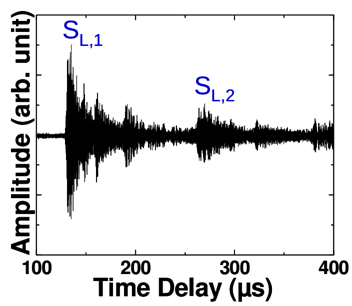


Figure 8. Measured reflected symmetrical PAW mode echoes in a 2.0 mm thick Al plate at room temperature from the edge opposite to the FUT in time domain.

3-2. Anti-symmetrical PAW

Recently using mode conversion L type wave can be converted into shear (S) waves for NDT applications [11-13]. It is known that there exist shear vertical (S_V) and shear horizontal (S_H) waves in the bulk materials [4, 5, 11]. Here integrated PAW transducers using the analogy of mode conversion from L wave to S_V and S_H modes have been developed. In Figure 9 a 66μm thick PZT/PZT composite film IUT transducer was coated on top of the Al plate at the edge of transducer side. The chosen mode conversion angle for this configuration using the analogy of L wave to S_V was 63.7° which was obtained from the phase matching angle [13] of the measured bulk L and S wave velocities of the Al plate. At this angle the energy conversion rate from the bulk L wave to the S wave is 83.1%, which is only 0.02% smaller than the maximum conversion rate [18]. Due to this mode conversion configuration the anti-symmetrical modes (A_{SV}) will be excited. The Al plate supports multimode A_{SV} propagation. The measured reflected anti-symmetrical A_{SV} PAW mode echoes at room temperature and 150°C in the time domain from the edge opposite to the IUT are given, respectively, in Figures 10(a) and 10(b). After traveling nearly a distance of 813mm the center frequency of the $A_{SV,1}$ echo was 8.1MHz. The signals arrived earlier than $A_{SV,1}$ echo were the higher order modes which have higher velocity than $A_{SV,1}$ mode [4,5,11]. 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 6dB weaker than that at room temperature. It indicates that PAW generated and received by such mode conversion approach is feasible for large distance in-situ NDT.

Figure 9. One IUT coated at the top surface near the edge of the Al plate for the generation and detection of anti-symmetrical A_{SV} PAW using mode conversion.

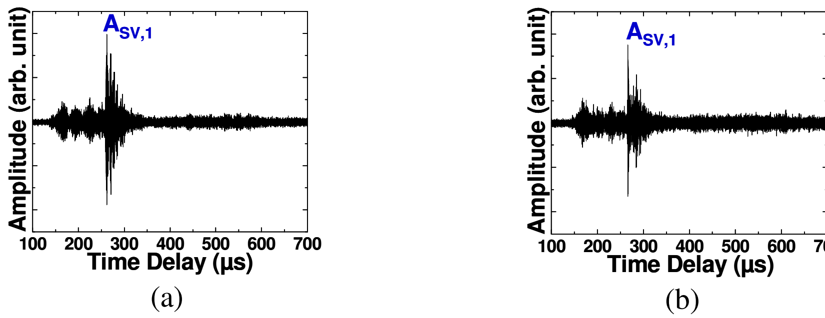


Figure 10. Measured reflected anti-symmetrical PAW mode echoes in a 2.0 mm thick Al plate at (a) room temperature and (b) 150°C from the edge opposite to the IUT shown in Figure 9 in time domain.

Figure 11 shows that one FUT which was also obtained from the multiple FUTs shown in Figure 2(b) was attached to the edge of the Al plate identical to the one shown in Figure 9. The anti-symmetrical A_{SV} PAW signals obtained in pulse-echo mode in time domain at room temperature in this Al plate is shown in Figure 12. The anti-symmetrical A_{SV} PAW waveform in Figure 12 is quite similar to that in Figure 10(a). The signal strength of $A_{SV,1}$ echo in Figure 12 was much weaker than that in Figure 10(a) due to the weak piezoelectricity of FUT and not optimized glue.

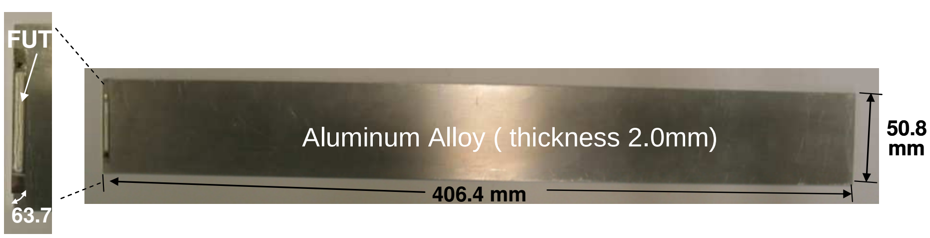


Figure 11. One FUT coated directly onto the top surface near the edge of an Al plate with an angle of 63.7° to generate and receive anti-symmetrical PAW.

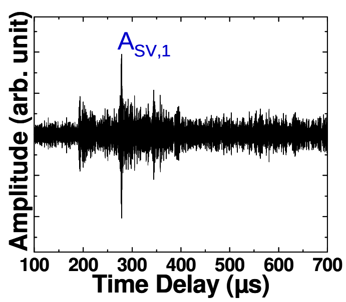


Figure 12. Measured reflected anti-symmetrical PAW mode echoes in a 2.0 mm thick Al plate at room temperature from the edge opposite to the FUT shown in Figure 11 in time domain.

3-3. Shear horizontal PAW

If the IUT is located at the edge indicated in Figure 13, shear horizontal types [4, 5, 11] of guided PAW can be excited and received using mode conversion. The thickness of this PZT/PZT composite film was 90μm. For this configuration symmetrical PAW echo traveled nearly 5.4mm and then converted to shear horizontal PAW modes and vice versa. For this configuration the chosen mode conversion angle using the analogy of L wave to S_H was 61.7° which was calculated using the phase matching between measured extension mode velocity $S_{L,1}$ and the shear wave velocity of the Al plate. The measured reflected shear horizontal guided SH PAW mode echoes at room temperature and 150°C in time domain from the edge opposite to the IUT are given, respectively, in Figures 14(a) and 14(b). After traveling nearly a distance of 813mm the frequency of the $S_{H,1}$ echo was 6.3MHz. The subscripts 1 and 2 denote the 1st and 2nd round-trip echo, respectively. $S_{H,2}$ echo traveled a distance of 1.625m. It is noted that the signal strength at 150°C was 5dB weaker than that at room temperature. The results showed that the signals for shear horizontal S_H PAW modes were less noise than those of anti-symmetrical and symmetrical PAW modes. The main reason could be that the IUT excites the zeroth order of shear horizontal mode efficiently and higher order modes not efficiently in this configuration shown in Figure 13 [5,11].

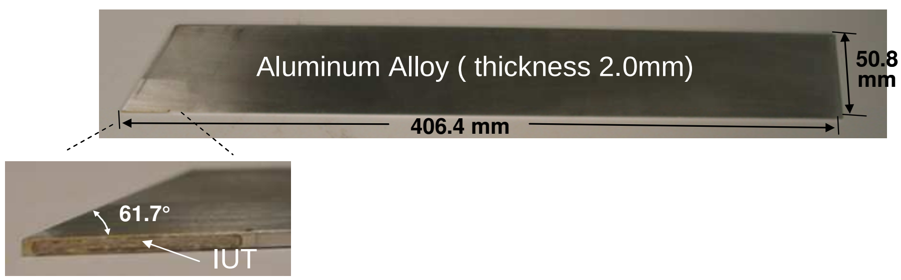


Figure 13. One IUT coated directly onto the top surface near the edge of an Al plate with an angle of 61.7° to generate and receive shear horizontal PAW.

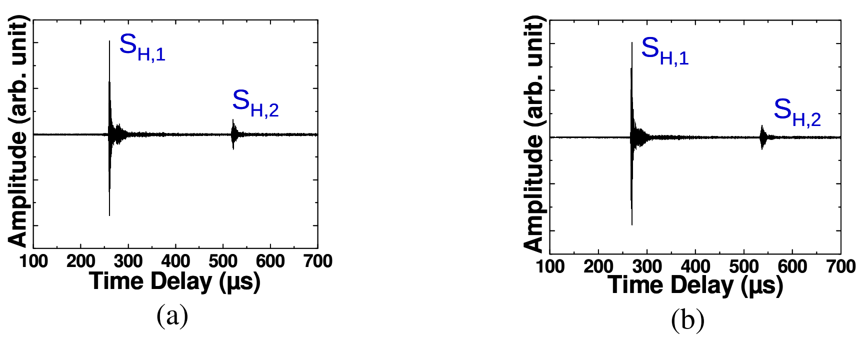


Figure 14. Measured reflected SH PAW mode echoes in a 2.0 mm thick Al plate at (a) room temperature and (b) 150°C from the edge opposite to the IUT shown in Figure 13 in time domain.

In order to demonstrate the long distance NDT capability of the SH PAW two artificial line defects, D1 and D2 with 0.95mm depth and 1mm depth were made onto the Al plate shown in Figure 15. D1 and D2 had width of 25.4 mm and 50.8mm, respectively as shown in Figure 16. At 150°C the measured PAW signals in the Al plate shown in Figure 15 are given in Figure 16. Figure 14(b) in which no line defects exist and Figure 16 in which two line defects present cleanly confirm that SH PAW can be used to perform NDT of defects in long distance at 150°C. In this example the defects were about 146.3mm and 223.5mm away from the IUT.

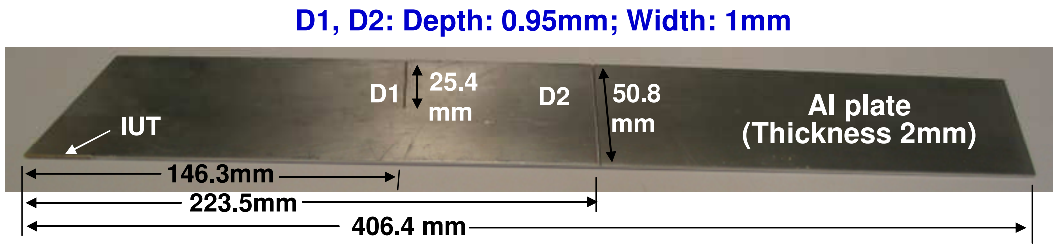


Figure 15. Two artificial line defects, D1 and D2 were made onto the Al plate shown in Figure 13.

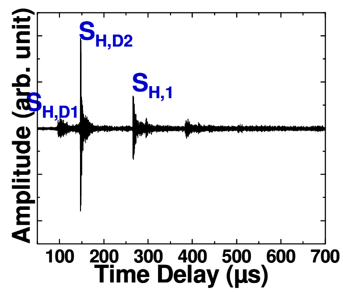


Figure 6. SH PAW signals detecting two artificial line defects, D1 and D2 in Figure 15.

Figure 17 shows that one FUT was attached to the edge of an Al plate with a length of 393.2 mm. The shear horizontal S_H PAW signals obtained in pulse-echo mode in time domain at room temperature in this Al plate is shown in Figure 18. The shear horizontal S_H PAW waveform in Figure 18 is quite similar to that in Figure 14(a). After traveling nearly a distance of 813mm the frequency of the $S_{H,1}$ echo obtained by FUT was 6.5MHz. The signal strength of $S_{H,1}$ echo in Figure 16 was 6dB less than that in Figure 14(a).

Figure 17. One FUT coated directly onto the top surface near the edge of an Al plate with an angle of 61.7° to generate and receive SH PAW.

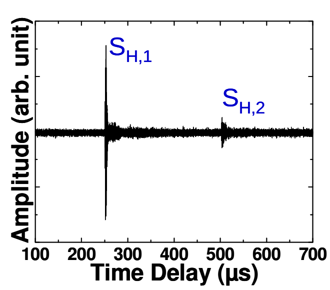


Figure 18. Measured reflected SH PAW mode echoes in a 2.0 mm thick Al plate at room temperature from the edge opposite to the FUT shown in Figure 17 in time domain.

4. CONCLUSIONS

Miniature and light-weight integrated (IUT) and flexible ultrasonic transducers (FUT) have been developed to generate and detect PAWs for in-situ and large distance (up to more than 1m) NDT applications. For IUTs thick films (>50µm) piezoelectric films were directly deposited onto the sensor locations using a sol-gel spray technique. For FUTs the piezoelectric films were coated onto 50µm thick polyimide films equipped with glues as flexible transducers. These flexible thick film piezoelectric transducers fabricated off-line were glued to the desired sensor locations. In this investigation both sensors were located at the edges of 2.0 mm thick Al and SS plates to excite and detect symmetrical, anti-symmetric and shear horizontal types of PAWs in pulse/echo mode. The propagation length reached more than one meter in frequencies of several MHz. In 2 mm thick plates line defects of 1 mm width and 1 mm depth were clearly detected at room temperature and 150°C. In 2 mm thick Al plates the waveform of shear-horizontal PAW is fairly short comparing to that of symmetrical or anti-symmetrical modes.

For IUT there is no need of couplant. However, in certain situations, accessibility to desired locations of aircraft components is limited for the fabrication of the IUTs, thus the alternative approach using FUT may be used. For the present study, the signal strengths of PAWs generated and received by the IUTs were stronger than those by the FUTs. Two main reasons are that (1) the optimization of the glue between the FUT and the edges of the plates has not been carried out which leads to high coupling loss and (2) the fabrication temperature of the IUT can be higher than 350°C which is the upper limit of the processing temperature of polyimide served as the substrates for FUT. The higher is the fabrication temperature of piezoelectric PZT/PZT composite film and the stronger is the piezoelectricity provided that the temperature does not exceed the PZT material transforming temperature.

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