1. Introduction

Due to the simplicity, speed, economy and capability to probe the interior of an opaque material, ultrasonic techniques are often used to perform nondestructive testing and characterization (NDT&C) of materials [1]. Many NDT&C are also mandatory to be performed at elevated temperatures, thus high temperature (HT) ultrasonic transducers (UTs) are in demand [2-3]. For applications of smart structures and materials there is also a critical need for integrated in-situ sensors for local and global damage detection and assessment. The purpose of this investigation is to demonstrate the fabrication of integrated HT longitudinal (L), shear (S) and surface (or plate) acoustic wave transducers directly onto desired structures or materials for NDT&C applications.

2. Shear and Longitudinal Wave Probes

The mode conversion from L to S waves due to reflection at a solid-air interface was reported [4,5]. It means that the L wave UT together with L-S mode conversion caused by the reflection at a solid-air interface can be effectively used as a S wave probe as shown in Fig.1. In Fig. 1, L_i waves generated by an L wave UT reach a solid-air interface and reflected as L_r and S_r waves. The equations governing the reflection and mode conversion with respect to the L wave incident angle \( \theta \) can be found in [6].

\[
\begin{align*}
R_{L-S} &= \frac{S_r}{S_i} \\
R_{L-L} &= \frac{L_r}{L_i}
\end{align*}
\]

Fig. 1 Reflection and mode conversion with an incidence of L wave at interface.

In this study, a mild steel with the L wave velocity of 5900 m/s and S wave velocity of 3200 m/s was used as the substrate. Figure 2, where \( R_{L-L} \) and \( R_{L-S} \) are energy reflection coefficients of the L and S waves, respectively, shows the calculated energy reflection coefficient for the mild steel substrate. It indicates that the maximum energy conversion rate from the L_i wave to the S_r wave is 97.5 % at \( \theta = 67.2^\circ \), and the reduction of the energy conversion rate is within 1% in the \( \theta \) range between 60.8° and 72.9°.

We have developed a paint-on technique to fabricate integrated L wave thick bismuth titanate (BIT)/lead zirconate titanate (PZT) composite film (> 40 µm) HTUTs [3]. The details of the fabrication techniques and film characteristics can be seen in [3]. Here a simple way is used to fabricate the S wave probe. First, let the L UT be fabricated in a plane parallel to the mode converted S wave direction on the substrate as shown in Fig. 3(a). By considering this criterion, the \( \theta + \phi \) needs to be 90°. From the Snell’s law, we can obtain \( \theta = 61.5^\circ \). At this angle, the conversion rate is 96.7% that is only 0.8% smaller than the maximum conversion rate at 67.2°, based on the result in Fig. 2. Figure 3(b) shows the ultrasonic signal in time domain of the received S_r wave in the pulse-echo mode at 350 °C. The S_n represents nth round trip of the S wave echoes traversing back and forth between the L UT and the probing end in Fig. 3(a). The center frequency of the S^1 echo was 6.7 MHz and the 6 dB bandwidth was 3.8 MHz. The SNR of S^1 echo was about 30 dB. The SNR is defined as the ratio of the amplitude of the S^1 echo over that of the undesired signals between the S^n echoes in Fig. 3(b). The signal strength of the S^1 echo at 350 °C was 5 dB smaller than that at room temperature.

If one would like to generate and receive both L and S waves at the same time, then the S wave probe shown in Fig. 3(a) can be modified to achieve such a purpose. In fact, it simply makes a
slanted surface with an angle 45° from the intersection of the slanted plane and the line from
the center of the L UT as shown in Fig. 4(a). The 45° angle plane will reflect the energy of the L,
wave into the L_{45°} wave normal to the probing end as shown in Fig. 4(a). Therefore, in principle, the
upper part of the L wave, generated from the L UT, can be used to produce the S, wave and the lower
part to produce the L_{45°} wave. Figure 4(b) shows ultrasonic signal in time domain in the pulse-echo
mode at 350 °C, in which the S_1 (S_1) and L_{45°} (L_1) waves are observed simultaneously. The L_1
represents the first round trip L wave echo traversing between the L UT and the probing end in
Fig. 4(a). The center frequencies of the S_1 and L_1 echoes were 6.6 MHz and 6.9 MHz and the 6 dB
bandwidths were 3.0 MHz and 3.8 MHz, respectively. During the top electrode fabrication of
the probe, the area of the top electrode was adjusted so that the amplitude of the reflected S_1 and L_{45°}
waves were nearly the same. The SNR of the L_1 and S_1 was about 20 dB.

Fig. 4 (a) Schematic diagram of an integrated L and S wave
probe with the L wave UT located in a plane parallel to the
direction of mode converted S wave where θ = 61.5°. (b) Ultrasonic signal at 350°C obtained with the L and S wave
probe in Fig.4(a)

3. Plate Acoustic Waves UTs

Plate or surface acoustic wave can be propagated in a distance of tens of cm on smooth metal substrates such as aluminum and steel and used for NDT&C of the substrate. In this study a 0.702 mm-thick stainless steel substrate is chosen. A 575µm-thick stainless steel mask with an interdigital transducer (IDT) electrode pattern (holes) was made using an electrical discharge machining method and the top aluminum electrode was deposited onto the BIT/PZT film by a vacuum evaporation method. Figure 5(a) shows the steel substrate together with thick BIT/PZT films and IDTs. The ultrasonic signals measured at 350°C in the pulse echo mode with a band pass filter between 0.8 MHz and 1.3 MHz is shown in Fig.5(b).

The measured plate acoustic wave velocity at room temperature was 2936 m/s which is smaller than the Rayleigh velocity 3030 m/s of the stainless steel substrate. Therefore the waves in Fig. 5(b) are
the 1st order anti-symmetrical mode of the plate wave. When the distance from the center of the IDT
to the edge A is represented with A (=47mm) and that to the edge B is B (=125mm), the plate wave
echoes shown in Fig. 5(b) are indicated with P_{2A}, P_{2B}, P_{2A+2B}, P_{4A+2B} and P_{2A+4B}. At 350°C the wave
velocity became 2754 m/s. In actual NDT applications, the edges A and B can be considered
as a large crack. Therefore the integrated plate wave sensor can be used for large distance NDT. It is also
observed that the wave attenuation in this frequency range for a distance of 30 cm is less than a few dB.

Fig. 5(a) Actual device of an integrated plate acoustic wave
operated in the pulse-echo mode. (b) Measured ultrasonic signals at 350°C

4. Conclusions

Integrated ultrasonic BIT/PZT around 90µm-thick piezoelectric films were fabricated onto steel substrates through a paint-on method. A S wave probe which uses the mode conversion from L to S waves and S&L wave probe simultaneously generating and receiving both L and S waves were demonstrated at 350°C. IDT has been also fabricated onto thick film UT on the stainless steel plate as a transducer for plate or surface wave generation and detection. The measurement results showed that plate acoustic waves of centre frequency of around 1MHz could be generated, propagated and received in a distance of more than 30 cm in pulse-echo mode at 350°C using our novel transducer. They can be used for long distance NDT&C and hence an excellent integrated sensor for diagnostics, prognostics health management of the aviation industry and other industries.

References