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High temperature integrated ultrasonic shear wave probes

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Integrated ultrasonic shear wave probes have been fabricated using steel substrates through a paint-on method with the use of mode conversion from longitudinal to shear waves. The probe can be operated up to 150 °C. A probe simultaneously generating and receiving both longitudinal and shear waves is also demonstrated. © 2006 American Institute of Physics. [DOI: 10.1063/1.2374684]

Due to the simplicity, speed, economy, and capability to probe the interior of an opaque material, the ultrasonic techniques are often used to perform nondestructive testing and characterization (NDT&C) of materials.¹ Many NDT&Cs are also mandatory to be performed at elevated temperatures, thus high temperature (HT) ultrasonic transducers (UTs) are in demand. In addition, ultrasonic techniques prefer and sometimes require UTs of large bandwidth and high efficiency. Various efforts have been devoted to the development of such piezoelectric HTUTs (Refs. 2–5) and they may be supplied by several companies. However, the reported efforts have so far devoted to longitudinal (*L*) wave UTs only. It is understood that shear (*S*) waves may be advantageous over *L* waves for NDT&C of materials because liquid and gas medium do not support *S* waves. For instance, the higher sensitivity to detect cracks or gaps filled with liquids could be expected using *S* waves than *L* waves in a pulse-echo technique since reflection coefficients of *S* waves at solid/liquid interfaces are unity, namely, total reflection, while those of *L* waves are less than unity.⁶ In addition, *S* waves have better spatial resolution than *L* waves to detect small defects such as cracks and inclusions in products and materials due to shorter wavelength of *S* waves as compared to that of *L* waves at the same frequency.⁶

For the evaluation of material properties, sometimes it is important to measure shear modulus and viscoelastic properties in which *S* wave properties are a requisite. Furthermore, a UT setup to generate and receive both *L* and *S* waves at the same sensor location would also be of interest because engineering constants such as Young's modulus require measurement of both *S* and *L* waves. In the past special crystal cut, for example, 10° rotated *Y*-cut lithium niobate and tilted *c*-axis zinc oxide thin films were reported to generate and receive both *L* and *S* waves simultaneously.⁷ In this study, methods are presented to achieve HT integrated ultrasonic *S* wave transducers and also provide a means to excite and receive both *L* and *S* waves at elevated temperatures.

The mode conversion from *L* to *S* wave due to reflection at a solid-air interface was reported.^{8,9} 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 a *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 θ can be given in Eqs. (1)–(3),¹⁰ where V_l and V_s are *L* and *S* wave velocities in the solid, respectively, and R_{ll} and R_{sl} are energy reflection coefficients of the *L* and *S* waves, respectively.

$$\frac{V_l}{\sin \theta} = \frac{V_s}{\sin \varphi}, \quad (1)$$

$$R_{ll} = \left[\frac{\cos^2 2\varphi - (V_s/V_l)^2 \sin 2\theta \sin 2\varphi}{\cos^2 2\varphi + (V_s/V_l)^2 \sin 2\varphi \sin 2\theta} \right]^2, \quad (2)$$

$$R_{sl} = \frac{4(V_s/V_l)^2 \cos^2 2\varphi \sin 2\theta \cos 2\varphi}{[\cos^2 2\varphi + (V_s/V_l)^2 \sin 2\varphi \sin 2\theta]^2}. \quad (3)$$

In this study, a mild steel with the *L* wave velocity $V_l = 5900$ m/s and *S* wave velocity $V_s = 3200$ m/s was used as the substrate. Figure 2 shows the calculated energy reflection coefficient based on Eqs. (2) and (3) 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 θ range between 60.8° and 72.9° .

We have developed integrated *L* wave thick film ($>40 \mu\text{m}$) HTUTs.⁴ Thick ceramic films as piezoelectric UTs were successfully deposited on metallic and nonmetallic substrates by a spray technique. In the film fabrication, a composite consisting of piezoelectric powders such as lead zirconate titanate (PZT) well mixed with solution such as PZT of high dielectric constant is directly sprayed onto the substrate. It is then dried and fired. Multiple coating is used to achieve preferable thickness which is related to the operating ultrasonic frequency. A corona poling technique is used to achieve the piezoelectricity of the film and the top electrode is accomplished by painting a silver paste. The attractive characteristics of these *L* UTs are that they (a) can be

FIG. 1. Reflection and mode conversion with an incidence of *L* wave at a solid-air interface.

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FIG. 2. Energy reflection coefficient vs incident angle θ .

integrated onto the desired planar or curved substrate at the desired NDT&C site with handheld equipments and under possible lowest temperature without a furnace, (b) do not need a couplant, (c) can operate in pulse-echo and transmission modes with a signal to noise ratio (SNR) better than 30 dB between 5 and 10 MHz, (d) can operate from -100 up to more than 400 °C, and (e) can be operated with an array configuration. Typically, the measured d_{33} of this PZT composite film is about 30×10^{-12} m/V, the K_t about 0.2, the relative dielectric constant 320, the density 4400 kg/m³, and the L wave velocity about 2200 m/s. Such integrated L wave HTUTs together with the above mentioned characteristics are used to achieve our HT integrated S wave probe presented here.

Our approach considers a simple way to fabricate the L wave UT and lets the L UT be in a plane parallel to the mode converted S wave direction as shown in Fig. 3(a). This approach could reduce the machining time of the substrate and thick UT film fabrication difficulty. By considering this criterion, the $\theta + \varphi$ needs to be 90° . From Eq. (1), 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. Therefore, Figs. 3(a) and 3(b) show the design schematic and actual device developed for this study, respectively. Figures 4(a) and 4(b) show the ultrasonic signal in time and frequency domains, respectively, of the received S_r wave in the pulse-echo mode at 150 °C. The S^n represents the n th round-trip of the S wave echoes traversing back and forth between the L UT and the probing end in Fig. 3. The center frequency of the S^1 echo was 5.7 MHz and the 6 dB bandwidth was 4.0 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. 4(a).

FIG. 3. (Color online) Schematic diagram and (b) actual device of an integrated S wave probe with the L wave UT located in a plane parallel to the direction of mode converted S wave where $\theta = 61.5^\circ$.

FIG. 4. Ultrasonic signal in (a) time and (b) frequency domains of the S wave probe shown in Fig. 3(b) at 150 °C.

The signal strength of the S^1 echo at 150 °C was 5 dB smaller than that at room temperature. It can be seen that the received L wave is not visible due to the fact that the dimension of the substrate has been chosen so that the reflected L wave from the probing end does not enter into the aperture of the L UT. The same design scheme has also been applied onto an aluminum substrate. Ultrasonic measurement results at 150 °C with good SNR have been obtained with the aluminum substrate as well.

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 can be modified to achieve such a purpose. In fact, it simply makes a slanted surface with an angle of 45° from the intersection of the slanted plane and the line from the center of the L UT as shown in Fig. 5(a). The 45° angle plane will reflect the energy of the L_i wave into the $L_{r,45^\circ}$ wave normal to the probing end as shown in Fig. 5(a). Therefore, in principle, the upper part of the L wave, generated from L UT, can be used to produce the S_r wave and the lower part to produce the $L_{r,45^\circ}$ wave. Figure 5(b) shows an actual device developed. Figure 6 shows ultrasonic signal in time domain in the pulse-echo mode at 150 °C, in which the S_r (S^1) and L_r (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. The center frequencies of the S^1 and L^1 echoes were 6.2 and 7.3 MHz and the 6 dB bandwidths were 4.0 and 5.9 MHz, respectively. As expected, there was no difference in frequency spectra of converted S waves in Figs. 4(a) and 6. During the top electrode fabrication for the device shown in Fig. 5(b), the area of the top electrode was adjusted so that the amplitudes of the reflected S_r and $L_{r,45^\circ}$ waves were nearly the same. The SNR of the L^1 and S^1 was about 20 dB. A similar approach was also applied onto an aluminum substrate and ultrasonic measurement results at 150 °C with good SNR were also obtained.

In conclusion, integrated ultrasonic S wave probes were fabricated onto steel substrates through a paint-on method

FIG. 5. (Color online) Schematic diagram and (b) actual device 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.

FIG. 6. Ultrasonic signal at 150 °C obtained with the L and S wave probe in Fig. 5(b).

with the use of mode conversion from L to S waves. The theoretical calculation indicates that the maximum energy conversion rate from the L to S wave is 97.5% at the L wave incident angle $\theta=67.2^\circ$ as shown in Fig. 2, and the reduction of the energy conversion rate is within 1% in the θ range between 60.8° and 72.9° . A novel approach was taken to fabricate the L wave UT and let the L UT be in a plane parallel to the propagation direction of the mode converted S waves as shown in Fig. 3. By considering this criterion, the θ is 61.5° and the reduction of energy conversion rate at this angle is only 0.8% smaller than the maximum conversion

rate at $\theta=67.2^\circ$. This approach could reduce the machining time of the substrate and thick UT film fabrication difficulty. A probe that can simultaneously generate and receive both L and S waves was also demonstrated. All the above mentioned probes have been made and operated up to 150 °C with a center frequency of 5–7 MHz, 6 dB bandwidth of 4–6 MHz, and SNR of more than 20 dB. Similar results have been obtained for ultrasonic probes with aluminum substrates. It is noted that the UT can operate up to more than 400 °C when bismuth titanate powders instead of PZT powders are used.^{4,5}

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