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Ultrasonic Probes Having Three Orthogonal Polarizations

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ABSTRACT

Ultrasonic probes which can simultaneously generate and receive two orthogonal polarized shear ($S_{\perp}$ and $S_{\parallel}$) and longitudinal (L) waves in screw shape have been presented. Thick piezoelectric films are directly fabricated onto the heads of such probes as L wave integrated ultrasonic transducers. $S_{\perp}$ and $S_{\parallel}$ waves are obtained using mode conversion method. Potential applications of such probes are discussed.

KEY WORDS: Ultrasonic birefringence, integrated ultrasonic longitudinal and shear wave transducer, nondestructive testing, material characterization

Thickness measurement including corrosion and erosion monitoring using ultrasonic technology is routinely used in industries at room or elevated temperatures. Certainly high accuracy is desired. However, factors affecting the measurement accuracy using ultrasound can come from texture [1], [2], stress [1], [3]-[5], etc which all alter the ultrasonic velocities in the material. In the other word, if the thickness of the material is given, ultrasonic velocity variations may be applied to measure the stress and texture [1]-[5]. In Reference [1] effects of statically applied stresses on the velocity of ultrasound in the material were studied at room temperature using the combination of three standard alone ultrasonic transducers (UTs); namely one longitudinal (L), one vertically polarized shear ($S_{\perp}$) and one horizontally polarized shear wave ($S_{\parallel}$). The combination of such three types of UTs at room temperature was also used

to measure the residual stress or texture in the textured steel [2], [3]. Furthermore acoustic birefringence involving just $S_{\perp}$ and $S_{//}$ measurements were also reported [6]. Some of experiments for the above mentioned studies were performed using electromagnetic acoustic transducers (EMAT), for example, in References [3] and [4]. However, EMAT cannot be used to measure the non-conducting substrates, and may be bulky and have low sensitivity.

Let a Cartesian coordinate system be xyz with the z direction being the through thickness direction or normal direction to a plate of the material, and x and y being the rolling and transverse directions of a plate such as steel, the stress-free velocities for the propagation along the z direction only depend on the texture coefficients W_{400} and W_{420} [2]-[5] and are given in an Voigt [7] approximation [3] by

$$\begin{aligned}\rho V_L^2 &= \rho h^2 / t_{d,L}^2 = C_{11} - 2C \left[\frac{1}{5} - \frac{16\sqrt{2}\pi^2 W_{400}}{35} \right] \\ \rho V_{S_{\perp}}^2 &= \rho h^2 / t_{d,S_{\perp}}^2 = C_{44} + C \left[\frac{1}{5} - \frac{16\sqrt{2}\pi^2}{35} \left[W_{400} - \sqrt{\frac{5}{2}} W_{420} \right] \right] \\ \rho V_{S_{//}}^2 &= \rho h^2 / t_{d,S_{//}}^2 = C_{44} + C \left[\frac{1}{5} - \frac{16\sqrt{2}\pi^2}{35} \left[W_{400} + \sqrt{\frac{5}{2}} W_{420} \right] \right]\end{aligned}\tag{1}$$

where V_L , $V_{S_{\perp}}$ and $V_{S_{//}}$ are the ultrasonic velocity and $t_{d,L}$, $t_{d,S_{\perp}}$ and $t_{d,S_{//}}$, the ultrasonic time delay of L , $S_{\perp}$ and $S_{//}$ waves in the substrate with a thickness of h , and $C = C_{11} - C_{12} - 2C_{44}$, respectively. Let the polarization of $S_{//}$ wave be along the x direction and that of $S_{\perp}$ be along the y direction during the experiments. Using Eq. (1), if one adopts an averaging method and knows the signal crystal elastic constants C_{ij} [2]-[5] and the density ρ of the material in Equation (1), two texture coefficients, W_{400} and W_{420} , can be calculated from the measured ultrasonic time delays, $t_{d,L}$, $t_{d,S_{\perp}}$ and $t_{d,S_{//}}$. Also an accurate measurement of the substrate (plate) thickness, h that is corrected for texture variations may be made [2].

Recently, integrated ultrasonic transducers (IUTs) have been made using the sol-gel based fabrication process [8], [9] consists of six main steps: (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 a layer of PZT composite (PZT-c) film, (4) heat treatment to produce a solid composite PZT-c 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 proper film (IUT) thickness for optimal ultrasonic operating frequencies. It is the objective to use such IUTs to achieve L UTs. The typical PZT-c film thickness in this study is 75 μm . Typically, the measured d_{33} of this PZT-c film is about 30×10^{-12} m/V, the K_t about 0.2, the capacitance and the dissipation factor at 1 kHz are about 0.75 nF and 0.03, respectively, the relative dielectric constant about 320, the density 4400 kg/m³ and the L wave velocity about 2200 m/s. A typical impedance Z chart around the center frequency 8 MHz of a PZT-c film is shown in Fig. 1 in which f_a and f_r are the measured anti-resonance and resonance frequency, respectively. Such IUTs has been operated with a center frequency ranging from 4 to 30 MHz. Their ultrasonic signal strength and bandwidth is comparable to those of the commercially available broadband UTs with backing, however, IUTs can be used at high temperatures [9].

Fig. 1. A typical impedance chart around the center frequency 8 MHz of a PZT-c film.

The mode conversion from L to S waves due to reflection at a solid-air interface, as shown in Fig. 2, was reported [10], [11]. It means that the L wave IUT together with L-S mode conversion caused by

the reflection at a solid-air interface can generate S waves effectively and be used as an S wave probe. Our approach considers a simple way to fabricate the L wave IUT and let the L IUT be in a plane parallel to axial direction of the probe as shown in Fig. 2. The only criterion is that in Fig. 2 $\cot \theta$ is equal to V_s / V_l so that the mode converted shear waves will propagate in the direction parallel to the axial direction of the probe. In this study, a mild steel with the L wave velocity $V_l = 5914$ m/s and S wave velocity $V_s = 3215$ m/s was used as the probe material. Therefore one can obtain $\theta = 61.5^\circ$. Using the energy reflection coefficient formula reported in Reference [11] the calculated energy conversion rate at $\theta = 61.5^\circ$ is 97.2% that is only 0.5% smaller than the maximum conversion rate at $\theta = 67.4^\circ$. In Fig. 2 a 45° angle is also made for the reflection of L wave along the axial direction of the probe as well. The arrangement shown in Fig. 2 enables both L and S waves propagate together along the axial direction of the probe.

Fig. 2. Reflection and mode conversion with an incidence of L wave at a solid-air interface.

Using the L to S wave mode conversion principle shown in Fig. 2 if one would like to generate two shear waves with orthogonal polarizations (birefringence) simultaneously, then $\theta = 61.5^\circ$ will be made at two orthogonal edges as shown in Fig. 3. Fig. 3(a) shows an integrated probe having two polarizations and the zoomed probe head is presented in Fig. 3(b). Let one S be the $S_\perp$ polarized in Y direction and the other $S_\parallel$ polarized in X direction as shown in Fig. 3(a). Figs. 4(a) and 4(b) show the

measured ultrasonic signal $S_{\perp}^n$ and $S_{//}^n$, respectively reflected from the end of the probe in time domain and pulse-echo mode at room temperature where the time delay of S^n is that of the n th trip S echo through the probe length plus that of the L wave travelling through the length from L IUT to the steel/air interface. The signal S_s indicated in Fig. 3(b) is a spurious signal which probably comes from the multiple reflections of L or S waves from an undetermined boundary. The measurement results shown in Figs. 4(a) and 4(b) can be made simultaneously using a two-channel ultrasonic system. During the top electrode fabrication for two IUTs shown in Fig. 3(b), the area of the top electrode and position can be adjusted so that the amplitude ratio of the reflected $S_{\perp}^2$ and $S_{//}^2$ can be adjusted. The center frequency and 6 dB bandwidth of the $S_{\perp}^2$ and $S_{//}^2$ signals are 12 MHz and 11 MHz, and 13.4 MHz and 12 MHz, respectively. Their SNRs are 36.1 dB and 36.6 dB, respectively. It is noted that such probe may be used as an ultrasonic interferometer which is sensitive to, for example, the anisotropy of the material to be measured, which induces a difference in particle displacement direction or velocity or both between two shear wave propagations along the material.

Fig. 3. (a) An integrated S wave probe having two polarizations ($S_\perp$ and $S_\parallel$) and (b) zoomed probe head having two IUTs.

Fig. 4. Ultrasonic signal in time domain of the (a) $S_{\perp}$ and (b) $S_{//}$ wave generated by the L IUTs shown in Fig. 3(b) reflected from the end of the probe at room temperature.

If a probe is desired to generate and receive L and $S_{\perp}$ and $S_{//}$ signals simultaneously, then one side of the probe shown in Figs. 3(a) and 3(b) can be modified according to the schematic shown in Fig. 2 to achieve such a purpose. In fact, only a slanted surface with an angle 45° is added at such side to reflect the L wave generated by the L IUT or the L wave coming from the reflection at the end of the probe as shown in Fig. 2. Fig. 5(a) shows the integrated probe having three polarizations and zoomed probe head is given in Fig. 6(b). Figs. 6(a) and 6(b) show the measured ultrasonic signal L^n and $S_{\perp}^n$ and $S_{//}^n$, respectively in time domain and pulse-echo mode at room temperature from the end of the probe. The time delay of L^n is that of the nth trip L echo through the probe length plus that of the L wave travelling through the length from L IUT to the 45° steel/air interface. The measurements results shown in Figs. 6(a) and 6(b) can be carried out simultaneously using a two-channel ultrasonic system. During the top electrode fabrication for the device shown in Fig. 5(b), the area of the top electrode and position can also be adjusted so that the amplitude ratio of the reflected L^2 , $S_{\perp}^2$ and $S_{//}^2$ can be varied. The center frequency and 6 dB bandwidth of the L^2 , $S_{\perp}^2$ and $S_{//}^2$ signals are 19.1 MHz and 17 MHz, 17 MHz and 16 MHz, and 18 MHz and 17 MHz, respectively. Their SNRs are 23.2 dB, 23.3 dB and 38.4 dB, respectively.

Fig. 5. (a) An integrated probe which can generate and receive L and $S_{\perp}$ and $S_{//}$ waves simultaneous and (b) zoomed probe head having two IUTs.

Fig. 6. Ultrasonic signal in time domain of the (a) L and $S_{\perp}$ and (b) $S_{//}$ wave generated by the L IUTs shown in Fig. 5(b) reflected from the end of the probe at room temperature.

In conclusion, integrated ultrasonic $S_{\perp}$ and $S_{\parallel}$ (birefringence) and L, $S_{\perp}$ and $S_{\parallel}$ probes have been presented. They were fabricated onto the heads of steel rods in screw shape through a sol-gel spray technique. The typical PZT-c film thickness in this study is 75 μm . Mode conversion from L to S waves and reflection from a 45° slope for L waves have been used. All the above mentioned probes were operated at room temperature with a center frequency of 12 – 19 MHz, 6 dB bandwidth of 11 – 17 MHz, and SNR of more than 23 dB. It is noted that these IUTs can operate up to more than 150 $^{\circ}\text{C}$ [11] and 400 $^{\circ}\text{C}$ if bismuth titanate instead of PZT powders are used [9]. Such probes may be used to measure thickness of a sample accurately with a correction of texture including texture coefficients such as W_{400} and W_{420} . The stress applied to the probe, for example, in screw form, may be also measured. Because they can sustain high temperatures, they may be also used on-line to measure Young's modulus, Shear modulus and anisotropy of the molded or casted parts during polymer injection molding and light weight metal die casting.

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