STUDY OF SURFACE ACOUSTIC WAVE DISPERSION USING LASER-ULTRASONICS

AND APPLICATION TO THICKNESS MEASUREMENT

Jean-Daniel Aussel and Jean-Pierre Monchalin
National Research Council Canada
Industrial Materials Research Institute
75 De Mortagne Blvd.
Boucherville, Québec, Canada J4B 6Y4

INTRODUCTION

Dispersion of surface acoustic waves (SAW) has been used to characterize subsurface anomalies [1], estimate physical property gradients [2], calculate the effective elastic constants of fiber composite materials [3] and evaluate thin film thickness [4] and microstructures [5]. In most cases, SAW were generated and detected using piezoelectric transducers either in direct contact with the sample [1], or coupled to it with a liquid couplant [3-5]. Coupling problems arise in the case of samples at elevated temperature or in motion. These problems are solved by laser-ultrasonics, which uses lasers to generate and detect ultrasound, without contact and at distance [6, 7]. This technique applied to SAW generation and detection has been used for the evaluation of material properties [8, 9], to near-surface flaw detection [8, 10] and to the measurement of the thickness of thin metal sheets [9, 11]. Most applications require conditions of generation, which do not affect the surface of the specimen, i.e. operation in the thermoelastic regime. In this case, rather weak ultrasonic displacement signals are generally produced, but considerable enhancement of the signal has been demonstrated by distributing the laser energy on a circle and detecting the displacement at the center of convergence of the generated SAW [8].

In this paper this converging SAW technique is used and dispersion effects are analyzed for the case when the specimen is not infinitely thick and is, in particular, made of several layers. A novel time-domain signal processing method is presented, based on narrow-band filtering of wide-band SAW pulses and crosscorrelation, which permits to measure both phase and group velocities as a function of frequency. Experimental velocities measured on a thick layered substrate are compared to theoretical calculations. The application of this method to on-line measurement of the zinc layer thickness deposited by a hot-dip galvanization line is discussed.

EXPERIMENTAL SETUP

The experimental setup is sketched in Fig. 1. A Nd:YAG laser of 10 ns pulse duration, 0.75 J maximum energy is used for SAW generation. A ring source is produced at the surface of the specimen by using a converging lens and an axicon [8]. The beam is sufficiently attenuated,
Fig. 1. Experimental apparatus for laser generation and detection of SAW pulses.

so that generation occurs in the thermoelastic regime. The ring diameter can be adjusted from 3 to 30 mm with a typical width of 0.2 mm by varying the axicon distance to the sample. The SAW converging toward the center of the ring is detected by an argon laser coupled to a heterodyne displacement interferometer described in reference 12. The probe beam is focused at the center of the ring through a dichroic mirror which transmits the generating laser beam but reflects light from the receiving laser.

SAW DISPERSION ON A THICK METALLIC LAYERED SUBSTRATE

We have used this experimental setup to measure the surface wave dispersion on thick metallic samples. The samples used are 25 mm thick copper (Cu) substrates coated with silver (Ag) layers of 20, 60 and 125 μm thickness, or chromium (Cr) layers of 7.5, 25 and 50 μm thickness. The Rayleigh velocity of the copper being 2235 m/s, 25 mm corresponds to about 10 ultrasonic wavelengths at 1 MHz, so the substrate can be considered infinite for frequencies above 1 MHz. The converging SAW signals generated by a 15 mm diameter annular source are shown in Fig. 2. Dispersion effects, which increase with layer thickness, can be readily seen. In the case of the Cr layers, high frequency components have a higher velocity, whereas the opposite occurs with the Ag layers. This can be explained by the penetration of the SAW, which propagates in the solid to a depth of the order of its wavelength. Low frequencies penetrate deeper and tend to propagate in the substrate, whereas high frequencies have less penetration and propagate mainly in the layer. Cr having a faster shear and Rayleigh velocity than Cu, high frequencies consequently propagate faster, whereas the reverse occurs for Ag.

The method generally used to measure velocity from broadband pulses, such as shown in Fig. 2, is based on the phase analysis of the Fourier transform of the ultrasonic signal [2, 13]. In our case, the Fourier transform of the converging SAW generated by an annulus of radius r can be expressed as:

\[ u(r, f) = U_0(f) e^{-a(f, r)} e^{-i[2\pi fr/c - \phi_0(f)]} \]  (1)

where \( f \) is the frequency, \( U_0(f) \) and \( \phi_0(f) \) are the initial amplitude and phase terms due to thermoelastic generation, \( a(f, r) \) is an attenuation propagation term, and \( 2\pi fr/c \) a phase propagation term. This term can be determined by using two different ring sources of radii \( r_1 \) and \( r_2 \).
From (1), the phase difference between the SAW generated by sources of radii \( r_1 \) and \( r_2 \) is:

\[
\delta \phi = 2 \pi (r_1 - r_2) / c = 2 \pi f t_p
\]  

Equation (2) shows that the phase velocity \( c \), or the phase delay \( t_p \), can be determined from the phase difference of the two converging SAW. This phase difference can be calculated either by Fourier transform of the two signals, or by Fourier transform of their crosscorrelation[14], using in addition a phase continuity algorithm to avoid \( 2\pi \) jumps [13].

Concerning the precision of this method, which operates in the frequency domain (FD), the standard deviation error on the propagation time, \( t_p \), is given by [14]:

\[
\sigma_{FD}(f) = [1 + 2 \text{SNR}(f)]^{1/2} / [2 \pi \sqrt{2} \text{SNR}(f)]
\]  

where \( \text{SNR}(f) \) is the frequency dependent signal-to-noise ratio. This error increases when the frequency or the signal-to-noise ratio decrease. An important limitation of this method originates from truncation of data. Truncation, or windowing, is needed to remove extra reflections or spurious signals, but it may strongly affect the phase spectra. The signal discontinuities at the edges introduce false frequency components, and the spectral leakage of the window integrates the noise over the entire frequency band [15]. One should also note, that the frequency resolution of this frequency domain method is fixed by the discrete Fourier transform to \( 1/T \), where \( T \) is the time duration of the truncated SAW signal. From the phase velocity and its variation with frequency, the group velocity \( c_g \) is then determined according to [13]:

\[
c_g = c^2 / (c - f \, dc/df)
\]  

This formula shows that the determination of the group velocity is very sensitive to errors on the phase velocity due to the derivative \( dc/df \), so the group velocity determined in this way will be generally much less accurate than the phase velocity.

To overcome these limitations, we have developed a method of analysis which operates in the time domain (TD) and which is, to our knowledge, novel. It consists in narrow-band filtering the ultrasonic signals around a center frequency \( f \) using frequency gaussian filters [16], and then calculating the envelope of the narrow-band pulses by taking the magnitude of the analytic signal [17]. The time delay between the two narrow-band signals, which in this case originates from two ring sources of different radii, represents the phase delay at the frequency \( f \), and the time delay between the two envelopes gives the group delay. They can be accurately measured by crosscorrelation [14]. This TD method is equivalent to the tone-burst method [18], except that in this case all the frequencies are obtained directly from the wide-band SAW and the narrow-band burst is obtained by digital processing instead of using a tuned pulsed oscillator. As in the case of the tone-burst method, an uncertainty of \( k/f \), where \( k \) is an unknown integer and \( f \) is the center frequency of the burst, can appear in the measurement of the phase velocity in the case of highly dispersive media. This uncertainty is eliminated by using a phase delay continuity algorithm to detect \( 1/f \) time jumps. This time continuity algorithm is, as shown by eq. 2, equivalent to the phase continuity algorithm used in the FD method.

The TD method has several advantages over the more classical FD method. Both phase and group velocities can be directly measured, the time truncation does not affect the crosscorrelation, mixed signals can sometimes be separated as we will show below, and finally the time uncertainty could be made smaller with proper choice of the bandwidth.
Fig. 2. Laser-generated and detected converging SAW signals (arbitrary units) on a thick copper substrate with silver or chromium coatings. The thermoelastic annular source is 15 mm in diameter.

Fig. 3. Time-domain measurement of the phase and group velocities on a thick Cu substrate with a 125 μm layer of Ag.

of the narrow-band filters. The error on the time measurement with the TD method is given by [14]:

\[ \sigma_{TD}(f) = \frac{3(1 + 2 \text{SNR})}{(2 \sqrt{2} \pi f \text{SNR})} \left[ (f + \Delta f/2)^3 - (f - \Delta f/2)^3 \right]^{1/3} \]  

(5)

where \( T \) is the time duration of each SAW pulse, SNR is the signal-to-noise ratio at the center frequency \( f \), and \( \Delta f \) is the bandwidth of the narrow-band filter. From eq. (3) and (5), the ratio of the two standard deviation errors \( \sigma_{TD}/\sigma_{FD} \) is given by:

\[ \frac{\sigma_{TD}}{\sigma_{FD}} = \frac{1 + \Delta f/12 f^2}{1 + \Delta f/12 f^2} \]  

(6)

which reduces in practice to \((T \Delta f)^{1/2}\), since \( \Delta f \) is generally less than \( f \). This shows that the TD method is superior to the more traditional FD method when \( \Delta f > 1/T \), i.e. when the bandwidth of the narrow-band filter is larger than the intrinsic frequency resolution of the discrete Fourier transform. It should be noted that this advantage does not appear very large if \( \Delta f \) is kept sufficiently small for adequate resolution. However, the expression of \( \sigma_{TD} \) does not take into account the additional spurious frequencies and additional noise introduced by truncation, which results in practice into a much larger gain in precision of the TD technique over the FD technique, as it is shown below.

The time and frequency domain methods have been applied to the thick Cu substrates coated with Cr and Ag using ring sources of 3 mm and 15 mm diameter. Typical experimental signals and the corresponding signals obtained after filtering, as well as their envelopes, are shown in Fig. 3. The experimental phase and group velocities deduced from these
signals by crosscorrelation (TD method) are shown in Fig. 4 with the results obtained by the FD method. It is clear that the TD method gives a better precision of determination of the phase velocity, particularly at low frequencies. In the case of the group velocity determination, the advantage of the TD method is even more obvious. With the FD method, meaningful group velocity results cannot be calculated in the case of the Cr layer, and large errors appear at high frequencies in the case of the Ag layer.

We have compared these experimental results to theoretical data obtained with the computer program described in reference 19, which is based on the harmonic solution of the equation of motion [20] with appropriate boundary conditions. The velocities vary from the Rayleigh velocity in the substrate at low frequency-thickness values, to the Rayleigh velocity of the layer at high frequency-thickness values. In the case of the Cr coating, dispersion curves cannot be calculated with this program above the shear velocity of the copper substrate. By comparing Fig. 4 and Fig. 5, we can observe a good qualitative agreement between the experimental and theoretical results.

SAW DISPERSION ON A SYMMETRICALLY LAYERED THIN SUBSTRATE

The study of this problem is of practical interest for application to the on-line determination of the zinc layer thickness in the hot-dip galvanization process. In this process, a steel sheet is covered on both sides by a zinc layer following high-speed dipping of the sheet in a bath of molten zinc. The thickness of the zinc coating is measured after the process, and on-line monitoring would provide useful information for process control. Laser-ultrasonics is a noncontact remote technique well suited to this case involving a hot and moving product. We have investigated this problem in the laboratory by using a set of steel specimens 0.6 mm thick, zinc coated on both sides by electro-deposition to thicknesses...
of 5, 10 and 20 μm. 0.6 mm is a typical sheet thickness, which generally ranges from 0.35 to 6 mm [21]. Electro-deposition produces specimens with uniform and fine grain layers, better suited to an initial evaluation of the technique than the less uniform and coarser grain coupons cut from hot-dip galvanized sheets. The experimental setup is the same as before, except that we used for laser detection a Fabry-Pérot interferometer described in reference 22. This interferometer demodulates the back-scattered light from the sample and is less sensitive to beam alignment and surface roughness. It is thus more suited for industrial applications.

The experimental results obtained with an uncoated specimen and a specimen symmetrically coated with 10 μm of zinc are shown in Fig. 6. Since the substrate cannot be considered thick (the ultrasonic wavelength of the SAW at 1 MHz is ~3 mm in steel), the generated SAW are dispersive with or without coating and an infinite number of symmetric modes and antisymmetric modes are generated [23]. For very small frequency-sheet thickness products, only the first symmetric $S_0$ and antisymmetric $A_0$ modes can propagate, and the determination of their velocities can be used to estimate either the sheet thickness or elastic constants [9, 11]. Other modes appear above cutoff values of the frequency-thickness products, which are multiples of $c_L/2$ and $c_T/2$, where $c_L$ and $c_T$ are respectively the longitudinal and shear velocities of the steel sheet. On sheets symmetrically coated, additional dispersion occurs due to the layered structure and the relative amplitudes of the different modes are modified.

We have applied the TD method for analyzing dispersion in this case. As shown in Fig. 6, this method permits to show distinctly the arrival of several modes. The group velocities measured from such a data versus frequency are shown for the 20 μm coated specimen in Fig. 7. We have also tried a comparison with theory. Theoretical velocities can be calculated from the solution of the equation of motion with proper boundary conditions [24]. Fig. 8 shows the theoretical velocities of a 0.6 mm steel sheet uncoated or symmetrically coated with two 20 μm zinc layers. Only the $A_0$ and $S_0$ modes have been plotted for sake of clarity. On the uncoated steel sheet, the velocities tend towards the steel Rayleigh velocity at high frequency, whereas on the zinc coated sheet they tend towards the zinc shear velocity [20]. As seen in Fig. 8, the experimental points measured by the TD method are in good agreement with theoretical predictions. Group velocity varies also with layer thickness for a given frequency. Fig. 9 shows for example the measured group velocity of the $S_0$ mode at 12 MHz for different zinc thicknesses. Such a plot can be used in principle to determine an unknown zinc thickness from the measurement of
Fig. 7. Experimental group velocities measured by the TD method on a 20 μm zinc coated steel sheets of 0.6 mm thickness. The lines are drawn for sake of clarity and do not correspond to theoretical data.

Fig. 8. SAW phase and group velocities of the first symmetric (S₀) and antisymmetric (A₀) modes of a 0.6 mm thick steel sheet. Theoretical curves: --- uncoated sheet, --- 20 μm zinc coated sheet. Experimental points: o uncoated sheet, • 20 μm zinc coated sheet.

Fig. 9. Variation of the group velocity of the S₀ mode at 12 MHz with the zinc layer thickness. The line is shown for sake of clarity.

the group velocity. However, before this technique could be applied to the control of the hot-dip galvanization process, further studies would be needed. The effect of unequal layers on the two sides of the sheet as well as the effect of coarse grain and texture need to be assessed.

CONCLUSION

We have measured the dispersion of SAW on thick and thin metallic substrates using laser-ultrasonics. This technique has the advantages of being broadband, remote and noncontact, and is nondestructive in the thermoelastic regime. In order to enhance the precision of the measurements, the signal-to-noise ratio has been increased by focusing the SAW with an annular generating source, and an accurate time domain signal processing
method has been developed. This method, based on narrow-band filtering and crosscorrelation, has the advantages over the traditional frequency domain phase analysis method of giving a better precision, of allowing to measure both phase and group velocities, of being less sensitive to truncations, and of permitting separation of various propagation modes. We have shown that laser-ultrasonics coupled to the method of signal analysis we have developed could be used in principle for the control of high-temperature coating processes, such as hot-dip galvanization.

ACKNOWLEDGEMENT

The authors wish to thank C.K. Jen for providing the computer program used for calculations of the theoretical data and for useful discussions, B. Champagne for providing the galvanized steel samples, N. Daneliak and J. Lait of Stelco Inc. for bringing to our attention the application to galvanization.

REFERENCES