NDE OF MULTILAYERD SYSTEM USING LASER-ULTRASONIC SAW

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Abstract

Laser-ultrasound spectroscopy, a non-contact ultrasonic technique was used to characterize a zinc coating on a steel substrate. This characterization is based on fitting the measured velocity dispersion of surface acoustic waves (SAW) to the dispersion calculated using the conjugates gradients algorithm (C.G). A short laser pulse was used to generate a wideband pulse of ultrasound and a laser interferometer was used for its detection. From a large number of echoes we identified the one corresponding to the SAW. Furthermore other useful informations were obtained from these data like attenuation and surface skimming longitudinal wave velocity. Measurements of the velocity dispersion of the Rayleigh wave were achieved up to 50 MHz. The evaluation of layer's parameters performed for similar cases, on a pseudo-experimental model, were obtained with accuracy better than 1% for (h, μ) and about 4% to 6% for λ. To account for the diffusion of iron in zinc, we modelled the system by three media: 2 layers of zinc on a steel substrate. The thicknesses and densities of the 2 layers are estimated from the percentage of iron in mass, and then the Lamé coefficients of the three media are evaluated by resolution of the inverse problem. The Rayleigh velocity dispersion curve resulting from these values presents a good agreement with the measured one.

Introduction

Surface acoustic waves (SAW) or Rayleigh waves have a broad field of applications in non-destructive evaluation (NDE) of layered media and in particular to coated materials and materials that have sustained surface modifications. In this work, we use laser-ultrasonics [1] not only for its industrial, remote sensing, and other qualities, but also because it is broadband. We have exploited this feature to measure SAW on galvanized steel sheets over a bandwidth of 5 to 50 MHz, which corresponds to SAW wavelength ranging between 600 and 50 μm, thus approaching the typical zinc coating thickness of 10 to 20 μm. In the first development of laser-ultrasonics the thickness of zinc coated steel was determined from measured SAW group velocity dispersion on a zinc coated steel using circular optical source and by detecting at the center of the circle with a heterodyne interferometer [2]. However, this paper was limited in laser-ultrasonics bandwidth (15 MHz). In order to evaluate coating thickness of about 10 μm, we used a different beam geometry which in addition to having a wider bandwidth allows to clearly separate and identify the various acoustic waves. The measured dispersion velocities of SAW can then be compared unequivocally to model calculations yielding accurate estimates of important coating parameters. In other but similar cases [3], these parameters were obtained with accuracy better than 1% for the coating thickness, h, and Lame coefficient, μ, and about 4% to 6% for the other Lame coefficient, λ.

Theory

We study the phase velocity dispersion of the Rayleigh-like mode on a steel sheet coated with a 12 μm zinc coating. Taking account of the diffusion of iron in zinc, we modelled the system by three media: 2 layers of zinc on steel substrate. The 3 media are assumed to be elastically isotropic and non-attenuating. The equations of dynamics and the generalized Hooke's law allow to write the expression of the harmonic waves of sagittal polarisation that propagate in each medium (the layers of thickness h_i and the substrate which is assumed to be semi-infinite).

Perfect boundary conditions between the three media provide a system of 10 linear and homogeneous equations for the three media system [4, 5]. Requiring the determinant to vanish for non-trivial solutions yields the surface wave velocity V_R in the system. The phase velocity dispersion curve $V_R(f)$ of the Rayleigh-like mode is obtained by varying the frequency f in a suitable range with the system.

This model requires the knowledge of densities (ρ_i) and Lame coefficients (λ_i, μ_i) of the three media (i = 1,2,3) and the thickness h_i of the two layers for the calculation of the Rayleigh wave velocity dispersion curve. As for any inverse problem, numerical convergence towards the parameter values of the studied system requires good estimates of their initial values. The approximate values of the Lame coefficients are determined from the measurement of the velocities of the Rayleigh wave and the surface skimming longitudinal wave (SSLW) on the substrate, and the density ρ is taken from the literature.

Experiment

The experimental set-up is based on high-frequency laser-ultrasonics [6], a non-contact ultrasonic technique. A pulsed laser is used to generate SAW on the sample and a Fabry-Perot interferometer is used for their detection. A laser light pulse of 3 ns duration (fwhm) is delivered by an excimer laser and, depending on the desired source geometry, it is focused to a point or line on the sample to generate a wideband pulse of ultrasound. Because many types of waves are generated on the sample (surface and guided waves) the detection point or line is positioned in such a way that the SAW reaches the detection location first (Figure 1). Furthermore, to minimize the total attenuation of the ultrasonic waves, the detection is positioned as close as possible to the source, as long as the air wave does not overlap with the surface waves.

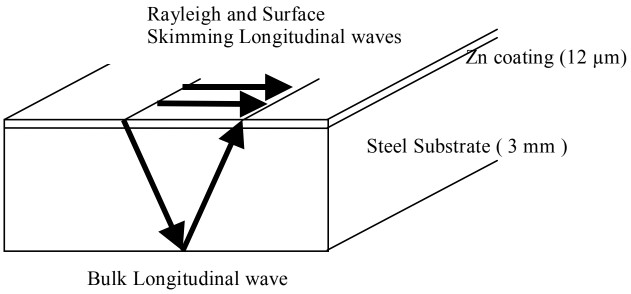

FIGURE 1. Surface acoustic waves measurement on coated substrate.

By assuming the substrate density from literature (ρ = 7870 kg/m^3) a first evaluation of the substrate's Lame coefficients (λ = 104.7 GPa and μ = 81.4 GPa) was achieved by measuring the Rayleigh wave velocity and the surface skimming longitudinal wave velocity, on a steel plate, without coating, using a line-source point-receiver configuration [7]. The main source of experimental error is the source-to-detection distance which was measured to within approximately 5µm.

For the measurements on a 3 mm thick steel substrate coated on both sides with a 12 µm thick zinc layer we used a line-source, line-receiver configuration (Figure 2). This allows to spatially average the signal and to reduce the amplitude of the diffuse signal. Measurements were taken for distances of 1.2 and 1 mm between generation and detection. For these separation distances, the obtained waveforms show the various waves distinctly, but below d = 1 mm, the three waveforms overlap, making it difficult to isolate the Rayleigh wave. On the other hand, at larger distances, the signal to noise ratio decreases, and the low-amplitude high-frequency components of the signal disappear. Therefore, to obtain the widest possible bandwidth, propagation distances of order 1 mm were considered optimal. In this case, the measurements were reliable to frequencies of up to 50 MHz.

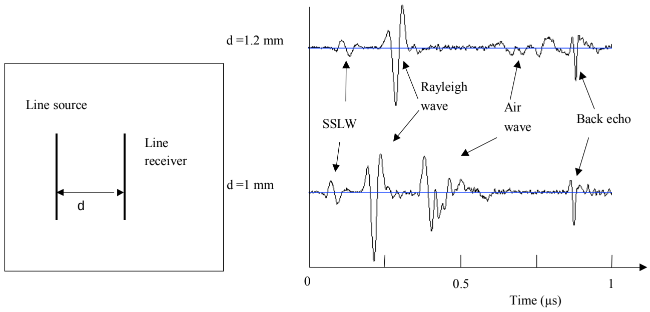

FIGURE 2. Measured waveforms on a zinc-coated steel sample with a line-source, line-receiver configuration.

Measured dispersion velocity

By cross-correlation of two Rayleigh waves at the two source-receiver distances 1.2 mm and 1 mm, we obtain the velocity dispersion shown in Figure 3. This dispersion is typical of a layer loading the substrate, where the phase velocity of the first Rayleigh-like mode decreases with increasing frequency. It starts with negative slope from a value close to the Rayleigh velocity of the steel substrate for zero frequency ($\cong$ 2979 m/s). However the data at frequencies lower than 10 MHz must be discarded because they are subject to windowing artefacts due to the short duration of the window used in the Fourier analysis and dispersion calculation. Thus these points will not be taken into account for the resolution of the inverse problem.

Beyond 10 MHz, as the frequency increases, the velocity decreases until we reach the highest measurement frequency. In theory, this monotonic decrease should continue until the layer thickness becomes large compared to the wavelength where it would tend towards the Rayleigh velocity of the zinc coating ($\cong$ 2168 m/s). At the highest frequency the wavelength (55 µm) is still large compared to the coating thickness (12 µm). The substrate contribution to the waves propagation velocity dominates the layer contribution because the dispersion corresponds to less than half of the calculated total dispersion [8].

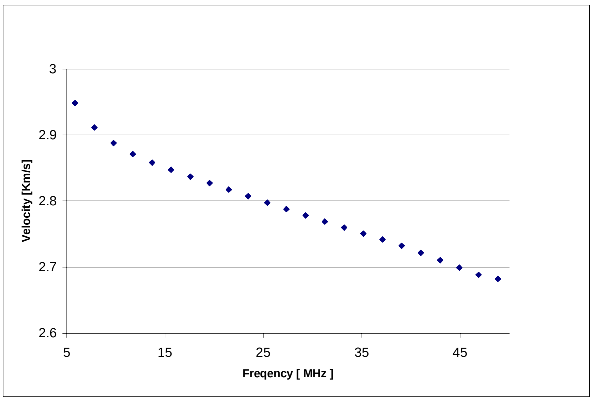

Figure 3. Measured Rayleigh velocity dispersion on Zn/Steel sample

Inverse problem

Let us consider the measured Rayleigh velocity dispersion, $V_R(f)$, of the galvanized steel sheet, which depends on the layers thicknesses h_i , densities ρ_i and Lame coefficients (λ_i, μ_i) of the three media.

Starting from a number Ne of experimental values of the Rayleigh phase velocity at various frequencies, we propose to determine the Lame coefficients (λ_i, μ_i) of the three media. As for the densities and thicknesses of the two layers of zinc they will be estimated from the measured iron content in each layer and from the steel density taken from literature.

To solve the inverse problem we first find the calculated velocities, V_c, by cancellation of the determinant and for estimated values of the adjustable parameters. We fit the measured velocities, Vm, to the calculated ones, Vc by minimizing the function:

$$D^2(\vec{p}) = \sum_{j=1}^{Ne} \frac{\left(Vm_j - Vc_j(\vec{p})\right)^2}{Ne},$$

i.e. the mean square difference between the measured and calculated velocities, using an iterative procedure. Here $\vec{p}$ is a vector regrouping the parameters h_i, ρ_i, λ_i and μ_i of the three media, Vm_j and Vc_j are the measured and calculated velocities at point j, and *Ne* is the number of experimental points.

The minimisation of $D^2(\vec{p})$ is achieved by using the Conjugate Gradients algorithm (CG) [9]. To have meaningful convergence of the CG algorithm, reasonable initial values of the 6 parameters (λ_i, μ_i) must be utilized. The initial values of the steel Lame coefficients are those previously determined from the Rayleigh and SSLW velocities measured on a steel plate without coating (λ = 104.7 GPa and μ = 81.4 GPa) and the density is taken from literature (ρ = 7870 kg/m^3). For the zinc coating, starting from the approximate thickness (12 µm) given by the manufacturer, the densities (ρ_1 = 7353 Kg/m^3 and ρ_2 = 7146 kg/m^3) and thicknesses (h_1 = 3 µm and h_2 = 9 µm) are estimated by taking account of a diffusion of iron respectively of about 33% and 6% through these two thicknesses, this diffusion was measured by chemical analysis as a function of depth. The global thickness is estimated from the "coating weight", i.e. from the intended weight by surface area of the deposited zinc layer as specified by the manufacturer, which corresponds to 12 µm.

The inverse problem is solved by adjusting the six parameters λ_i, μ_i and keeping the three densities and two layers thicknesses constant on the "Ne" experimental points represented by (*) in Figure 4. A summary of the initial and final values of the adjustable parameters and of the densities is given in Table 1. The optimised Vc (continuous line) is compared to Vm in Figure 6. The root mean square difference D between Vm and Vc is 3.5 m/s.

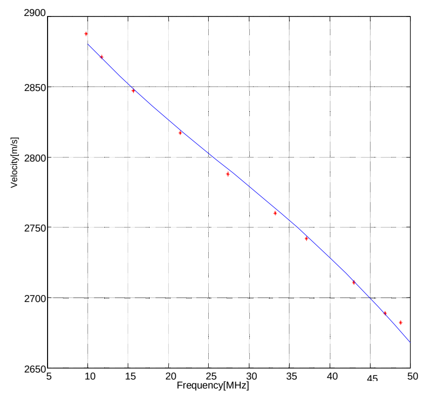

Figure 4. Measured (*) and fitted (solid line) velocity dispersion.

To estimate the precision with which the fitting procedure can obtain the 6 parameters, we vary one parameter at a time until D increases by about 25%. Using this criterion, we find that the precision is 5% for λ_i, 1% for μ_1 and h, and 0.5% for µ.

The fitted parameters are reasonnable when compared to literature values and when considering that texture (i.e. the non-isotropic crystallographic orientation distribution of the grains) may cause the elastic constants of the substrate and coating to vary substantially. Also, the fitting procedure did not cause the Lame coefficients of the substrate to differ substantially from those found for the uncoated substrate, using the SSLW and Rayleigh wave. Therefore the procedure appears to work reliably.

Table 1. Initial values, final values and root mean square difference D between measured and calculated dispersion velocities.

Medium	Parameter Value	λ[MPa]	μ[MPa]	ρ[Kg/m^3]	h[μm]	D[m/s]
Layer 2	Initial Value	36.1	43.6	7146	9	3.5
	Final Value	34.7	37.7			
Layer 1	Initial Value	36.1	43.6	7353	3	
	Final Value	35.8	41.0			
Substrate	Initial Value	104.7	81.4	7870	∞	
	Final Value	105.8	79.9			

Conclusion

We showed the possibility to characterize a 12 μm thick zinc layer deposited on a 3 mm thick steel plate using laser-ultrasonics. From only two measurements at two different distances between source and receiver, the Rayleigh waveforms are isolated from SSLW, air waves, and bulk waves, and their velocity dispersion is calculated by cross-correlation. The source-detection separation distance is chosen as short as possible to increase the signal bandwidth and better sense the properties of the thin layer, but long enough to allow the separation of the various waveforms.

The measured Rayleigh wave velocity dispersion between 10 and 50 MHz is fitted to a three-media model calculation whereby the three media are the substrate, zinc coating and interface region. We assume that the density and thickness of the three layers are known. The inverse problem is solved for the Lame coefficients (λ_i, μ_i) of the three media. With realistic initial values, the model parameters may be fitted without requiring independent measurements of the substrate properties.

The mean square difference between the measured and calculated dispersion (3.5 m/s) is found to be less than that which was obtained previously (4.6 m/s) when the coating was modelled with only one layer [7].

The model with 2 layers may be more realistic because it takes into account the gradual diffusion of iron from the substrate into the coating in accordance with the measurements obtained by chemical analysis. According to the mathematical procedure used to solve the inverse problem, the precision of these estimated parameters are: 5% for λ_i of the layers and substrate, 1% for μ_1 and μ_2 of the layers, and 0.5% for μ of the substrate. This is comparable to that which was obtained previously. However, it is interesting to note that the specific shear moduli of the two layers (i.e. the shear moduli divided by the density) differ by approximately 5%, which is significant. Moreover, the fitted intermediate layer constants are intermediate to those of the substrate and coating, as one would expect. Therefore, it appears that this three-layer model does have some validity, and one cannot simply argue that the improved mean square residual (as compared to reference 7) is due to the additional fitting constant. However, more measurements and additional validation are required before this can be said with certainty.

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