RAYLEIGH VELOCITIES FOR THE EVALUATION OF COATING HARDNESS

A. Abbate, J.F. Cox, S.C. Schroeder, B. Knight and J. Frankel

U.S. Army Tank-Automotive Armaments Command, Benet Laboratories, AMSTA-AR-CCB-TA, Watervliet, NY 12189-4050

ABSTRACT

The Rayleigh or surface wave velocity in a metallic coating electro-deposited on steel was measured and an experimental correlation was found between the velocity and the hardness of the coating. Since qualitative coating properties are commonly inferred from hardness tests, this result suggests the utilization of nondestructive surface ultrasonic velocity measurements to evaluate the coating hardness over regions which are inaccessible to conventional hardness tests, or where it is not possible to allow a hardness indentation. Here we propose a nondestructive ultrasonic technique to evaluate the hardness of electrodeposited chromium coatings, based on the empirical relationship we have relating hardness and Rayleigh velocity. In view of available experimental evidence of the relationship between surface hardness and Rayleigh velocity in other bulk metals this relationship should be investigated in other coatings as well.

INTRODUCTION

The performance of mechanical components which have to support either static or cyclic loads is sensitive to their surface condition, because that is where failure usually starts. This is especially true when the surface is exposed to high temperatures, high pressure or stress pulses, and corrosive gases or liquids. To extend the life of these parts, commonly protective coatings are applied to the surface. It is useful to accurately characterize these coatings, from the viewpoint of elastic properties, spatial and depth uniformity, and adhesion.

Qualitative measurements of the surface properties are commonly obtained using hardness and scratch tests, or more quantitative nondestructive tests such as X-rays or ultrasonics. Hardness tests are the most commonly performed in view of their ease of employment, and in fact an empirical relationship was previously developed, connecting the hardness ranges of the coating under consideration and its resistance to wear and erosion under extreme environments. Unfortunately these tests have other limitations. In some instances single spot measurements of the hardness are not appropriate: one cannot obtain a complete mapping of the surface hardness, indentations are left, and the scatter is usually large. In our case it's totally destructive: the hardness measurements are made not normal to the coating but from the side after the specimen is cut and polished.

To overcome the limitations of hardness testers and to improve our understanding of the materials characterized, a laser-based "hybrid" ultrasonic system was utilized to study low contractile (LC) chromium coatings electro-deposited on the inside surface of steel tubes. In the hybrid system, surface (Rayleigh) waves are thermoelastically generated by a laser pulse on the coated surface of the tube and are detected using a piezoelectric wedge transducer (figure 1). This system maintains the advantages of broad-band laser generation of surface waves while maintaining the low cost, simplicity and sensitivity of piezo-electric transduction in detection.

The Rayleigh wave propagating along an uncoated plane surface is non-dispersive; a pulse maintains its shape as it travels along the surface. We see for a coated surface that the original pulse is decomposed into two main components, i.e. into two wave packets. For chromium on steel, one packet of higher frequency range has probed the coating and arrives first while the other which has propagated mainly in the steel substrate arrives later, because the velocity in chromium is higher than in the steel (figures 2 and 3). We use wavelet signal processing techniques for these two packets, to obtain the velocity of Rayleigh waves in LC chromium and the steel substrate (figures 4 and 5).

We measured bulk as well as Rayleigh velocities of ultrasonic waves in chromium coatings on steel. The measured bulk and surface wave velocities are self-consistent. But we also found an experimental correlation between the surface velocity and the hardness for the LC chromium (figure 6). This suggests the possibility of utilizing a nondestructive ultrasonic test for quantitative determinations of the "quality" of a coating. The surface acoustic velocity can be measured to estimate the hardness and thus the "goodness" of chromium coatings, thus providing the advantage of using a nondestructive technique over one that is destructive and qualitative.

In the work here presented, it is shown that a wavelet based analysis of the laser generated dispersive surface waves can be used for the characterization of the chromium coatings electro-deposited on steel substrates. Description of the system as well as experimental results are given.

LASER ULTRASONIC HYBRID SYSTEM

Laser ultrasonics usually connotes the use of laser generation and laser detection of ultrasonic waves at a surface. The detection is accomplished using a laser interferometer. This presents new flexibility in measurements of surface properties. From surface-wave velocity measurements, information can be deduced about surface texture, residual stress, and the thickness and properties of coatings. In various cases, the coating-substrate arrangement presented a sufficient acoustic mismatch for the stimulation of guided waves in the coating. Laser ultrasonics can extend the range of application of conventional ultrasonic techniques, by overcoming the limitations offered by the

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necessity of using couplants and providing detection without the modulating effects of the piezoelectric transducers[1]. Unfortunately, laser-ultrasonics has been limited by its sensitivity and complexity on the optical-detection side.

We opted here for a hybrid system. An example of the experimental setup used for the generation and detection of the surface acoustic waves on the inside of a chromium plated tube is given in figure 1. It includes a computer controlled X-Y positioning system(not shown), a pulsed laser and commercial transducers. To generate the surface acoustic wave, a Q-switched polarized Nd:YAG laser was used. A 4 nsec pulse is generated with a typical energy of 5 mJ. A photodiode is used to detect the pulse and trigger the digital oscilloscope used to acquire the ultrasonic waveforms. A high precision X-Y positioner was utilized to allow for accurate and repeatable movement of the laser with respect to the test specimens. Detection was accomplished using a commercial transducer having a longitudinal PZT element. The transducer is grease-bonded to a plexiglass wedge, and the wedge to the specimen. During the experiments, the transducers remained at a fixed position, while the position of the laser head was varied using the positioner. This approach has the advantage of keeping the wedge-specimen coupling constant, at the same time allowing the part to be scanned. The source-receiver distance is changed by moving the laser head which is held on the positioner.

WAVELET PROCESSING.

In order to evaluate the quality of the coating, the dispersion of the surface wave group velocity must be calculated from the experimental curves. Various filtering techniques have been used to obtain the time of arrival of the acoustic energy as a function of the acoustic frequency. Time-frequency wavelet decomposition can be used for this purpose, where the square of the magnitude of the complex analytic wavelet transform defines, in the time and frequency domains, the envelope of the ultrasonic signal, and thus is optimal for calculating the velocity of the sound energy traveling along the surface. Briefly, the wavelet transform $W_o(a,b)$ represents the output of a particular filter bank, whose passband filters are all constructed using a single mother wavelet function $h(t)$. For a fixed value of the scale a, the output $W_o(a,b) = W_o^a(b)$, is a filtered version of the input signal $o(t)$. By choosing $h(t)$ as a passband filter of gaussian shape and central frequency f_o, then the filter associated with a, has a central frequency $f = f_o/a$. By measuring the ultrasonic signals in two different positions, r_1 and r_2, and comparing the two wavelet transforms, the group delay $\tau = (r_2 - r_1)/v$, is easily obtained as a function of a and thus of the frequency f. The surface velocity of the coating can be estimated from the dispersion curve obtained from the wavelet transform decomposition. For high frequencies ($f > 4$ MHZ) the acoustic wavelength is proportional to the coating thickness, thus the group delay at these frequencies yields the group surface velocity for the coating. The measurement for much smaller values of frequencies is used to calculate the substrate surface velocity which is extremely uniform from one sample to another, with variations less that 0.1 %, and can be used to verify the measurements[2].

APPLICATION TO CHROMIUM COATINGS

Nine hollow steel right circular cylinders, with nominally parallel inner and outer surfaces were plated with low contractile (LC) chromium on the inside in a flow-through electroplating facility, and several current densities and electrolyte flow rates were used to produce different properties in the coatings.

The specimen tubes were then heat treated to remove dissolved hydrogen and one ring of 1 7/8 in. thickness was cut from each cylinder (Fig 1). Coating hardnesses (Knoop, 50 gm.) were measured on polished samples cut from each tube in a plane normal to the tube axis, i.e. perpendicular to the direction of growth of the plate. Generally these readings were taken at three coating depths and then averaged. Bulk sound velocities were obtained with commercially available one quarter inch diameter 5 MHZ longitudinal and shear transducers. These were grease-coupled and pressed to the outer diameter of the rings so that the sound would travel across the ring wall and be reflected back to the transducer. The total time for passage of the sound wave across that wall thickness was measured by means of the pulse-echo technique using two echoes and obtaining the time difference between them for zero crossing at the same cycle. Then the thickness at the same position was also measured. Subsequently only the chromium deposit was removed by electropolishing from the steel substrate and the thickness and time of passage for both sound waves were again measured. Great care was taken to achieve high accuracy in the distance and time measurements. This is required because the thickness changes due to chromium removal were less than 0.01 in. and the corresponding time differences were less than 80 nsec. for the case of longitudinal waves. The thicknesses of the samples were measured with a resolution of 0.00003 in. and a repeatability of 0.0001 in., and the time to 1 nsec. Each of the nine rings was measured at four positions along its circumference. Seven evenly spaced points were chosen along the tube wall at each position and each point was measured three times.

The "hybrid" technique was used for surface wave generation. We used laser generation, and detection was accomplished by using a plastic wedge coupled to a longitudinal piezoelectric transducer of 5 MHZ but with enough bandwidth (2 to 10 MHZ) so some relevant dispersion effects could be detected. The bulk and surface wave velocities in the chromium coating were self consistent. The frequency dependent effects found for the surface waves traveling in the coating are discussed next.

SURFACE WAVES IN COATINGS

When Rayleigh waves travel over flat isotropic homogeneous lossless media they do not disperse. That is, their phase velocity is constant with frequency. However, if the acoustic properties of the media change with depth then the elastic surface wave velocity will become dispersive in a manner dependent on the depth profile. The velocity of the SAW propagating in a layered medium depends on the frequency of the wave or of its components, the thickness of the coating and the mechanical properties of both the coating and the substrate material. The laser pulse energy goes partly into the generation of a broadband surface acoustic pulse, which contains a range of frequencies, so that each acquired surface wave signal contains data for frequencies of interest. To extract these data, the acoustic response signals were processed by software in order to separate the various frequency components, and determine the correspondent velocities, i.e. the dispersion curve.

If a broadband acoustic signal is used, the plot of the velocity as a function of the frequency can be used to determine the thickness of the coating, by either using approximate solutions, or experimental calibration curves, or computer fits. The acoustic velocity at the lowest frequency is proportional to the acoustic velocity in the substrate, assuming that the wavelength at this frequency is at least 10 times larger than the coating thickness. Figure 5 gives the velocity frequency relationship obtained by wavelet techniques from the signal displayed in figure 4. It can be seen that the lower frequencies traveled at the lower velocities in the steel substrate and the higher frequencies at the higher velocities of the chromium coating. The thickness of the coating can also be estimated from the transition.

It is possible to correlate the measured acoustic velocity to the coating material surface hardness by means of a calibration curve such as the one plotted in figure 6 for low contractile chromium electroplated on steel. We can generalize this relationship by using a first order approximation:

$$v = f(H) \qquad \textbf{(1)}$$

where v and H represent the acoustic velocity and its hardness number, respectively. Equation 1 has to be inverted to extract the hardness number from the velocity measurement.

Using the experimental data in figures 2-5 and the computer analysis discussed in the previous section, it was possible to evaluate the Rayleigh velocity of the materials under study. These values are: for the steel substrate, 2955 m/sec; and for the chromium coating, 3340 m/sec. These values match the steel literature values.

RESULTS AND DISCUSSION

The effect of dispersion in the detected surface wave pulse for chromium on steel is seen graphically in figure 2. The top waveform shows the surface wave detected by the surface wave transducer after the pulse traveled on a pure steel surface. The bottom waveform shows the signal after the surface wave travels over the same distance, and with the same arrangement, but here the surface was chromium on steel. The higher frequency components of the ultrasonic surface wave having traveled in the chromium, which has a velocity higher than steel, arrive first, followed by the lower frequency components which traveled in the steel. Figure 4 shows how the two relevant velocities can be obtained by a wavelet technique [2] for the data in figure 3. Also the surface wave velocity obtained for the coating has a much smaller estimated error than the bulk velocities since it was obtained not by using a gauge length of 0.005 in. but keeping a wedge transducer in one spot and moving the source with known precision over larger distances.

The central relationship we find here, namely that the surface wave velocity increases as the hardness increases (figure 6) has not been explained so far. Hardness has been associated with texture (grain orientation) and grain size. These have been used to explain the sound velocity changes associated with the change in texture obtained in rolling of metals. Relationships have also been found for case hardening of steel between hardness and surface wave velocity, but here the velocity decreases with hardness as opposed to what we find, namely an increase of Rayleigh velocity with hardness. The shear velocity measurements were made with the shear polarization once in the hoop direction and once in the axial direction. Any angular dependence potentially reflects deviation from isotropy in the plane of the coating. No dependence of shear wave velocity in the chromium plate could be detected with shear wave polarization, but one should keep in mind the 2% estimated error of the measurement. The stress acoustic constant for the chromium is not available but even then it is very unlikely that much sensitivity for differences in residual stress for axial and hoop residual stress in the coating exists. Now we consider the large change in the surface wave velocity of about 16% with normalized current density. Potential contributors to velocity changes are impurities, dislocation density and texture. Neither impurities nor dislocation density changes can be expected to produce such large velocity changes. Previously the only changes in sound velocities of a magnitude equal to or greater than we saw here were found in cold rolled metals and were associated with texture changes.

CONCLUSION

The preceding demonstrates the effectiveness of the "hybrid" technique in measuring dispersion effects in chromium coated steel. The results also correlate the hardness of the coating with the sound velocity of a surface wave.

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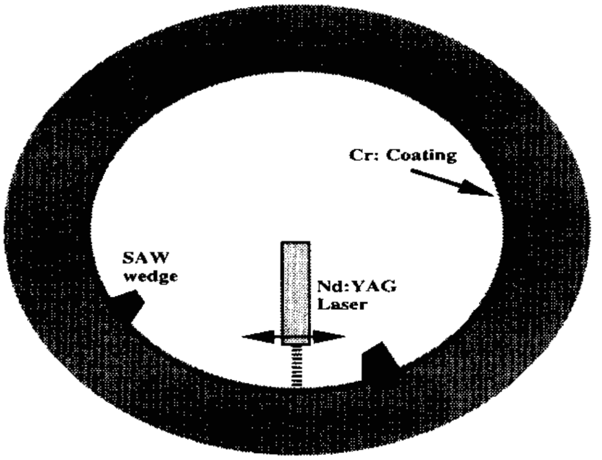

Figure 1. Experimental setup used in the laser ultrasonic measurements.

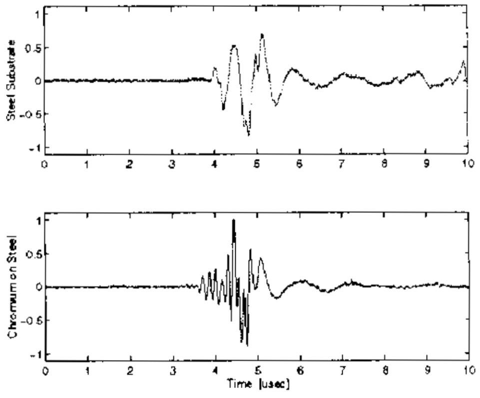

Figure 2. Typical signals detected on steel substrate (Top curve) and chromium coated sample (Bottom curve).

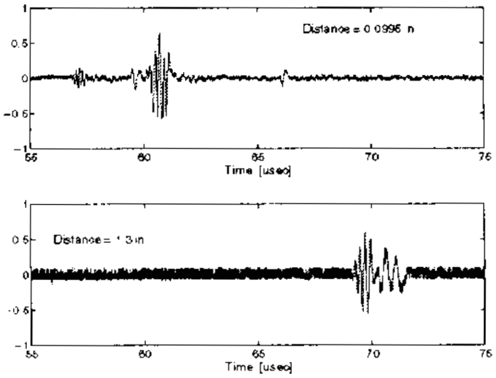

Figure 3. Experimental signals obtained at two different source-receiver separation distances, measured in a section of a coated steel tube.

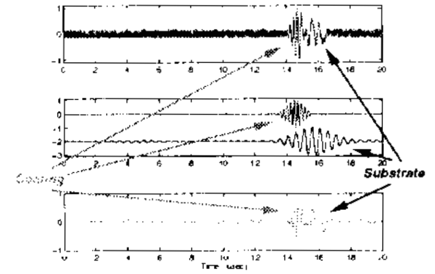

Figure 4. (Top) Surface wave signal on a steel substrate coated with chromium. (Middle) Two largest wavelet components of the top signal related to the coating and the substrate, and (Bottom) their sum.

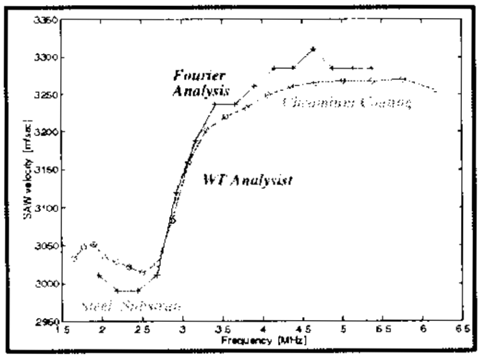

Figure 5. Dispersion curve of top signal of Figure 4.

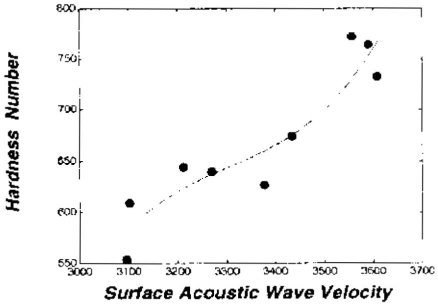

Figure 6. Plot of microhardness and surface wave velocity for chromium coatings on steel.