ULTRASONIC CHARACTERIZATION OF MICROSTRUCTURALLY MODIFIED SURFACES OF STEELS SUBJECTED TO ELECTRON-BEAM IRRADIATION

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ABSTRACT

A nondestructive method is presented for the determination of depth and elastic properties of modified surface layers. The parameters can be conveniently observed as variations in velocity with changes in frequency of Rayleigh surface waves. As a test of this technique, studies were conducted on an AISI 1053 plain carbon steel that has been subjected to electron-beam irradiation. The electron-beam treatment allowed for the creation of thin, microstructurally modified surface layers. On samples with an approximate 1 mm thick rapidly solidified, martensitic surface layer on a pearlitic substrate, the Rayleigh velocity varied from 2984 m/s at low frequency (deep penetration into the substrate to 2960 m/s at high frequency (penetration confined only to the surface layer). The nondestructive determination of the layer thickness was found to be better than 10%.

INTRODUCTION

New rapid solidification techniques have recently been developed in order to improve the wear resistance, corrosion resistance, fatigue, and hardness properties of metals and alloys. The directed energy source technique of electron-beam glazing is one such method involved in the creation of thin, modified layers on alloy surfaces. Electron beam treatments on metal surfaces can achieve formation of metastable, amorphous and crystalline microstructures, extension of solid solubilities, and grain size/precipitate alteration.

Tucker and Ayers observed that electron-beam glazing possesses great potential in coating deposition applications. Cold rolled steel coupons were lightly covered with a nickel-based brazing alloy powder (particle diameter 50 μm) and sintered to the substrate. The sintered layer was then fused to the substrate by rastering the sintered surface with an electron-beam welder. The rapid cooling rates obtainable through self-substrate quenching (10⁷ K/s) can produce amorphous phases of the nickel-based brazing alloy.

The need for enhanced surface properties in applications in which high wear and corrosive environments are encountered has led to the development of a number of surface modification technologies, e.g., rapid solidification, plasma spraying, ion implantation, electro-deposition.

In the work reported here, surface acoustic waves (Rayleigh) were utilized to characterize modified layers produced by electron-beam surface glazing. Plain carbon steel samples were subjected to the electron-beam glazing process. A nondestructive evaluation technique (NDE) was developed and employed to investigate the modified surface layers by means of Rayleigh surface waves by characterizing the properties of modified surface layers, as well as by evaluating the layer thickness.
EXPERIMENTAL

Specimen Preparation and Characterization

Several 7.6 cm x 2.5 cm A 0.6 cm slabs of AISI 1053 (0.53% carbon) steel were austenitized at 1025 °C for 45 minutes. One of the samples was subsequently quenched in an ice-brine to produce a bulk martensite. The remaining samples were furnace cooled to 650 °C, allowed to isothermally transform for 15 minutes and air-cooled to room temperature. This resulted in a pearlitic microstructure. The specimens were eventually subjected to electron-beam surface heat-treatments. The electron-beam glazing technique employs a high intensity/energy collimated beam of electrons. The directed energy beam strikes the surface of a metal or alloy, causing the subsequent heat-treatment (or melting) of a thin surface layer. High cooling rates on the order of 10^6 K/s are obtained by self-substrate quenching. The parameters that dictate the effectiveness of this process are the following: beam energy, beam intensity, beam shape, and scan rate.

After completion of the preliminary characterization by means of optical metallography and mechanical testing, each of the samples was subjected to an identical surface modification process. A 25 KV accelerating voltage was employed to accelerate a 2.5mm diameter beam of electrons (emitted from a tantalum filament) to the specimen surface. The beam current was 9 milli-amps. The beam power was, therefore, 225 watts. The scan rate of the electron-beam across the length of each specimen was 0.3 cm/s. After each scan of the electron-beam, the beam was translated 0.0254 cm across the width of the specimen, so as to microstructurally modify the entire surface. After the initial heat treatments of the specimens to obtain bulk pearlitic and martensitic specimens, several preliminary measurements were performed. Rockwell macrohardness tests were conducted and the densities of the specimens were measured. In addition, standard metallography and microstructural analyses were carried out. Longitudinal and shear ultrasonic bulk wave velocity measurements were obtained on these samples, utilizing the pulse-echo overlap technique. Elastic moduli were calculated from the ultrasonic data.

Ultrasonic Rayleigh Waves Characterization

For NDE surface layer characterization, the technique utilized was the ultrasonic generation of Rayleigh surface waves. These waves can be induced in a material by means of piezoelectric generation and detection with standard ultrasonic transducers. The surface wave energy diminishes rapidly with increasing depth into the bulk of a material. Therefore, this waveform represents a two-dimensional wave that attenuates as 1/r (r is the distance from a point source). In addition, Rayleigh wave propagation in a uniform material is nondispersive in that Rayleigh velocity is independent of frequency.

The velocity \( V_R \) of Rayleigh surface waves can be expressed in terms of a constant \( \gamma \), and the shear wave velocity and Poisson's ratio \( \nu \):

\[
\gamma = \frac{V_R}{V_t} = \frac{0.87 + 1.12\nu}{1 + \nu}
\]

Rayleigh wave fronts are elliptical in nature and travel along the direction of propagation in a planar fashion and orthogonal to the surface. This wave motion is illustrative of the fact that the Rayleigh wave is a combination of vertically polarized shear (SV) waves and longitudinal waves.
The major axes of these ellipses depict the vertical particle displacements (SV motion) of the Rayleigh waves, whereas the minor axes represent the horizontal (or longitudinal) displacements. For surface layer analysis, the orthogonal component of the Rayleigh wave motion is of principal interest and the effective depth of penetration of the Rayleigh surface wave may be assumed to be approximately one wavelength (λ_R). Therefore, the penetration depth of the Rayleigh waves may be varied by changing the frequency of the waves of constant velocity (in a homogeneous medium) according to the relation: \( V = f\lambda_R \) where \( V_R \) is Rayleigh surface wave velocity (phase), \( f \) is the Rayleigh wave frequency and \( \lambda_R \) is the Rayleigh wavelength, which can be assumed to be equal to the penetration depth.

In the present investigation, the generation of Rayleigh waves is obtained by means of a specially designed and constructed mode-conversion device. An illustration of this device appears in Figure 1. The wedge device consists of two machined, 2024 aluminum wedges that are placed in an aluminum sliding mount. Each wedge has an active surface area in contact with the specimen of approximately 2.54cm long by 700μm wide (w). A piezoelectric transducer is mounted inside each wedge; the wedges are machined down to knife-edge surfaces such that the contact angle made between the knife-edge and the sample is approximately 60°. The generation and detection of the Rayleigh waves are accomplished by conversion of the generated longitudinal wave and by subsequent reconversion of the detected wave.

Rayleigh wave frequencies from 2.2 to 15.5 MHz were used to characterize electron-beam treated samples. The minimum value of frequency was determined by the need to have at least a half-wavelength equal to (or less than) the width of the wedge (i.e., \( F_{\text{min}}^{V_R} \)).

\[
\frac{V_R}{2w} = \frac{3002 \text{ m/s}}{1400 \text{ μm}} = 2.1 \text{ MHz}.
\]

At the lower frequency limit, waveguide effects predominate, thereby prohibiting low frequency mode conversion coupling of longitudinal waves into Rayleigh waves into the sample. The observed frequency minimum of 2.2 MHz correlates well with the theoretically predicted frequency minimum of 2.1 MHz. At high frequencies, difficulties arise from enhanced attenuation, which increases with frequency.

Various sources of attenuation may account for the apparent frequency ceiling. Wedges constructed of single crystals of germanium or aluminum, were reported to raise the observed frequency ceiling from 15.5 MHz up to 270 MHz. Fisher, et al. state that polycrystalline wedges, as are the aluminum wedges in this investigation, are essentially limited to frequencies lower than 20 MHz because of massive grain boundary scattering.

RESULTS AND DISCUSSION

The results of the preliminary sample characterization on bulk pearlitic and martensitic specimens are shown in Table 1, where Rockwell macrohardness, ultrasonic velocity data, and elastic constants are presented. Noteworthy in Table 1 is the fact that both the longitudinal and shear wave velocities in pearlite were higher than in martensite.

A pearlite sample of AISI 1053 steel was examined after electron-beam surface heat treatments. The metallographically determined depth of modified surface layer and transition zone, as well as microhardness data of the martensitic layer and pearlitic substrate appear in Table 2. Photomicrographs
of the transition zone, between the pearlitic substrate and surface layer, and
the surface martensite appear in Figures 3 and 4. Figure 3 presents a plot of
Rayleigh wave velocity of the 1053 steel sample, as a function of penetration
depth in both the martensitic layer and pearlitic substrate. For the 1053
alloy, the Rayleigh velocity of the pearlitic substrate was found to be 3002
m/s. This represents a 1.4% difference in velocity between layer and substrate,
with the pearlitic substrate Rayleigh velocity being the greater. Figure 4
illustrates several important points. The surface wave characterization was
performed on both the electron beam modified and nontreated surfaces of samples.
Thus, Rayleigh characterization on the nontreated surface represents the
sampling of the bulk (substrate) microstructures of pearlite, a uniform medium
as seen by the Rayleigh waves. For such a medium, the Rayleigh velocity would
remain constant with changing frequency. This fact is illustrated in Figure 4
by a horizontal line. Rayleigh wave characterization, at high frequencies, on
the electron-beam modified surface represented sampling of both the martensitic
layer. At reduced frequencies, both the modified layer and the pearlitic
substrate were scanned by the Rayleigh waves. As with the nontreated surface,
sampling of only the layer material rendered a horizontal line indicating a
constant velocity in a uniform, nondispersive medium. However, Rayleigh waves
with penetration depths greater than the layer depth yielded velocities that
were the resultant of velocity contributions from several different
microstructures being insonnated simultaneously. This change in velocity
appears in Figure 4 in the form of an increase in Rayleigh velocity with
increasing depth of penetration through the modified layer structure into the
pearlitic substrate. At a frequency of 4.2 MHz (equivalent layer was 2960 m/s;
however, at 2.2 MHz (penetration depth of 1357 μm), the apparent Rayleigh
velocity was 2984 m/s.

Metallographic examination of modified layer depth appear in Table 2 for
the 1053 steel. The average layer depth was found to be 1034 μm with a 167 μm
transition zone. From Figure 4 the depth of the layer could be estimated to be
1080 μm.

A simple mathematical model can be formulated, using a "law of mixtures"
argument to predict the apparent Rayleigh velocity. The relationship can be
expressed as \( V_R = xV_m + (1-x) V_p \), where \( V_R \) is the apparent Rayleigh velocity
as measured, \( V_m \) is the Rayleigh velocity in the surface layer, \( V \) is the
Rayleigh velocity in the substrate. Also, \( 0 < x > 1 \), the ratio of penetration of
the Rayleigh wave through modified layer and substrate. This simple model
predicts the apparent Rayleigh velocity, observed in a region of mixed sets of
elastic moduli, with a high degree of accuracy. The Rayleigh wave technique
proved, therefore, to be an accurate and reproducible tool for the
characterization of modified surface layers and determination of layer depths.
Use of the law of mixtures equation rendered a predicted apparent Rayleigh
Velocity \( V_R \) of 2980 m/s, where the data were obtained from the mixed
microstructure regions of the curve in Figure 4. This value of \( V \) agrees
very well with the measured \( V \) of 2984 m/s to within 0.1%.

This technique demonstrates great potential for nondestructive evaluation
of thin modified surface layers on top of metallic substrates, both for
materials characterization and gauging of layer thickness.

**SUMMARY**
Samples of pearlitic plain carbon steel were treated by an electron beam glazing process in order to obtain a case-hardened, microstructurally modified surface layer of martensite.

Microhardness and ultrasonic sound velocity data indicated that the modified surface layers possessed a higher hardness and lower velocity than the substrate materials.

Rayleigh wave velocity during simultaneous sampling of layer and substrate material was effectively utilized to make a nondestructive estimate of the depth of the microstructurally modified surface layers, and to characterize the elastic properties.

The observed (apparent) Rayleigh wave velocity follows the law of mixtures, of layer and substrate velocities.

REFERENCES


Figure 1. Schematic diagram of the mode conversion technique for generation and detection of Rayleigh surface waves on surface modified samples.

Figure 2. Rayleigh surface wave velocity, as a function of penetration depth.
Table 1: Ultrasonic Velocity and Elastic Moduli of Bulk

<table>
<thead>
<tr>
<th>Density (kg/m³)</th>
<th>Shear Mod.</th>
<th>Young's Mod.</th>
<th>Poisson's Ratio</th>
<th>Shear Vel.</th>
<th>Young's Vel.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.336</td>
<td>0.531</td>
<td>21,396</td>
<td>0.295</td>
<td>5167</td>
<td>31,676</td>
</tr>
</tbody>
</table>

Table 2: Hardness, Metallographic Case Depth

| Layer | 29.5 R² | 29.0.5 R² | Peartite R² | 29 KHN-P | R² | Peartite I4+R | p, (1053) | T, 033.8 | Sample Thickness
|-------|---------|-----------|-------------|---------|----|---------------|-----------|-----------|-----------------
|       |         |           |             |         |    |               |           |           |                |

Note: T= transition zone

Macrohardness conducted @ Load = 100 Kg, 150 Kg
Microhardness conducted @ Load = 500 Grams and 20X magnification.
Figure 3. Transition zone of 1053 sample, illustrating transformation from pearlitic substrate to microstructurally modified surface layer (500x).

Figure 4. Martensitic needles in surface layer of 1053 sample (1250x).