INTRODUCTION

Electromagnetic acoustic transducers (EMATs) are ideal for on-line inspection of hot metal sheets, because they provide a noncontacting means for generating and detecting ultrasound in metals. EMATs are especially attractive for probing steels and magnetic alloys, because their transduction efficiency is larger than in nonferromagnetic materials. The source of the enhanced efficiency is magnetostriction, the change of length of a ferromagnetic material that accompanies magnetization.

This work demonstrates two novel applications of EMAT-generated ultrasound: (1) determining key features of the magnetostriction of a steel sample and (2) monitoring precipitation in a commercial high-strength low-alloy (HSLA) steel. This new technique of measuring magnetostriction offers the convenience of being noncontacting, in contrast to the standard strain-gage method. The second application follows from the sensitivity of magnetostriction to the form and concentration of precipitates. Magnetostriction has the advantage over some other magnetic measurements in being sensitive to a broader range of potential effects of precipitates; it reflects effects of precipitates not only upon domain wall motion, but also upon rotation of domain magnetization.

The transduction mechanism of EMATs in ferromagnetic materials is more complicated than in nonferromagnetic metals. In nonferromagnetic metals, EMATs generate and detect ultrasound through Lorentz forces, which are proportional to an applied static magnetic field. However, in ferromagnetic materials, the transduction efficiency is a nonlinear function of the applied static field, because there is a second mechanism for generating waves - magnetostriction. A significant aspect of magnetostrictive transduction is that, at low static fields, it is much more efficient than transduction by Lorentz forces. In fact, for the range of fields used in this work,
transduction by Lorentz forces is negligible, and measurements of the EMAT wave amplitude may be taken to reflect the magnetostrictive contribution only.

R.B. Thompson [1-3] has shown that shear horizontal (SH) waves can be generated magnetostrictively with the setup shown in Figure 1. A static magnetic field $H$ establishes an axis of tension (or compression) due to magnetostriction. The ac current in the meander coil creates an oscillating field $\delta H$ that adds perpendicularly to the static field and, in effect, rotates the axis of tension (or compression) in the surface plane, thus, creating a shear strain. The wavelength $\lambda$ of the resultant SH wave is approximately twice the spacing between current elements of the meander coil that are parallel to $H$. A particular SH mode may be excited by setting the frequency $f$ of the ac current such that $f\lambda$ matches the phase velocity of the desired mode. In this study, the fundamental SH mode, $SH_0$, is excited.

Thompson has shown that the generation efficiency of the SH wave is proportional to

$$\xi |\lambda| \frac{\delta H}{H}$$

(1)

where $\lambda$ is the magnetostriction coefficient (the longitudinal strain due to $H$), $\xi$ is the skin depth ($\xi = \sqrt{\mu \sigma \omega}$), $\mu$ is the transverse incremental permeability, $\sigma$ is the conductivity, and $\omega$ is the angular frequency. The transverse incremental permeability is used here, because the oscillating field $\delta H$ is perpendicular to the static field $H$. This expression applies at near-saturation static fields, where the magnetization is nearly parallel to the total magnetic field. Since the detection efficiency of SH waves by EMATs also is proportional to expression (1), the amplitude of the signal from an EMAT receiving ultrasound that itself is generated by an EMAT is proportional to the square of expression (1).

EXPERIMENTAL TECHNIQUE

Measurement of Propagating $SH_0$ Waves

The amplitude of propagating waves generated magnetostrictively by EMATs was measured with Setup 1 shown in Figure 2. A single meander-coil EMAT was used to generate $SH_0$ waves of 6 mm wavelength. A gated amplifier issued pulses consisting of eight cycles of sinusoids at 551 kHz, and the amplifier output was adjusted continuously to maintain a constant EMAT current of 5 A. (In this paper, all currents are specified by their amplitudes.) The wave amplitude was measured with a shear piezoelectric transducer that

![Figure 1. Setup for magnetostrictively generating SH ultrasonic waves with an EMAT. The meander coil carries ac current I, and H is applied by an external magnet. The resultant elastic displacements are parallel to the sample surface.](image)
was pressed flush against one edge of the sample with its axis of displacement aligned parallel to the plane of the sample. The amplitude of the $SH_0$ wave transmitted directly from the EMAT to the edge of the sample was monitored as the magnetic field was decreased from high levels.

During all types of measurements, samples were mounted between C-shaped pole pieces of an electromagnet. Samples were positioned carefully in the electromagnet in such a way as to minimize pulling on the ends of the sample due to magnetic attraction between the sample and the pole pieces.

**Measurement of Standing $SH_0$ Waves**

In Setup 2 of Figure 2, a single meander-coil EMAT of 1.5 mm wavelength was used with a diplexer both to generate and detect standing $SH_0$ waves. The diplexer served as a “switch box” to route pulses from the gated amplifier to the EMAT and to route microvolt signals excited by standing waves from the EMAT to a preamplifier and superheterodyne receiver. The gated amplifier issued pulses consisting of 175 cycles of sinusoids at approximately 2 MHz. To boost the amplitude of received signals, the excitation frequency and EMAT position on the sample surface were selected to establish standing waves across the width of samples. As the magnetic field was varied, the frequency was adjusted constantly to compensate for velocity changes and maintain the resonance condition. (Velocity changes on the order of 0.1% originated from the $\Delta E$-effect [4], which is softening of the shear modulus caused by domain wall motion and rotation of domain magnetization.) Also, the output of the gated amplifier was adjusted constantly to maintain a constant EMAT current of 5 A.

The maximum amplitude of the standing wave built up by the pulse was recorded and may be taken as proportional to the amplitude of a traveling wave issued by the EMAT, since the pulse duration is short relative to the reciprocal of the ring-down rate. The wave amplitude was recorded as the magnetic field from the electromagnet was ramped down from about 80 kA/m (1000 Oe).

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**Figure 2.** Experimental setups for measuring the amplitude of $SH_0$ ultrasonic waves. The ULC and A710 samples were measured in Setups 1 and 2, respectively.
Other Magnetic Measurements

The magnetization, magnetostriction, and incremental permeability were measured separately. The B-H curve of a sample was obtained by measuring the voltage induced across a solenoid wound around a sample. A strain gage was glued onto a sample to give a contacting measurement of the magnetostriction. Measurements on the top and bottom of the sample were averaged together in order to avoid recording extraneous strains due to bending of the sample that might occur during magnetization. The transverse incremental permeability was measured through an eddy current technique. Rose et al. [5] have shown that the incremental permeability $\mu$ is proportional to the unique frequency $f_0$ that leaves the real inductance of a coil unaffected when the coil is brought close to a ferromagnetic material. In the present work, a flat, spiral, oval coil was used, and $f_0$ was measured as a magnetic field was applied. (The frequency $f_0$ varied between ~10 kHz (near saturation) and ~150 kHz (at low fields).) The coil was oriented in such a way as to measure the incremental permeability mostly along a direction perpendicular to the applied static field (that is, parallel to $\delta H$ in Figure 1). With this configuration, $\mu$ was expected to be $B/H$ near saturation, and $\mu$ was derived as a function of the applied field by scaling $f_0$ so that $\mu$ equaled $B/H$ at high fields (with values of $B$ taken from the B-H curve and $H$ expressed in units of A/m).

RESULTS AND DISCUSSION

Measurements in ultra-low carbon steel

To determine the range of static magnetic fields over which expression (1) holds, the amplitudes of propagating SH$_0$ waves generated magnetostrictively by EMATs (Setup 1 in Figure 2) were measured on a 26 x 13 x 0.08 cm plate of ultralow-carbon (ULC) steel that was hot- and cold-rolled and annealed. (The grain size was 13 $\mu$m and the carbon concentration = 0.003 mass %). The top surface of the sample was wet-ground with 400 grit sandpaper and chemically polished with an aqueous solution of oxalic acid and hydrogen peroxide. Wave amplitudes are shown in Figure 3 as a function of both the applied static magnetic field and the current in the transmitter EMAT. The curves have been normalized with respect to their high-field amplitudes, which are found to rise linearly with the EMAT current (in accordance with expression (1), since $\delta H$ should be proportional to the current). While the width of the low-field peak increases with current, its relative

![Figure 3. Amplitudes of SH$_0$ waves recorded in Setup 1 with peak currents in the transmitter EMAT of 25 A (0), 5 A (0), 0.5 A (0), and 0.1 A (x). The dashed curve is the amplitude of waves excited by the piezoelectric transducer and detected by the EMAT.](image-url)
height is maximized for an intermediate current (closer to 5 A than 0.5 or 25 A). Included in this figure is a plot of data collected when the functions of the EMAT and piezoelectric transducer are reversed; that is, when waves are generated by the piezoelectric transducer (excited by 400 peak V pulses) and detected by the EMAT. This particular curve seems similar to the wave amplitude that would be generated by an EMAT carrying much less than 0.1 A of current. This result is evidence that the reception efficiency of the EMAT varies with static magnetic field similarly as the low-current limit of its generation efficiency.

Figure 4. Measurements in the ULC sample. (a) B-H curve. (b) Normalized transverse incremental permeability (○) and B/H-approximation (—). (c) Magnetostriction. (d) Estimates of $|\lambda|$: $|\lambda| \propto H \sqrt{\mu}$ (○), $|\lambda| \propto \Psi \sqrt{\mu}$ (◇), and strain gage measurement (dashed line). Each estimate is scaled arbitrarily.

Measurements of the B-H curve, transverse incremental permeability, and magnetostriction of the ULC sample are shown in Figure 4. As expected, at the coercive force (H-intercept of the B-H curve), the incremental permeability reaches a maximum and the magnetostriction reaches a local minimum, and, near the "knee" of the B-H curve, the magnetostriction reaches a maximum. Above ~20 kA/m, the incremental permeability agrees well with the B/H-approximation, which indicates the regime of near-saturation fields, where magnetization is nearly parallel to the applied magnetic field.
Features of the relative magnetostriction may be inferred from the amplitude of the SHω wave. Figure 4(d) shows an estimate of the absolute value of the magnetostriction based upon substituting measurements of the wave amplitude Ψ (excited with a current of 5 A in the EMAT) into the following alternative form of expression (1):

\[ |\lambda| \propto H \Psi \sqrt{\mu} \]  

(2)

This expression is expected to be valid in the near-saturation regime, and, indeed, the estimate agrees with strain-gage measurements of the absolute value of the magnetostriction (see Figure 4(d)) above ~20 kA/m, which is the lower limit of the near-saturation regime given above by the measured incremental permeability.

However, the estimate deviates significantly from the strain gage measurement at low fields, apparently because the estimate is cut off by the proportionality to H. If this factor were removed from the estimate, then at least the shape of the estimate would agree better with the strain-gage measurement (see curve in Figure 4(d)). Undoubtedly, there must be an additional term depending mildly upon H that would improve agreement with the strain gage measurement even further, but the significant result to be noted is that, at low fields, most of the H-dependence of the estimate appears to be carried by the wave amplitude. Hence, the wave amplitude may be used to predict the field at which the peak in the magnetostriction occurs. All the wave amplitudes (except the 25 A curve) in Figure 3 have a peak at 0.9 kA/m, similar to the magnetostriction (Figure 4(c)). This proportionality between magnetostriction and the wave amplitude is an important fact to consider in any future attempt to model the wave amplitude at low fields.

Measurements in HSLA steel

To demonstrate the effects of microstructural changes upon wave amplitude, measurements were performed on ASTM A710 grade A, class 3 steel, a low-carbon, HSLA steel that was age-hardened by copper precipitates ([C] = 0.04 mass % and [Cu] = 1.20 mass %). The samples examined in this work were austenitized at 899 °C for 90 minutes, water-quenched, aged at either 482 °C or 593 °C for 90 minutes, and air-cooled. Previous work determined that the samples had little texture [6]. The microstructure of this steel was investigated by Hicho et al. [7], and results may be summarized as follows:

1. The austenitizing temperatures used in this study produced fine-grained ferrite with an average grain size of 15 μm. The same average grain size was obtained, whether the sample was austenitized for 30 or 90 minutes, or whether it was aged at 482 °C for 30 minutes or aged at 649 °C for 90 minutes.

2. Small-angle neutron scattering (SANS) analysis indicated that the sample aged at 482 °C was left in the underaged condition; that is, the volume fraction of Cu precipitates was not maximized, and fine-scale Cu-rich precipitates were created. These precipitates were too small to be detected optically. (Typically the diameters are less than 5 nm [8].)

3. SANS analysis indicated that the sample aged at 593 °C was overaged; that is, the maximum volume fraction of precipitates was achieved and Cu precipitates became coarser.

4. Impact tests conducted on standard (ASTM E-23) Charpy specimens indicated that the overaged sample had more than twice the toughness of the underaged sample at -18 °C (255 vs. 120 J absorbed).

Bars of size 130 x 20 x 8 mm were cut out, and all measurements were performed on a single surface of each sample that had been wet-ground using a sequence of sandpapers.
ranging in roughness between 60 and 800 grit. Then about 30 to 40 μm of material was removed by chemically polishing the surface.

The ability to predict the location of the magnetostriction peak from the SH₀ wave amplitude is demonstrated again with the A710 steel sample (compare Figures 5(c) and 5(d)). In this case, standing SH₀ waves were measured with Setup 2 in Figure 2, and, since the waves were both generated and detected by an EMAT, the magnetostriction at high fields should be roughly proportional to the square root of the wave amplitude. The wave amplitude also reflects an unusual aspect of the magnetostriction of this sample: it remains positive at high fields, in contrast to the magnetostriction of the ULC steel sample.

Measurements of the wave amplitude also successfully predict differences between the magnetostrictions of the underaged and overaged A710 samples. Figure 5(c) shows that, in the overaged sample, the magnetostriction is larger at all fields and that the peak shifts from 5.6 ± 0.8 kA/m (70 ± 10 Oe) to 3.2 ± 0.8 kA/m (40 ± 10 Oe). These changes are mirrored

Figure 5. Measurements of (a) B-H curve, (b) transverse incremental permeability, (c) magnetostriction, and (d) SH₀ wave amplitude in the underaged (---) and overaged (o) A710 samples.
in the wave amplitudes (Figure 5(d)), although not as successfully above ~40 kA/m (500 Oe). Figure 5(b) shows that the transverse incremental permeability is not much different for the two samples; hence, the skin depths for the two samples should be similar, and differences in the wave amplitude can be attributed mostly to differences in the magnetostriction.

Significant differences also appear in the B-H curves (Figure 5(a)). Similar to magnetostriction, the magnetic induction at saturation is much larger in the overaged sample. It is likely that these increases in the saturation magnetic induction and magnetostriction are due to Cu precipitates, since most other potential sources of the changes (different textures, grain sizes, or external stresses) may be eliminated. Ongoing experiments are attempting to confirm this hypothesis.

CONCLUSIONS

This study demonstrates that measurement of the amplitude of EMAT-generated SH waves provides a noncontacting method for predicting key features of the magnetostrictive curve. Also, this measurement may be used to monitor microstructural changes in steel. In the case of A710 steel, coarsening of Cu precipitates was detected. This result points to the possibility of using EMATs as an online NDE tool to indicate when the toughness of this steel is optimized. Future endeavors will attempt to determine whether this technique can be used to sense the formation of the small strengthening Cu precipitates during the early stages of aging.

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