ELASTIC AND MAGNETIC CHARACTERIZATION OF METALS FROM ONE SURFACE

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INTRODUCTION

Materials characterization exemplifies quantitative NDE because it demands quantitative measurements of basic physical properties and quantitative theoretical models that relate the physical properties to the service requirements. One of the most important applications of quantitative NDE is the prediction of mechanical strength of a structural material from measurements that do not mechanically deform it. This can only be accomplished through an understanding of the microstructural sources of strengthening followed by carefully designed measurements of those physical properties that reflect the key microstructures. An examination of the content of this volume shows many papers devoted to predicting hardness, strength, drawability and residual stresses from physical property measurements that can be made nondestructively under field conditions. Most of these papers conclude that more accurate predictions can be made if more than one physical property is measured because the correlations observed are limited in the range of alloys and heat treatments over which reliable results can be obtained.

This paper represents a first step in the direction of obtaining two or more independent measurements from one sensor in order to predict the hardness of armor plate. At the present time, the government buys armor plate to a hardness specification that demands measuring the hardness at many locations on large blocks of metal under what are nearly field conditions. It is expensive to prepare the surface, make a hardness indentation and measure its dimensions with a hand-held microscope on a multiton block of steel on a shipping/receiving dock. Therefore, there is an interest in electronic probes that can infer the hardness from one or more measurements on surfaces that may be rough and rusty and certainly too large to be brought to a conventional hardness testing machine. If such a portable probe can be developed, it would find applicability in many industrial areas such as the fabrication and maintenance of such large objects are rolling mill rolls and submarine hulls.

ULTRASONIC CHARACTERIZATION WITH EMATS

It is well known that the numerical value of the velocity of sound reflects the microstructure and therefore can be used to infer the hardness of the material {1}. The problem is to measure the sound velocity

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without machining a sample with special, parallel surfaces and without introducing errors from the coupling between the transducer and the part. By using EMATs, the coupling problems can be eliminated and surface waves can be used to overcome the necessity for preparing flat, smooth and parallel surfaces on opposite sides of the part. For the program reported here, two kinds of surface waves were investigated. Ordinary Rayleigh waves were excited and detected by EMATs {2} constructed out of either permanent magnets or pulsed electromagnets and meander coils. Surface skimming SH (shear horizontal) waves were excited and detected both by periodic permanent magnet EMATs {3} and by pulsed electromagnets that applied their magnetic fields parallel to the long wires of a meander coil {4}. By placing the EMAT coils at an accurately known separation distance, a simple transit time measurement would be sufficient for defining the sound velocity in the material. For the frequencies employed, 1 to 2 MHz, the waves can be expected to measure the properties of the metal to a depth of approximately one wavelength which is 0.06 to 0.12 inches. Thus, the influence of rust and dirt on the immediate surface is minimal.

In order to first establish that the two sound velocities do indeed reflect the hardness condition of armor plate, compact transmitter and receiver EMATs for both kinds of waves were mounted on wheels so that the separation distance between them could be varied in a controlled and accurate way. To excite and detect Rayleigh waves, the probe consisted of a permanent magnet mounted over a meander coil so that the magnetic field was perpendicular to the surface of the sample. For launching and detecting shear horizontal (SH) waves, a periodic array of permanent magnets was mounted over a "race track" coil. By choosing the size of the permanent magnets and the frequency of operation, the SH waves could be made to skim along the surface and be detected by a receiver separated from the transmitter by an accurately known distance. To measure the velocity of sound, the arrival time of a particular zero crossing in the middle of the tone burst detected by the receiver EMAT was monitored while the separation distance was changed by a micrometer screw attached to the frame that supported the transducers in careful alignment. A Hewlett Packard Model 5335 Universal Counter/Timer operating in the time averaging mode displayed the arrival time to an accuracy of about 1 nanosecond while the micrometer screw moved one of the EMATs with an accuracy of ±0.0001 inches. By performing a linear regression analysis on the shift in arrival time versus the change in separation distance data, a velocity of sound accurate to ±0.2% could be obtained.

Four armor plate samples with hardness values ranging from 352 to 495 Brinell numbers were supplied by Aberdeen Proving Ground in the form of 6" x 6" plates either 1/2" or 1" in thickness. Their surfaces were rusty and rough since they were in the "as received" condition from the steel mill. No attempt to modify the surface was attempted. Two scans over one inch path lengths were performed in two orthogonal directions to detect any anisotropy or texture. Only the sample with a Brinell hardness of 477 showed much texture and in this case the Rayleigh wave velocities at 0 and 90 degrees differed by 1.4%. In the other samples, the velocities in orthogonal directions differed by less than 0.3% which is near the experimental error.

In the case of the Rayleigh waves, the velocity vs. distance curves fit a straight line very well but the SH waves showed systematic deviations of the points from the "best fit" line. These deviations occurred on the plate samples with 1/2" thickness and were shown to arise from energy reflected from the back side of the plate arriving at the receiver slightly out of phase with the direct, surface skimming wave. To avoid this source of error, higher frequency SH waves were generated with a meander coil and a pulsed electromagnet that applied the field parallel to the long wires of the EMAT {4}. These precautions allowed the use of EMAT coils that were many wavelengths long so that the acoustic beam would be confined to the top surface and no side lobes of the radiation pattern could reflect from the bottom surface.

The results of these velocity measurements are shown in Table I for the four samples. Note that as the hardness changes, the two velocities change by more than a percent which is greater than the experimental error of a few tenths of a percent. Thus, a probe that can measure the wave velocity along the surface to an accuracy of a few tenths of a percent can be used to infer the hardness. It must be noted, however, that a graph of hardness versus velocity is not a simple curve but is double valued with two velocities being associated with one hardness value in the high hardness range. This is a clear example of the importance of measuring more than one physical property so that this redundncy can be removed.

In an isotropic material, two elastic constants are sufficient to define all the elastic parameters of that material and the two wave velocities given in Table I could be used to define the shear modulus and the Poisson's ratio. Unfortunately, the two velocities are nearly equal so a small error in either one can yield large errors in Poisson's ratio and hence even larger errors in such other moduli as Young's modulus. However, it is interesting to calculate the elastic constants of the four samples of different hardness. The shear modulus, G, comes directly from the shear horizontal wave velocity by multiplying the square of the velocity value by the material density. Poisson's ratio, σ, is related to the ratio of the Rayleigh wave velocity to the shear wave velocity, Vr/Vs, through the equation {5}:

$$\sigma = \{(Vr/Vs) - 0.870\} \div \{1.120 - (Vr/Vs)\} \quad (1)$$

Young's modulus, E, is related to the shear modulus and Poisson's ratio by

$$E = 2G(1 + \sigma) \quad (2)$$

Table II shows the results of these calculations for the three samples that exhibited isotropy in the Rayleigh wave velocity. The larger variation of Young's modulus with hardness would indicate that there might be a more accurate and regular correlation between the longitudinal wave velocity and the hardness than there is between the shear modulus and the hardness. Preliminary studies indicate that a single loop EMAT coil driven by a unipolar pulse of current can generate a longitudinal wave that skims along the surface and can be detected by a single loop receiver EMAT coil separated from the transmitter. If the separation

Table I. Precision values for the velocity of Rayleigh and shear waves in the surface of four armor plate samples. (Units are in inches per μ/sec.)

Brinell No.	Shear Wave Velocity 0° = 90°	Rayleigh Wave Velocity 0°	Rayleigh Wave Velocity 90°	Ratio Vr/Vs
352	0.1270±0.0002	0.1189±0.0006	0.1187±0.0006	0.9354
363	0.1262±0.0001	0.1168±0.0007	0.1169±0.0003	0.9255
477	0.1250±0.0001	0.1137±0.0003	0.1154±0.0003	0.909-0.923
495	0.1263±0.0001	0.1155±0.0006	0.1160±0.0004	0.9169

Table II. Values of the elastic constants of the three isotropic samples. (Units are in MPa)

Sample	G	σ	E
352	82.03	0.35	221
363	80.93	0.29	208
495	81.13	0.23	200

distance is known, the longitudinal wave velocity can be measured directly. Such a configuration of EMAT coils can also be used to measure the Rayleigh wave velocity because a Rayleigh wave is also generated at the same time as the longitudinal wave.

MAGNETIC CHARACTERIZATION

In the final configuration of hardness measuring probe, it would be difficult to measure the wave velocities by physically changing the separation distance between the transmitter and the receiver EMAT coils. It would be much better to have the EMAT coils at a well defined and known separation distance and simply measure the transit time between launching a wave and receiving it. Such a probe would best be designed around a compact electromagnet that generates the required high magnetic fields for a time that is too short to damage the magnet by ohmic heating. Such an electromagnet is shown diagrammatically in Fig. 1. It consists of a laminated "E" shaped core with drive coils wound around the joints between the pole pieces. When these coils are driven with a pulse of • current from the discharge of a capacitor, a tangential magnetic field is generated over the material being tested in the gap between the magnet pole pieces and a field normal to the surface appears in the gap between

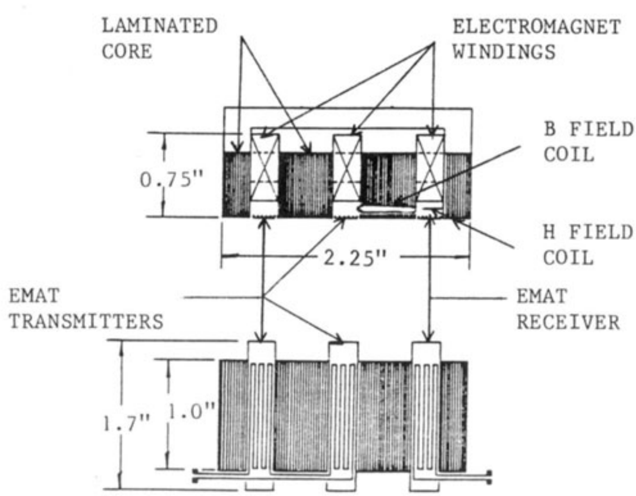

Fig. 1. Magnetic/ultrasonic probe for measuring both ultrasonic and magnetic properties of the magnetic metal on which the probe is placed.

each pole piece and the material. Since the field is time dependent, it diffuses into the material only to a depth comparable to the electromagnetic skin depth at the frequency associated with the duration of the applied current pulse. Therefore, large magnetic fields that are either tangential or normal to the surface of the armor plate can be produced. By placing meander coils in the tangential fields in between the pole pieces, Rayleigh waves can be produced. More important, it is possible to insert small pickup coils in the gaps between pole pieces or under a pole piece to make quantitative measurements of the field strengths at these locations and then to deduce information about the magnetic properties of the material bridging the gap between the pole pieces. A coil in the tangential field between the pole pieces will measure the magnetic H field in the surface because this field must be continuous across the boundary. A coil placed in the gap under a pole piece or wrapped around the laminated core near the gap will measure the normal component of the magnetic induction B field in the material because this component of the magnetic field must be continuous across the surface.

If the poor but simple assumption is made that the leakage of flux can be neglected, the B and H fields thus measured can be plotted against one another to produce an approximate hysteresis graph for the material that fills the space between the pole pieces and closes the magnetic circuit. Such a graph can be used to indicate comparative values for the intercepts with the B and H axes and thus measure comparative values for the Coercive Force (the H intercept at $B = 0$) and the Remanence (the B intercept at $H = 0$). If either of these measureables can be correlated with the hardness, then the same probe that generates surface acoustic waves will also generate magnetic property data that can be used to distinguish between hardness levels that exhibit the same Rayleigh wave velocities.

Figure 2(a) shows a graph of the current versus time waveform applied to an electromagnet similar to that diagrammed in Fig. 1. The current is labeled with an I. The resulting B and H fields are labeled with a B and an H respectively. Figure 2(b) shows the "hysteresis loop" obtained when the B and H fields that occur at the same time are plotted against one another. Here, the four loops obtained on the four samples with different hardness levels are superimposed. These loops do not appear like normal hysteresis loops because the driving current is not sinusoidal but is a rapidly decreasing function of time. Thus, the fields developed in the second and third quadrants are greatly diminished. However, the figure demonstrates that hardness differences can be detected in the magnetic response. In particular, the B values at a certain H field appear to correlate with the hardness level. Figure 2(c) shows the results of plotting the B field against the current in the electromagnet. Here, only the first quadrant of data is displayed and the shape of the curves is more reminiscent of a common hysteresis loop. This is because the pole pieces of the electromagnet are being driven into saturation by the amount of current being applied. Again, the separation of the B values at a fixed current can be used to distinguish between different hardness levels.

MAGNETOACOUSTIC CHARACTERIZATION

The electromagnet pictured in Fig. 1 allows both magnetic property and Rayleigh wave velocity measurements to be made from one small probe. The configuration allows space for three EMAT coils at equal separation distance. If the two coils on the left are driven in series by the same transmitter circuit, a Rayligh wave is launched simultaneously from each coil. If the third coil acts as a receiver, these two waves will be detected as two consecutive signals separated by the transit time

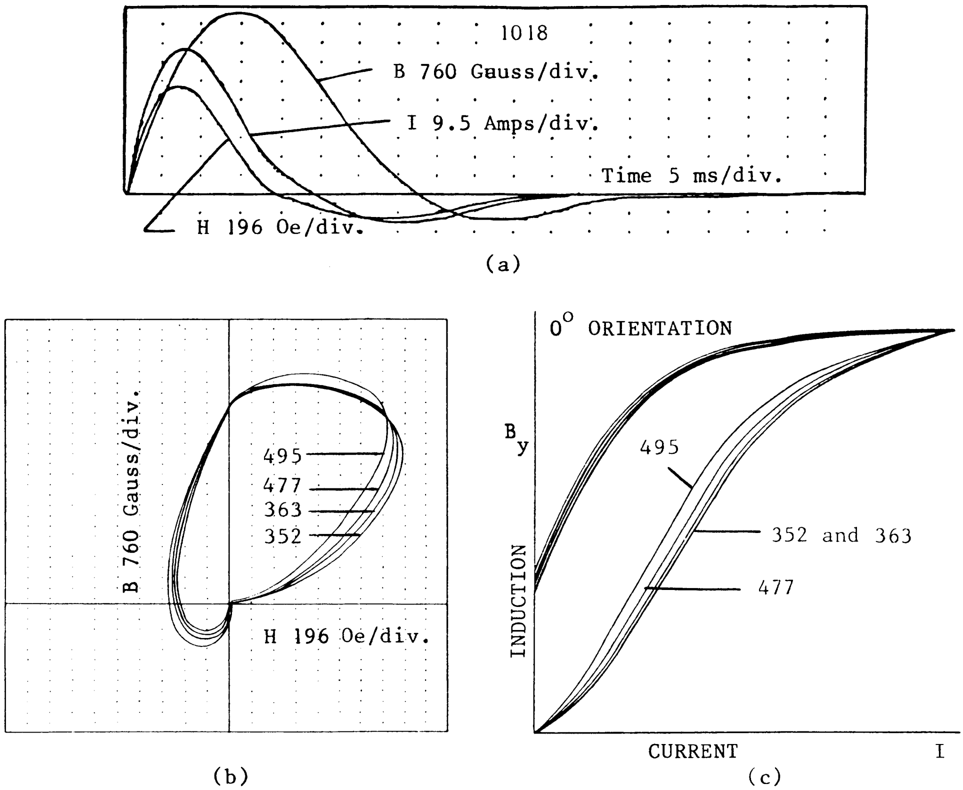

Fig. 2. Magnetic fields produced by an electromagnet driven with a pulse of current. (a) Time dependence of the current I, the induction B and the magnetic field H. (b) B vs. H curves recorded on armor plate samples of differing hardness. (c) Magnetic induction B in the electromagnet yoke as a function of the current in the electromagnet.

required for the Rayleigh wave to propagate between the two transmitter coils. Thus, the velocity of the Rayleigh wave can be immediately deduced by dividing the separation distance between coils by the transit time. Not only can the velocity be measured but the attenuation coefficient of the surface wave can be calculated from the ratio of the amplitudes of the two consecutive signals in the receiver channel. By using this attenuation coefficient, it is possible to extrapolate the measured signal amplitudes back to the wave origin and arrive at a measure of the wave amplitude directly under the EMAT coil that launched the wave. This quantity is directly related to the transducer efficiency which, in this case of operation on a ferromagnetic steel, is a measure of the magnetostriction coefficient of the metal {6}. It was found that this magnetostrictive coefficient is a strong function of the hardness level especially in the high hardness range. Thus, the amplitude information contained in the output of the receiver EMAT coil of the probe shown in Fig. 1 can also be used as an independent means of inferring the hardness of the armor plate.

HARDNESS DETERMINATION

The previous sections of this paper describe the methods used to measure five separate physical properties of the armor plate samples.

These five quantities are the Rayleigh wave velocity, the shear wave velocity, the ratio of these velocities (which determines the Poisson's ratio), the magnetic induction at a fixed current level and the magnetostrictive coefficient. All five of these measurements are plotted against the hardness in Fig. 3. Examination of these graphs shows that only the magnetic induction is a monotonic function of the hardness number and thus might be easily used to infer an unambiguous hardness from a measureable quantity. However, the accuracy of this approach would be poor because the induction only changes by about 20 percent and is certainly not a linear function of hardness. The property that is most sensitive to hardness is the magnetostrictive coefficient since it changes by more than an order of magnitude between Brinell hardness number of 477 and 495. Unfortunately, the magnetostriction appears to change very little over most of the intermediate hardness values and hence would be inaccurate as a hardness prediction parameter in this range. The two velocity functions are comparable in their behavior relative to hardness changes so either could be used to infer the hardness. However, as mentioned before, the hardness is a double valued function of the velocity the thus must be used in conjunction with another measureable to determine the unambiguous hardness value for an unknown sample.

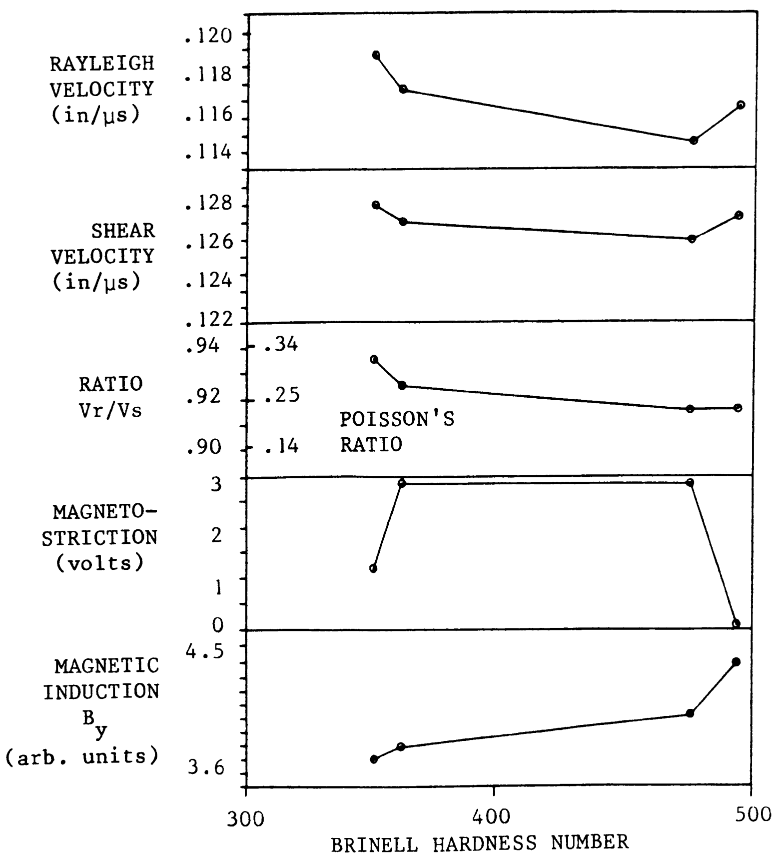

Fig. 3. Graphical relationship between the five quantities measureable with a small electromagnet probe and the hardness of armor plate.

CONCLUSION

The most accurate hardness value and the ability to cover a wide range of hardnesses will be achieved only by combining several of the measurements presented in Fig. 3. Many more samples representing a wide variety of hardness values will have to be measured with an instrumented electromagnet probe such as that shown in Fig. 1 before a multi-parameter correlation procedure can be developed to give the most accurate prediction of the hardness for an unknown sample of armor plate. It is clear that the key to achieve a viable hardness measuring instrument lies in measuring many physical properties simultaneously.

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