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Magnetic Measurements of Iron Steels by Using Ultrasonics
超音波を利用した鉄鋼材の磁気測定

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1. Introduction

The magnetic characteristics of materials have been measured by a variety of techniques, including conventional contact methods with sensitive magnetic field sensors [1-3], electron microscopy techniques in which modification of electron motion by the Lorentz force is detected [4], and optical methods which exploit the Kerr effect [5]. Scanning a surface with a sensitive magnetic field sensor provides direct information on the material surface, although it is generally difficult to maintain contact with rough surfaces and the technique is not suitable for environments subjected to magnetic fields. The electron microscopy and optical techniques require substantial equipment and are thus limited to laboratory use. Here we present a more convenient alternative magnetic sensing combined with ultrasonic inspection.

Ultrasonic waves can propagate through optically opaque substances, such as the human body, metals, and concrete. The majority of existing ultrasonic techniques are restricted to determining the mechanical properties of materials from the elasticity or mass density of the target. Recently, a method for measuring electromagnetic properties through acoustic-wave coupling has been reported [6], and magnetic sensing via ultrasonic excitation has been demonstrated [7]. In this method, the acoustically stimulated electromagnetic (ASEM) response is detected by a narrowband antenna tuned to the center frequency of the incident ultrasonic waves.

A major advantage of the ASEM method is that it is compatible with conventional ultrasonic pulse-echo sensing, and can be used for evaluating the electromagnetic properties of a material detected by the pulse-echo inspection. In this paper, we show the close correlation between the magnetization curve and the signal intensity of the ASEM response. The signal intensity increases in the process leading to magnetization and show a maximum peak in the condition of saturated magnetization. Mapping the magnetic flux density penetrated into an iron steel plate, we found a characteristic flux distribution around an artificial defect of the plate.

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2. Measurement principle

In the linear response regime, the mechanical and magnetic equations can be written as $(i, j = 1, 2, 3 \text{ and } m, n = 1, 2, \cdots, 6)$[8]

$$S_m = s^H_{mn} T_n + d_{jm} H_j \, , \qquad\qquad (1)$$
$$B_j = d_{jm} T_m + \mu^T_{ji} H_j \, ,$$

where the S, T, H and B are the strain, stress, magnetic field and magnetic flux density components, respectively. The coefficients relating these quantities, s, d and μ are the elastic compliance, the piezomagnetic constant, and permeability constant, respectively. To study the ASEM response in the process toward magnetization, we here discuss the magnetic flux density ΔB modulated by the stress ΔT at a finite external field H. It is known that the permeability constant generally depends on the stress [9] and the μ^{T_1} is larger than the μ^{T_2} in a condition of

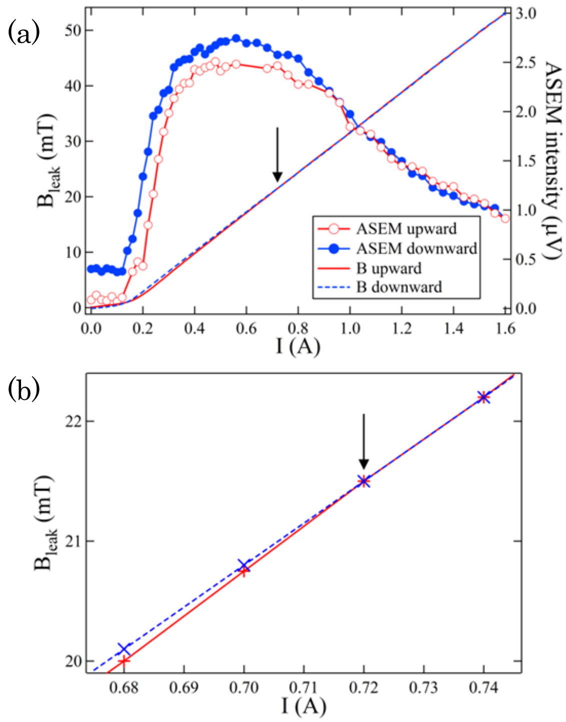

Fig. 1 (a) Magnetic-field dependence of the ASEM intensity and the $B_{\rm leak}$ on an iron steel plate. The transversal axis represents the electric currents applied to an electromagnetic coil. The arrow indicates a saturation point of magnetization. (b) The enlarged view of the reference curves at the saturation point.

compressive stresses $T_1 < T_2$ in the case of positive magnetostriction (for instance, iron steels). It follows that the stress ΔT induces the ΔB through the change of the permeability constant $\Delta\mu$ caused by the stress under a finite external field H as well as the component through the piezomagnetic constant. Namely, the magnetic flux density modulated by the stress under a finite H is given by

$$\Delta B_j \approx d_{jm}\Delta T_m + \Delta\mu_{ji}H_i. \qquad (2)$$

The H dependence of the ASEM response can be thus attributed to the second term of eq. (2).

The ASEM measurements have been performed by a probe method [6] in this study. An iron steel plate specimen (JIS G 3101 SS400, size: 20 × 50 × 0.8 mm) with a 1 mm artificial hole is subjected to external magnetic fields along the direction of the long axis of the plate by using a commercial electromagnetic coil. To obtain the reference curves of magnetization, the leakage magnetic flux density B_{leak} from the surface of the specimen is measured by a Hall sensor (Lakeshore, MFT-3E03-VH) mounted on the steel plate.

3. Experimental Results and Discussion

Figure 1 shows the H-dependence of the ASEM response and the B_{leak}. As seen in Fig. 1(b), magnetic hysteresis almost vanishes above an electric current $I = 0.72$ A (which corresponds to H = 36 kA/m), indicating the saturation of magnetization. The ASEM intensity increases with increasing H in the low-field region while the intensity decreases when the magnetization is fully saturated. We interpret the H-dependence of the ASEM response as follows. Ferromagnetic materials like iron steels are composed of randomly oriented microscopic magnetic domains. In the low-field region, the multi-domain system is very sensitive to the external magnetic fields. The applied field penetrates the material and aligns the domains, resulting in significant increase in the permeability μ. The $\Delta\mu$ caused by the stress is also enhanced in the magnetization process [10]. The ASEM intensity thus increases with increasing the magnetic fields. When the magnetization is saturated (the domains are fully aligned), however, the permeability becomes insensitive to the tensile (compressive) stress in the case of positive (negative) magnetostriction, leading to a decrease in the ASEM intensity. In the strong-field limit, the single domain structure becomes sufficiently stable and the permeability will not be affected by the mechanical stress of an order of 10 kPa applied by ultrasonic waves.

Figure 2 represents the magnetic flux distribution around a 1 mm hole in a steel plate specimen. In this experimental condition, the applied H corresponds to a current of about 1.4 A.

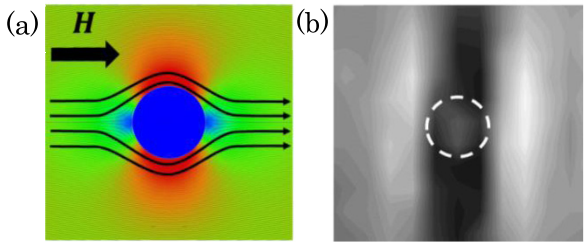

Fig. 2 Magnetic flux distribution around a 1 mm hole in a steel plate. (a) Numerically calculated image. (b) ASEM image at I = 1.4 A. In the suppressed B region on the horizontal side of the hole, the larger ASEM intensity is obtained.

Assuming $B \propto B_{\mathrm{leak}}$, the numerical calculations indicate that the flux densities on the horizontal and vertical sides of the hole corresponds to current conditions of 1.2 A and 1.6 A in Fig. 1(a), respectively. The ratio of the ASEM intensity between both sides is thus expected to be about 1.5, which is consistent with an experimentally obtained intensity ratio of 2.

4. Conclusion

We have clarified the behavior of the ASEM intensity in magnetization processes and demonstrated the magnetic flux mapping in a steel plate. This technique will provide a new method for nondestructive metal inspection.

Acknowledgment

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