Local probing of magnetic hysteresis properties through acoustically stimulated electromagnetic response
音響誘起電磁応答を通した磁気ヒステリシス特性の局所プローブ

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1. Introduction

A magnetic hysteresis curve contains a number of independent parameters, such as permeability, coercivity and hysteresis loss, of the target ferromagnetic material, which are known to be sensitive to crystal orientation, grain size, stress and so on. Magnetic inspection is therefore used for nondestructive inspection of defects or residual stress in steel products and infrastructures.[1)]

Although standard magnetic flux density B versus magnetic field H ($B-H$) curve obtains the accurate magnetic character of a bulk sample, local probing or spatial mapping are beyond their scope. On the other hand, scanning techniques with a magnetic sensor can image the leakage flux density B_{leak} from the surface of materials. However, B_{leak} is quite insensitive to intrinsic magnetic flux (magnetization) confined in materials below saturation fields. Therefore, hysteresis properties in the low-field region are not clearly probed through the B_{leak}.

Recently, a unique technique for locally probing magnetic hysteresis characters has been developed using pulsed ultrasonic techniques.[2)] The principle of this technique is based on the generation and detection of acoustically stimulated electromagnetic (ASEM) response through magnetomechanical coupling. The intensity of ASEM response is proportional to the local piezomagnetic coefficient d_{loc} defined in the acoustically excited area. The field-dependence of the ASEM intensity (ASEM hysteresis curve) is thus identified with the hysteresis curve of the $d_{\mathrm{loc}}(H)$ that includes specific parameters of ferromagnetic materials.

The purpose of this study is to clarify the local hysteresis characters in different surface conditions of steel. It is known that the magnetic properties are influenced by the crystal grain size that depends on annealing temperatures or cooling process.[3)] The grain size on the outer face of steel in manufacturing process is usually smaller compared with that in the inner part. In addition, the magnetic easy axis in individual grains tends to be aligned along the rolling direction in its manufacture process. Using a carefully prepared ring-shaped steel specimen, we have investigated the relationship between the ASEM hysteresis curve and the steel surface condition.

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2. Experimental Setup

We prepared a ring-shaped carbon steel specimen (S25C, JIS G4051:2009) with 50 mm diameter (**Fig. 1(a)**). The specimen was cut into a ring shape plate with a thickness of 19 mm from a 25 mm thick plate with mill scale (iron oxide layer), directly delivered by a steel manufacture company. The one face of 25 mm thick plate was removed by machining over 6 mm and its surface is defined as the "inner" face as shown in Fig. 1(a). On the other face, only mill scale was removed by acid pickling and its surface is defined as the "outer" face. The initial residual stress was relaxed by annealing. In addition, we also

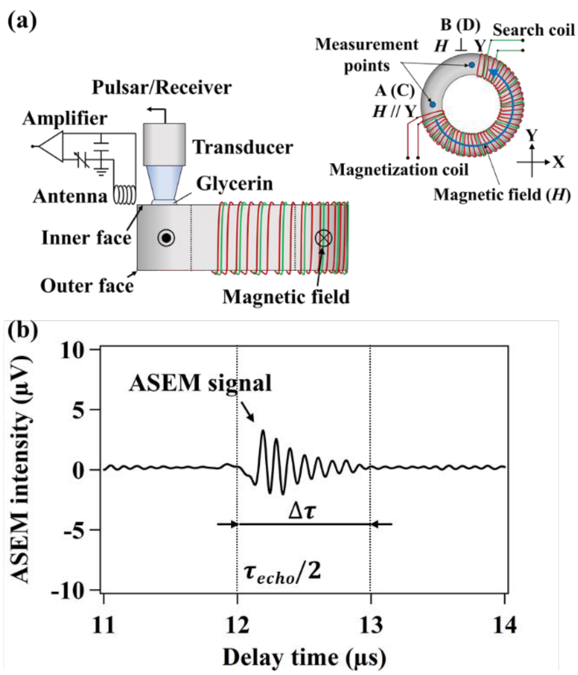

Fig. 1 (a) Schematic of a steel specimen. The axis Y is parallel to the rolling direction. (b) Typical real-time waveform.

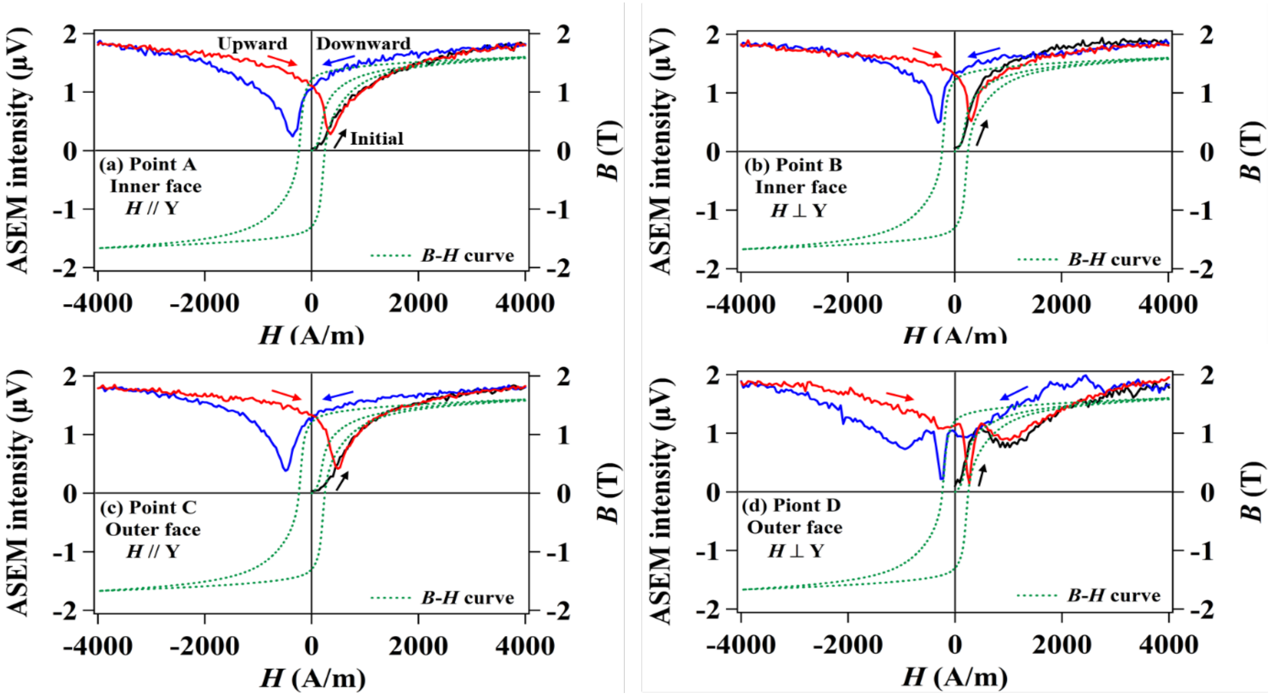

Fig. 2 ASEM hysteresis curves at individual measuring points (a) A, (b) B, (c) C and (d) D. The dotted line represents the standard $B-H$ curve.

marked the rolling direction of the steel plate (Y axis in Fig. 1(a)). The measuring points A (C) and B (D) are the positions at which magnetic field H is parallel and perpendicular to the rolling direction on the inner face (the outer face), respectively.

The $B-H$ curve was measured by applying electrical currents through a magnetization coil and by detecting induced currents through a search coil. Because of the ring shape specimen, correction of the demagnetizing fields can be neglected.

We have performed ASEM measurement using a transducer (10 MHz) with a polystyrene pillar for avoiding the transducer excitation noise.[2)] The ASEM signal is picked up through a resonant loop antenna turned at 9.7 MHz. **Figure 1(b)** shows a typical ASEM waveform generated from the steel specimen. The ASEM signal is observed at half the echo delay time ($\tau_{\mathrm{echo}}/2 = 12$ μs).

3. Results and discussion

The hysteresis curves of ASEM intensity (corresponding to $|d_{\mathrm{loc}}(H)|$) are shown in **Fig. 2**. The intensity is defined as the averaged value of the signal amplitude $|V_{\mathrm{sig}}(H,t)|$ integrated between $t=\tau_{\mathrm{echo}}/2$ and $t=\tau_{\mathrm{echo}}/2+\Delta\tau$, where $\Delta\tau$ is an integration time of 1 μs. The minimum observed at $H_{\mathrm{min}} = 270-490$ A/m in the ASEM hysteresis curves indicates a demagnetized condition at the local point. The observed values of H_{min} are roughly in agreement with coercivity $H_{\mathrm{c}} = 250$ A/m evaluated from the standard $B-H$ curve.

A striking feature is that the hysteresis curve at Point D is largely different from the usual behavior reported in carbon steel plates.[2)] At this moment, we have no clear idea to explain the secondary minimum observed around 940 A/m. The anomalous behavior may be attributed to the smaller grain size or martensite transformation formed on the outer face. Detail microscopic studies of crystal structure are now in progress.

4. Conclusion

Local magnetic properties are obtained in a carbon steel through ASEM response, suggesting a specific character depending on the surface condition.

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