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Phase sensitive detection of acoustically stimulated electromagnetic response in steel
鉄鋼における音響誘起電磁応答の位相検波

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1. Introduction

Ultrasonic imaging technique is widely used as non-invasive probe in medical and industrial fields. Since echo signals are usually analyzed, the majority of existing applications are restricted to diagonosing structural or elastic properties of matters. In recent years, however, electric or magnetic properties have been successfully visualized by ultrasonic scanning.[1,2] The principle of this technique is based on the generation and detection of electromagnetic fields induced by electro- or magneto-mechanical coupling.[3] This acoustically stimulated electromagnetic (ASEM) response has been observed in a variety of material, such as GaAs, plastic, wood, bone, steel and so on. The amplitude of ASEM signal is proportional to effective piezoelectric or piezomagnetic coefficient $d_{\rm loc}$ averaged in an acoustically excited area, providing local crystalline qualities or magnetic properties. Especially for ferromagnetic materials, magnetic hysteresis curve can be locally probed by the ASEM method.[4] Because the hysteresis curve contains a number of independent parameteres of ferromagnetic materials, this unique technique will be a useful method for nondestructive evaluation (NDE) of steel products or infrastructures.

We here focus on the magnetic hysteresis curve of ASEM signal voltage in steel. The magnetic-field H dependence of the signal voltage corresponds to that of piezomagnetic coefficient $d_{\rm loc}(H)$. In our earlier studies,[4] the hysteresis curve was obtained by measuring an average absolute value of real-time waveform. Namely, the phase change was neglected. The purpose of this work is to develop a phase sensitive detection (PSD) scheme in the ASEM method and to derive the real and imaginary part of the corresponding complex piezomagnetic coefficients.

2. Experimental methods

The measurement setup is shown in **Fig. 1 (a)**. A 10 MHz transducer with a delay line (27mm-length polystyrene pillar) is used for separating between the transducer excitation pulse and the ASEM signals.[3] The ultrasonic focal point (focal spot size: about 1 mm) can be scanned by moving the transducer integrated with a resonant loop antenna (frequency: $f_{\rm res}=9.7$ MHz). Rectangular 100 V pulses are delivered in 20-period bursts with 50 % duty cycle at a 1 kHz repetition rate. The pulse width is set to the inversed resonant frequency $f_{\rm res}^{-1}$. A synchronized sinusoidal wave generated from the pulsar/receiver is used for a reference signal for PSD. The signal waveform is averaged over 1000 repetitions. The direct ASEM signal $V_{\rm sig}$ starting at the delay time $t=\tau_{\rm echo}/2$ is observed (the upper data in **Fig.**

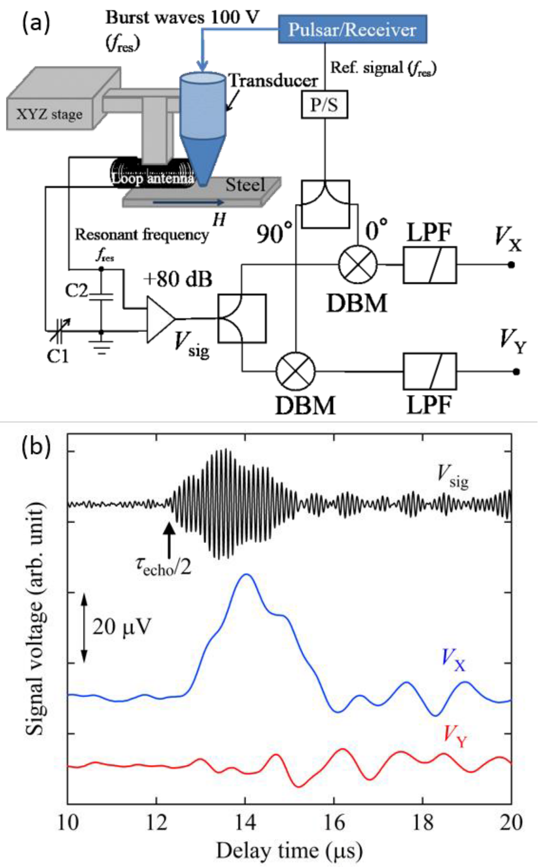

Fig.1 (a) Schematic of PSD scheme for ASEM method. (b) Typical ASEM waveform generated from a steel plate. The upper, middle and bottom data represent the direct ASEM signal ($V_{\rm sig}$), the “in-phase” component (V_X) and the “quadrature” component (V_Y) after PSD, respectively.

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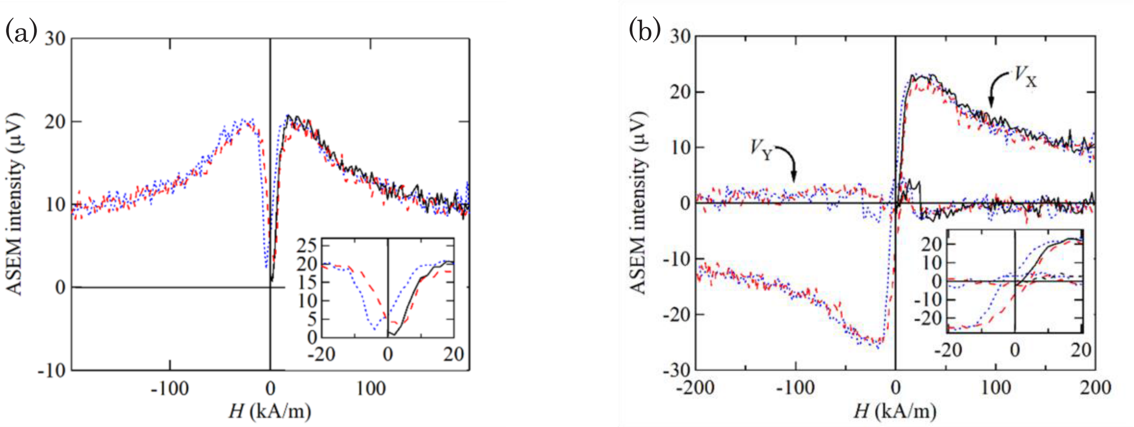

Fig. 2 Magnetic hysteresis curves of the ASEM intensity in a steel sample. The solid line represents the initial magnetization curve. The dashed and the dotted line represent the upward and downward field data in the hysteresis loop, respectively. The inset shows an enlarged representation. (a) ASEM intensity obtained from the direct signal V_{sig}. (b) ASEM intensity obtained from the signal V_X and V_Y after PSD.

1(b)), where τ_{echo} is the delay time of echo signal reflected on the steel plate. The V_{sig} is divided into the "in-phase" component (V_X) and the "quadrature" component (V_Y) after PSD. The middle and the bottom data in Fig. 1(b) shows typical waveform after PSD. The ASEM intensity $\overline{V_{\mathrm{sig}}}$, $\overline{V_X}$ and $\overline{V_Y}$ are defined as the averaged value of signal voltage $|V_{\mathrm{sig}}(t)|$, $V_X(t)$ or $V_Y(t)$ integrated between $t = \tau_{\mathrm{echo}}/2$ and $t = \tau_{\mathrm{echo}}/2 + \Delta\tau$, respectively, where $\Delta\tau$ is the integration time.[4] The value of $\Delta\tau$ is set to 500 ns in the direct signals and 1 μs in the signals after PSD, respectively.

A steel sample measured (size: 100 × 100 × 2.0 mm) is cut from a 11 mm thick steel plate (JIS G 3101 SS400) by machining. The sample is subjected to external magnetic fields along the direction of parallel of the plate surface using a home-made electromagnetic coil.

3. Results and Discussion

We first describe the relation between the signals after PSD (V_X and V_Y) and the complex piezomagnetic coefficient. When the applied alternating stress is written by $T = T_0 e^{i\omega t}$, the flux density in the linear response regime will be generally expressed by $B(H) = B_0(H)e^{i(\omega t - \delta(H))}$, where $\delta(H)$ is the phase delay of $B(H)$ from T and will depend on the external field H. The piezomagnetic coefficient $d(H)$ is thus defined by the ratio of B and T as the formula: $d(H) = B/T = (B_0/T_0)\cos\delta - i(B_0/T_0)\sin\delta = d'(H) - id''(H)$. The real and imaginary components is thus obtained in the PSD scheme.

The averaged value $\left|\overline{V_{sig}}(H)\right|$ is proportional to the absolute value of local piezomagnetic coefficient $|d_{\mathrm{loc}}(H)|$ on the acoustically excited spot. The hysteresis curve corresponding to $|d_{\mathrm{loc}}(H)|$ is shown in **Fig. 2(a)**. The minimum observed at $H_{\mathrm{min}} = \pm 4$ kA/m in the hysteresis curve indicates a demagnetized condition; H_{min} corresponds to the so-called coercivity H_c.[4]

Let us next discuss the "in-phase" component V_X and the "quadrature" component V_Y. We assume that the phase delay is negligible in the single domain regime at high fields because the ferromagnetic spin resonance is much higher than 10 MHz. Thereby, we defined $\delta = 0$ at a high magnetic field of 200 kA/m. **Figure 2(b)** shows the H-dependence of ASEM intensity obtained by V_X and V_Y. The "in-phase" component indicates a symmetric feature for magnetic-field inversion. Furthermore, the field crossing the transverse axis is well in agreement with the H_{min} observed in the hysteresis curve of $\left|\overline{V_{sig}}(H)\right|$. These results provide strong support for the validity of our phase tuning process. The H-dependence of $\overline{V_X}(H)$ ($\overline{V_Y}(H)$) can therefore be deemed to be proportional to $d'(H)$ ($d''(H)$).

4. Conclusion

The PSD scheme has been developed in the ASEM method. The signal voltages are well divided into the "in-phase" and the "quadrature" components, indicating the complex piezomagnetic coefficient at high frequency in steel.

Acknowledgment

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