Non-Destructive Plastic Deformation Estimation of Metals Using GMR Sensor-Based Eddy-Current Measurement

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ABSTRACT

This study presents the development of a non-destructive plastic deformation estimation technique for paramagnetic metals, such as aluminum alloy and stainless steel, using Giant-Magneto Resistive (GMR) sensor-based eddy-current measurement. Plastic deformations in metallic structures can occur when the loading exceeding the yield strength of the material is applied. In addition, plastic deformation can induce the initiation and growth of fatigue cracks, leading to the catastrophic failure of metallic structures. Therefore, it is crucial to detect and evaluate the severity of plastic deformation in advance to ensure structural integrity and safety. Plastic deformation in metallic materials causes perturbation (or dislocation) in the material lattice, resulting in changes in electrical resistance (or electrical conductivity). Thus, in this study, the plastic deformation-induced electric resistance variation was estimated using eddy-current measurement. The sensitivity of eddy-current measurement was enhanced by replacing the conventional pick-up (sensing) coil with a GMR sensor. Test specimens using aluminum alloy (Al6061-T6) and stainless steel (SUS304) were fabricated, and various tensile plastic strain levels were applied using a hydraulic loading machine. The phase values were extracted from the eddy-current raw signal, and the relationship with the plastic strain level was investigated. Additionally, the influence of the external magnetic fields was minimized by applying a constant weak magnetic field using a permanent magnet. The experimental results indicate that the phase values of the eddy-current signal increase as the extent of plastic deformation. The uniqueness of this study lies in 1) the fabrication of the eddy-current probe based on the GMR sensor, 2) the minimization of the external magnetic field to enhance the eddy-current measurement, and 3) the experimental validation of the plastic deformation estimation using the eddy-current phase values.

INTRODUCTION

Plastic deformation, one of the damage types of metallic structures, such as bridges and pipelines, is caused by unexpected tensile forces exceeding the yield

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strength due to the impact load from vehicles or vessels or seismic loadings. In addition, plastic deformation can lead to fatigue cracks and result in catastrophic failure of the structures as cracks grow and reach fatigue life [1]. Therefore, detecting and estimating plastic deformation in the early stage is important for the safety of metallic structures. Eddy Current Testing (ECT) is a non-destructive testing method that evaluates material properties based on electromagnetic characteristics [2]. Plastic deformation alters the material lattice, changing the electrical conductivity (or resistance). Here, the eddy current signal is affected by the electrical resistance of the metallic material [3]. Thus, ECT measurement can indirectly estimate plastic deformation by capturing the electrical resistance changes [4-5]. In this study, an eddy-current probe was designed and fabricated using a Giant-Magneto Resistive (GMR) sensor with higher sensitivity than the conventional coil. Then, the ECT was performed on the test specimens with various plastic deformations. The eddy-current phase values were extracted from the raw signal, and the relationship with the plastic strain level was investigated.

THEORETICAL BACKGROUND

Relationship between plastic deformation and electrical resistance

Plastic deformation occurs when an external tensile force exceeding the yield strength is applied to the material. Inside the metallic material, the lattice structures are perturbed, which is called dislocation and slip. The perturbation of lattice structure increases electron scattering and restricts the movement of free electrons, resulting in decreased electrical conductivity and increased electrical resistance [6]. The total electrical resistance of metals (ρ) due to plastic deformation can be expressed as follows [7].

$$\rho = \rho_i + \rho_1 \tag{1}$$

where ρ_i represents the ideal (initial) resistance and ρ_1 is a variation of electrical resistance due to plastic deformation (dislocation). Furthermore, it can be written that the relative electrical resistance change is proportional to plastic deformation (ε_p), as follows.

$$\frac{\rho_1}{\rho_i} = A\varepsilon_p \tag{2}$$

where A is the proportional coefficient.

Electrical resistance estimation using eddy-current measurement

The conventional working principle of ECT is as follows: (1) When an alternating current (or a voltage) is applied to the excitation coil, a primary magnetic field is generated, which induces an eddy current in the material, and (2) This eddy-current generates a secondary magnetic field, which induces the electrical current (or voltage) in a pick-up (sensing) coil, and (3) the defects and material properties can be estimated by analyzing the electrical signal obtained from the pick-up coil [8]. It was numerically and experimentally shown that the eddy-current phase value (φ) and the electrical resistance can be expressed as a logarithm function as below [9],

$$ln|\varphi| = kln|\rho| + c \quad (3)$$

where k and c are the slope and y-intercept of the function, respectively. Thus, in this study, the electrical resistance variation induced by plastic deformation is estimated non-destructively using the eddy-current phase value [10].

GMR sensor-based eddy-current measurement

The GMR effect occurs in a multilayer structure composed of a non-magnetic layer between two ferromagnetic layers. When the electron spins in the ferromagnetic layers are aligned, free electrons can easily pass through the non-magnetic layer, reducing electrical resistance. In contrast, when the spins are misaligned, the movement of free electrons is restricted, and resistance increases [11]. Here, the spin direction is influenced by the strength and direction of an external magnetic field. Thus, the magnetic field can be measured using the electrical resistance of the sensor [12]. The GMR sensor can be manufactured with chip type and easily downsized, which is helpful for eddy-current measurement.

In this study, the pick-up coil is replaced with a GMR sensor, which can directly measure the secondary magnetic field by the eddy-current in the target material with higher sensitivity. Here, it should be noted that the working principle of conventional ECT is still valid because the GMR sensor measures the secondary magnetic field induced by the eddy-current in the target material [13]. In addition, The magnetic field B generated by eddy-current in the target material can be expressed using the magnetic potential W, as shown below [6],

$$B = \nabla \times \nabla \times W \propto \varphi \quad (4)$$

This expression theoretically indicates that the phase value obtained from the secondary magnetic field measured by the GMR sensor is linearly proportional to that obtained from the electrical current (or voltage) of a conventional eddy-current pick-up coil.

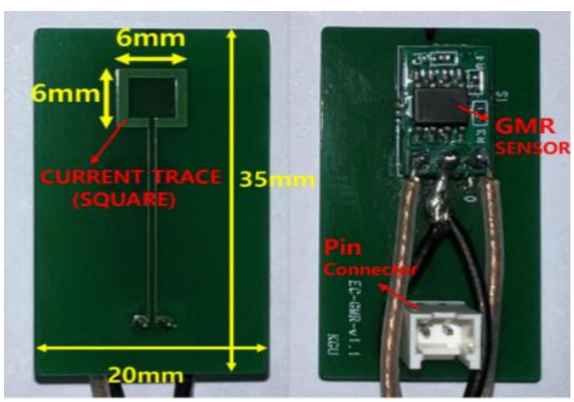
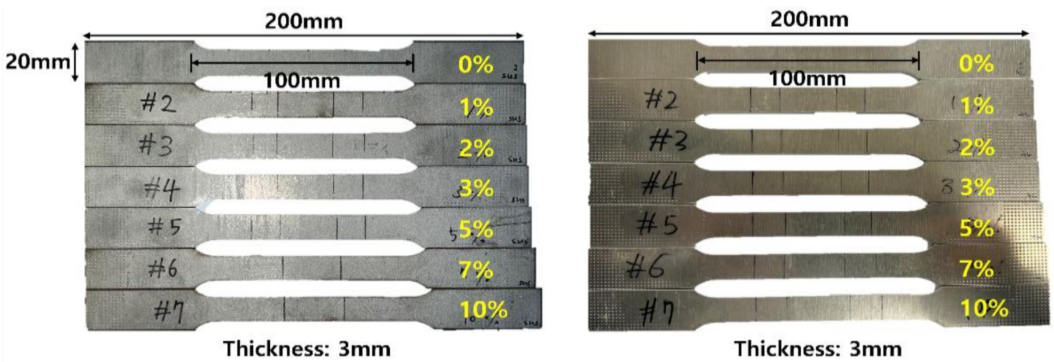


Figure 1. Eddy-current probe with GMR sensor

EXPERIMENTAL VERIFICATION

Experimental configuration

For ECT, an eddy-current probe was designed and fabricated, combining a square-shaped current trace (6mm per side, 1 mm thick) printed on the PCB board for the excitation and the GMR sensor (AAH002-02E, NVE) for the sensing (Fig. 1). The National Instruments (NI) data acquisition (DAQ) system consists of an Arbitrary Waveform Generator (AWG, NI PXI-5421) for the excitation, a Digitizer (DIG, NI PXI-5122) for the sensing, and an additional DC Power Supply (Keysight, E3644A) to supply DC power to the GMR sensor. A sinusoidal electrical voltage is applied to the excitation coil via the AWG, and the electrical voltage signal from the GMR sensor is obtained using DIG. The DAQ system was controlled and synchronized using LabVIEW software, and the acquired data was additionally processed using Python.



(a) SUS304 specimens (b) Al6061-T6 specimens

Figure 2. Test specimen fabrication

Plate specimens with 3mm thickness were designed and fabricated using paramagnetic metal (SUS304 and Al6061-T6) according to the ASTM E8 Standard. Then, various tensile plastic strain levels were applied to the specimens (deformation ratio of 0%, 1%, 2%, 3%, 5%, 7%, and 10%) using a hydraulic loading machine (Fig. 2).

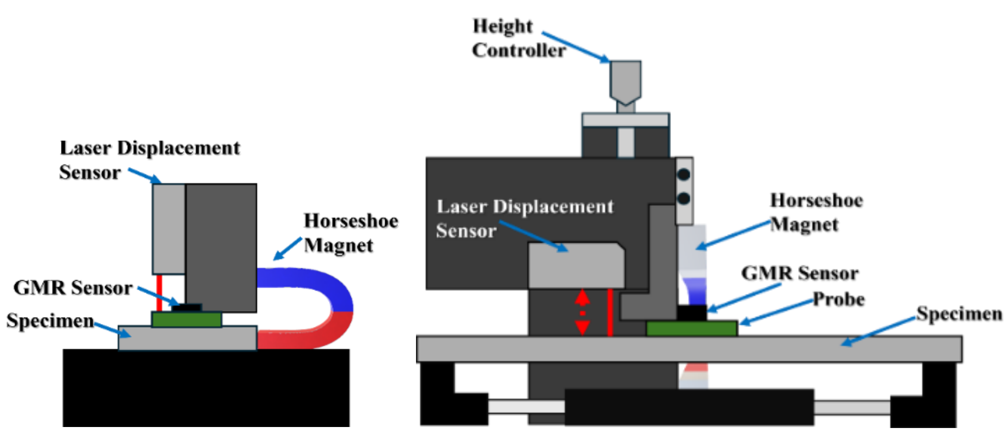


Figure 3. Specimen holder with permanent magnet

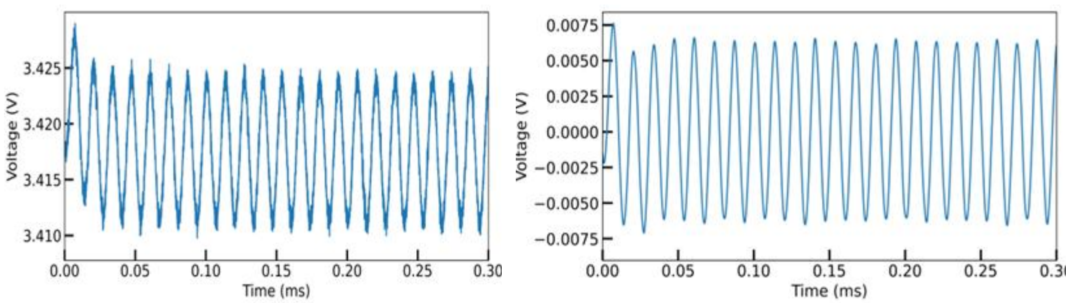
In ECT, it is known that the distance between the probe and the surface of the target structure (lift-off) significantly affects the measurement results [9]. To minimize the lift-off effect, a commercial smartphone holder was modified to the specimen holder, and a vertically movable moving stage was installed. In addition, a laser displacement sensor was mounted on the stage to maintain a constant lift-off, even when the specimen thickness changed due to plastic deformation due to the tensile loading. Here, the GMR sensor is highly sensitive to unexpected external magnetic fields from electrical devices. Thus, to reduce measurement errors, a permanent magnet (horseshoe magnet) was installed near the sensor to provide a weak and stable bias magnetic field [14].

Data acquisition and analysis

A sinusoidal input waveform (75 kHz, 2 Vpp) was applied to the excitation coil using the AWG, and the electrical voltage signal from the GMR sensor was measured by the DIG at a 20 MHz sampling rate. A 5V DC voltage was supplied to the GMR sensor, and each measurement was repeated 50 times to improve the signal-to-noise ratio. Here, the excitation frequency was determined based on the eddy current skin depth theory, as below [15].

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \tag{5}$$

In Equation (5), δ represents the skin depth of the eddy current in the tested specimen, f is the excitation frequency. σ and μ are the electrical conductivity and magnetic permeability of the target material, respectively. Considering the thickness of undeformed specimens (3 mm), the appropriate skin depth was calculated as 1-1.5 mm. In addition, the thickness of the 10% plastic deformed specimen was reduced to 2.91mm for SUS304 and 2.901 mm for Al6061-T6 due to Poisson's ratio. Considering the available frequency of the GMR sensor used in this study is limited to 30-75 kHz and selecting the appropriate skin depth as 1/3 to 1/2 of the specimen thickness, the excitation frequency was set to 75 kHz for SUS304 and 30 kHz for Al6061-T6.



(a) Raw Data (b) Filtered Data

Figure 4. Signal filtering in the time domain at 75 kHz (Zoomed-0.3ms interval)

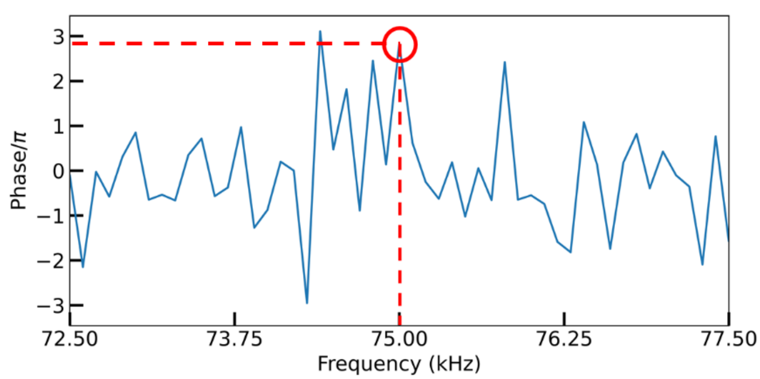
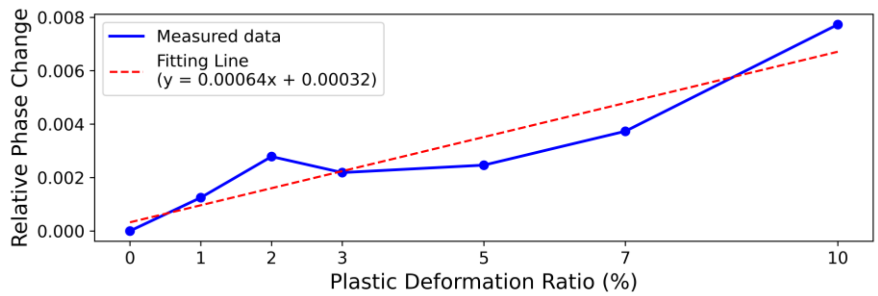


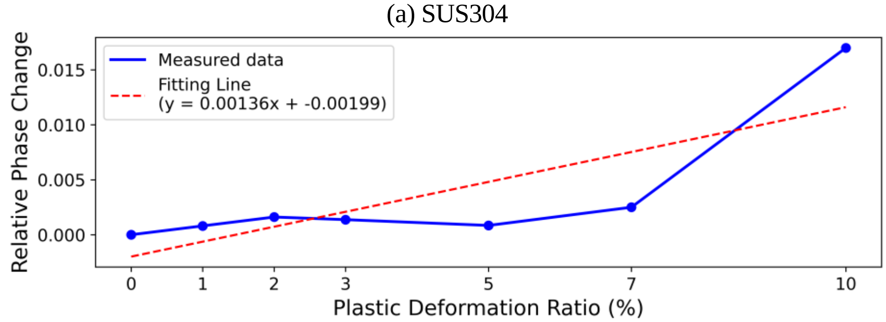
Figure 5. Filtered data in the frequency domain for phase value extraction

The phase value is extracted from the obtained eddy-current signal using Python to estimate the plastic deformation ratio. Fig. 4(a) shows the raw signal in the time domain, containing a DC component and high-frequency noise. To remove these components, a band-pass filter with 18.75-375 kHz was applied using Python, as shown in Fig. 4(b). After filtering, the Fast Fourier Transform (FFT) was applied to the filtered data. Fig. 5 shows the resulting phase in the frequency domain, where the red circle indicates the phase value at 75 kHz.

Experimental Results



(a) SUS304



(b) Al6061-T6

Figure 6. Experimental results

Fig. 6 presents the normalized phase change $(\varphi_i - \varphi_0)/\varphi_0$, where φ_0 is the reference phase value at 0% strain (no plastic deformation). The blue line represents the experimentally obtained values, and the red dashed line indicates the linear fitting result. The fitted equations for each material: for SUS304, $y = 0.00064x + 0.00032$; and for AL6061, $y = 0.00136x - 0.00199$, where x represents the plastic deformation ratio, and y is the normalized phase change. The fittings indicate that the plastic deformation ratio can be nondestructively estimated by measuring the relative phase change and Equation (2).

CONCLUSIONS

In this study, plastic deformation of Al6061-T6 and SUS304 specimens was estimated using the eddy-current phase value measured by a Giant-Magneto Resistive (GMR) sensor. The results show that the normalized phase change value increases with increasing plastic deformation ratio. Based on the results, plastic deformation can be non-destructively estimated through magnetic field measurements induced by eddy-current. Future works include developing (1) quantitative estimation of plastic deformation, and (2) localization of plastic deformation. In additions, external factors causing the measurement error will be investigated and eliminated. Ultimately, the study aims to develop an algorithm that automatically estimates the ratio and location of plastic deformation in structural components.

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