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Characterization of residual stresses in ferrous components by magnetic anisotropy measurements using a hall effect sensor array probe

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Characterization of residual stresses in ferrous components by magnetic anisotropy measurements using a hall effect sensor array probe

Abstract
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Keywords
Hall effect, magnetic sensors, coils, magnetic annealing, nondestructive evaluation, QNDE

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CHARACTERIZATION OF RESIDUAL STRESSES IN FERROUS COMPONENTS BY MAGNETIC ANISOTROPY MEASUREMENTS USING A HALL EFFECT SENSOR ARRAY PROBE

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ABSTRACT. A new surface sensor probe comprising an angular array of Hall effect sensors has been developed for characterization of residual stresses in ferrous materials by means of stress-induced magnetic anisotropy measurements. The sensor probe applies a radially spreading ac magnetic field to a test sample, and detects stray fields in different directions simultaneously to determine the principal stress axes. In situ measurements were conducted on a annealed steel plate under four-point bending stresses to evaluate the probe performance. The ratio of stray field signals measured along and perpendicular to the stress axis varies linearly with the surface stress, indicating the possibility of characterizing residual stresses in ferrous components using the sensor array probe.

Keywords: Magnetic Anisotropy, Magnetomechanical Effects, Magnetostriction, Magnetization Curves
PACS: 75.30.Gw, 75.80.+q, 75.60.Ej

INTRODUCTION

This paper reports on a recent study aimed at improving a novel magnetic measurement technique for characterization of residual stresses in ferrous components. Previously several magnetic methods, including magnetic hysteresis [1], Barkhausen noise [2], magnetoacoustic emission [3], nonlinear harmonics [4], stress-induced magnetic anisotropy (SMA) [5] and magnetically induced velocity change of ultrasonic waves [4,6], have been studied with respect to their potential for quantitative evaluation of stress state in ferromagnetic materials. These techniques are based on the magnetomechanical effect, by which stresses, including applied and residual stresses, influence the distribution of magnetic domains and the dynamics of domain wall motion under magnetizing fields [7]. This in turn affects magnetic properties, such as magnetic permeability, which can be measured and correlated with the stress state.

Among the magnetic techniques SMA has been shown effective in determining both the principal stress directions [2,5,8] and stress levels [2]. The method in general utilizes surface sensor probes to apply magnetizing field in one or multiple directions, and detect magnetic signals along and/or perpendicular to the field directions [2,5,8].

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Determination of principal stress axes is often carried out by rotating the sensor probe to measure the angular variations of the magnetic signals. For industrial applications, however, it is desirable to alleviate the need of probe rotation in order to reduce inspection time and any measurement error due to probe wobble. Special sensor probe designs have been developed to address these issues. Kwun and Burkhardt used an excitation coil wound on a ferrite core to apply radial magnetizing fields and detecting signals using induction coils in two orthogonal directions [4]. Isono and Abuku developed a special sensor probe with nine legs to measure SMA signals in different directions simultaneously [9]. In this work, a surface sensor probe comprising an angular array of Hall effect sensors has been developed for detecting magnetic anisotropy without the need of probe rotation. The performance of the sensor probe was evaluated by performing in situ SMA measurements on an AISI 1018 steel plate under four point bending stresses. The results indicate the feasibility of using the Hall sensor array probe to determine the principal stress axes, and to estimate the stress level from the detected stray magnetic field signals based on experimental calibrations.

A HALL EFFECT SENSOR ARRAY FOR MAGNETIC ANISOTROPY MEASUREMENTS

The Hall effect sensor array probe developed in this work is shown in Fig. 1. It consists of an excitation coil wound on a ferrite rod to apply a radially spreading ac magnetic field to a test sample, and nine Hall effect sensors ICs (model: A1321ELHTL-T, Allegro Microsystems, Inc.) arranged in a semi-circular array to detect the component of stray field perpendicular to the sample surface along different directions simultaneously (Fig. 1 (a)). The probe operates by the principle that for magnetically isotropic materials the leakage fluxes will be equal in all directions, whereas any magnetic anisotropy, for example induced by residual stresses, will give rise to stronger stray field signals along the easy magnetic axis. The principal stress axes can therefore be determined by measuring the angular variation of the stray field using the Hall sensor array without the need of probe rotation.

Several design concepts were implemented in order to improve the probe performance. Hall effect sensors were used in favor of induction coils for signal detection in view of the fact that the use of the former would offer more consistent sensing performance among the sensors in the array. The flat frequency response of Hall effect sensors is also desirable for future development of a multiple frequency SMA technique towards measuring depth profiles of residual stresses in ferrous materials.

The excitation coil and the ferrite core of the new sensor probe are surrounded by a 125 μm (0.005”) thick layer of Mu-metal (Fig. 1(a)), which is a soft magnetic material with a nominal relative permeability of 10^5. The Mu-metal film is used as a shield to prevent or reduce the amount of magnetic field from the ferrite core from reaching the Hall sensors directly, so that any detected signals will be contributed primarily by the magnetic flux emanating from the samples. This helps reduce background signals and in turn improve the sensitivity of the detected signals to the magnetic properties of the test material.

Figure 2 shows an example of the Hall sensor array outputs measured from a cold-rolled AISI 1018 steel plate, which was found by conventional x-ray diffraction to have residual stresses of 35 MPa and -114 MPa along the longitudinal and transverse axes respectively. When the probe was placed on the sample, the detected stray field signals, when plotted against the angular position of the sensors, exhibit a sinusoidal variation with a period of 180º due to stress-induced magnetic anisotropy. The signals are significantly

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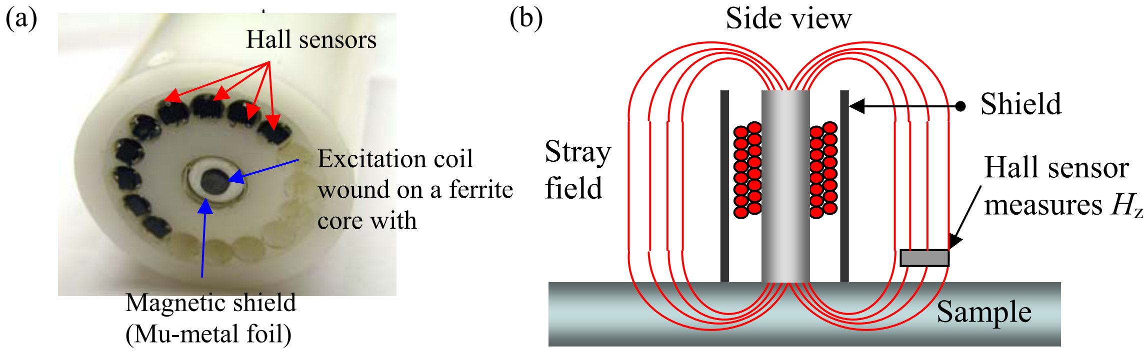

FIGURE 1. (a) A photograph showing the array probe which consists of an excitation coil wound on a ferrite core, and nine Hall effect sensors which are shielded of excitation field coming directly from the ferrite core by using a high permeability Mu-metal foil. (b) A schematic showing the stray magnetic fluxes detected by the Hall effect sensors in the array.

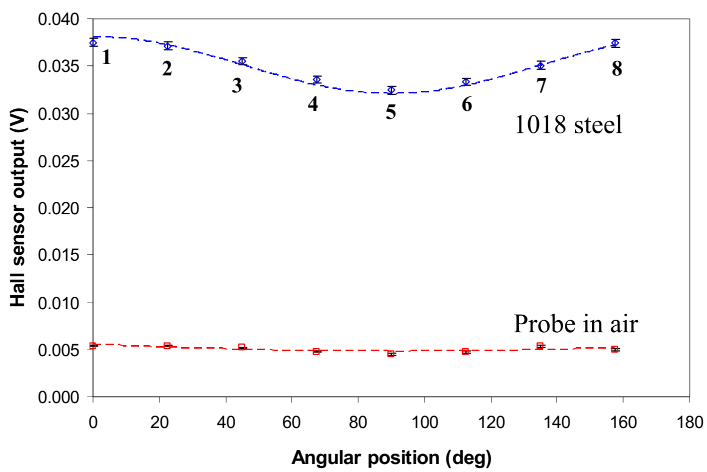

FIGURE 2. The outputs of the Hall sensor array as a function of the angular position of the sensors when the probe is placed on a cold-rolled 1018 steel plate (top) and in air (bottom). The numerical labels specify the individual Hall sensors in the array. Only eight out of nine sensors (sensors 1 to 8) were used in this work due to the limited number of analog-to-digital channels supported by the data acquisition hardware.

weaker when the probe is in air due to the combined shielding effects of the Mu-metal film and the absence of a ferromagnetic material to direct magnetic fluxes from the excitation coil to the sensors. The small but detectable variations of the sensor outputs in air (Fig. 2) are due to the inherent sensitivity differences among the sensors in the array, which were corrected for in the four-point bending experiments described in following section.

EVALUATION OF SENSOR PERFORMANCE UNDER BENDING STRESSES

In order to evaluate the stress sensitivity of the technique, in situ SMA measurements were carried out using the array probe on a stress-relief annealed AISI 1018 steel plate 50.8mm×76.2mm×1.3mm (2"×3"×0.05") in a four point bending configuration (Fig. 3(a)). The surface stress along the longitudinal axis of the sample was measured using a resistive strain gage. The probe was aligned with the Hall effect sensors # 1 and #9 along the longitudinal axis (Fig. 3(b)). An 1 kHz sinusoidal excitation field was used to magnetize the sample. The skin depth δ was estimated to be 0.23 mm (0.009") at 1 kHz.

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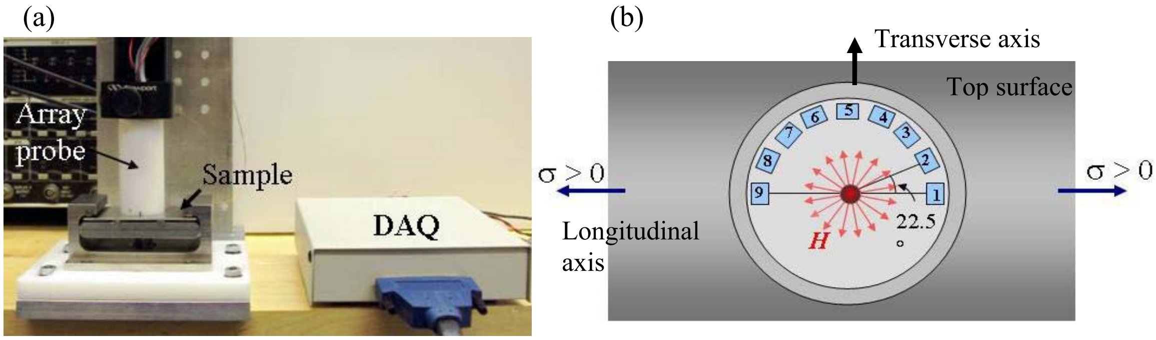

FIGURE 3. (a) The experimental setup for in situ SMA measurements on the annealed 1018 steel plate under four point bending stresses. (b) A schematic diagram showing the angular positions of the Hall effect sensors relative to the longitudinal and transverse axes of the sample. The numerical labels indicate the angular positions of the sensors. Under applied bending stresses, the top surface of the plate is under tension (i.e. $\sigma > 0$) along the longitudinal axis.

Such frequency was chosen to limit field penetration (considered to be 3δ) to within the upper half of the sample plate above the neutral plane, which would be under tension along the longitudinal axis when the plate was subjected to bending stresses. Only eight out of nine Hall effect sensors (#1 to #8) were used in the study due to the limited number of analog-to-digital channels supported by the data acquisition hardware. Fourier analysis was performed to determine the harmonic contents of the sensor outputs.

ANGULAR DEPENDENCE OF STRAY FIELD SIGNAL UNDER STRESSES

The angular variations of the Hall sensor outputs at the fundamental frequency are shown in Fig. 4 for various surface stress levels. Without any applied stress the sensor outputs, after correction for inherent sensitivity difference among the sensors, shows essentially a flat response indicating a lack of magnetic anisotropy in the annealed sample. Under bending stresses, the magnitude of the stray field along the longitudinal axis (detected by sensor #1 as shown in Fig. 3(b)) increases while that along the transverse axis (detected by sensor #5) decreases. The result can be interpreted qualitatively in terms of the stress-induced magnetic anisotropy. Under bending stresses, the top surface of the plate was under tension along the longitudinal axis. Due to the magnetomechanical effect, the magnetic permeability along the longitudinal axis (denoted by μ_1 in Fig. 5(b)) becomes larger than that along the transverse axis. Therefore a larger fraction of the injected magnetic fluxes would flow along the longitudinal axis, which would eventually come out of the sample and were detected by the Hall sensor on the axis (i.e. #1). This accounts for the larger stray field signal detected along the longitudinal axis than along the transverse axis under bending stresses as shown in Fig. 4.

In order to support the interpretation, the distribution of stray field was simulated by using the finite element method (FEM) for a magnetically anisotropic plate (Fig. 5(a)). As shown in Fig. 5(b), the calculated perpendicular component of the stray field above the surface shows an anisotropic pattern. It is evident in the FEM simulation that, by comparing the stray fields at two positions (denoted by 1 and 2 in Fig. 5(b)) which are at the same distance from the plate center, the stray field along the longitudinal axis is larger than that along the transverse axis. The simulation result supports the interpretation of stress-induced changes in the stray field pattern, which are manifested as an angular dependence of the stray field signals as shown in Fig. 4.

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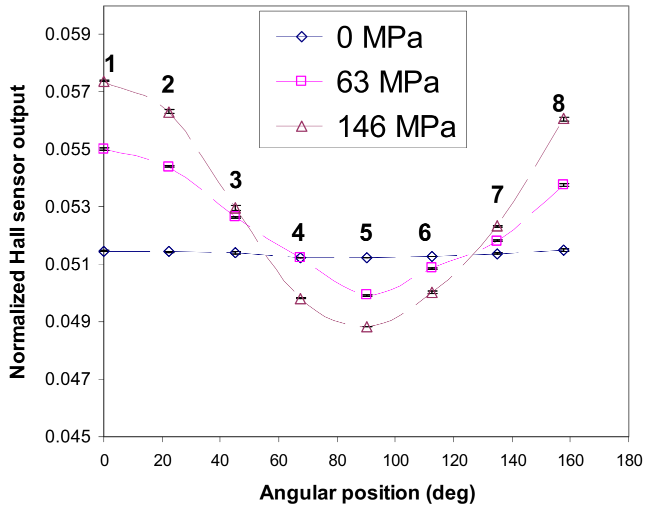

FIGURE 4. Plot of the amplitude of the fundamental harmonic of the sensor outputs as a function of the angular position of the sensors at different surface stress levels. The dotted lines are empirical fits to the data using a sinusoidal function of the angular position of the sensors.

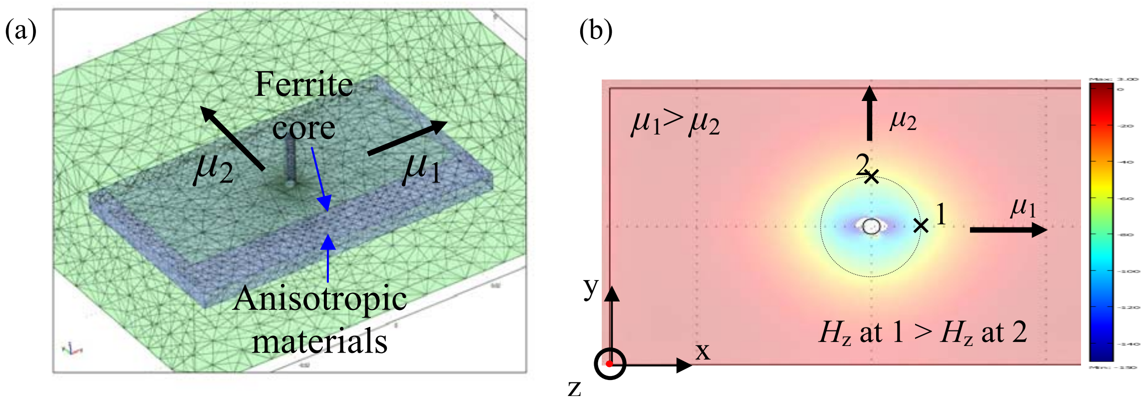

FIGURE 5. (a) Mesh configuration used in the numerical calculations of stray field pattern above a magnetically anisotropic plate using the FEM method. (b) Calculated perpendicular component of the stray field H_z at a height of 0.5mm above the plate surface. The results show a larger stray field at position 1 on the longitudinal axis than at position 2 on the transverse axis.

It should be noted that although a sinusoidal excitation field was used to magnetize the sample, high order harmonics were also observed in the Hall sensor outputs due to magnetic hysteresis of the sample. Of special note is the third order harmonic of the sensor outputs (Fig. 6), which exhibits similar angular variations as the fundamental harmonic under bending stresses but with stronger stress dependence (c.f. Fig. 4). The present results are consistent with the previous findings reported in the literature [10] that the third order harmonic of induction signals often exhibit stronger stress dependence than the fundamental harmonic.

In order to evaluate the stress sensitivity of the present measurement technique, the relative change in the sensor outputs at the fundamental frequency, which is characterized by the ratio of sensor #1 output to sensor #5 output, is plotted as a function of the surface stress level in Fig. 7. For the fundamental harmonic, the signal ratio was found to increase approximately linearly with surface stress level at a rate of 0.11% per MPa, and decreases reversibly on unloading. The ratio of the third order harmonic amplitude of sensor #1 output to that of sensor #5 varies by 0.27% per MPa change in stress up to 120 MPa,

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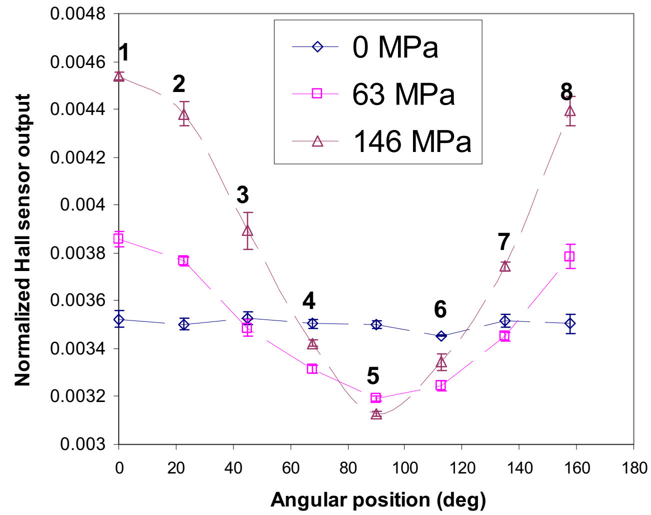

FIGURE 6. The angular variations in the third order harmonic amplitude of the sensor outputs at various surface stress levels.

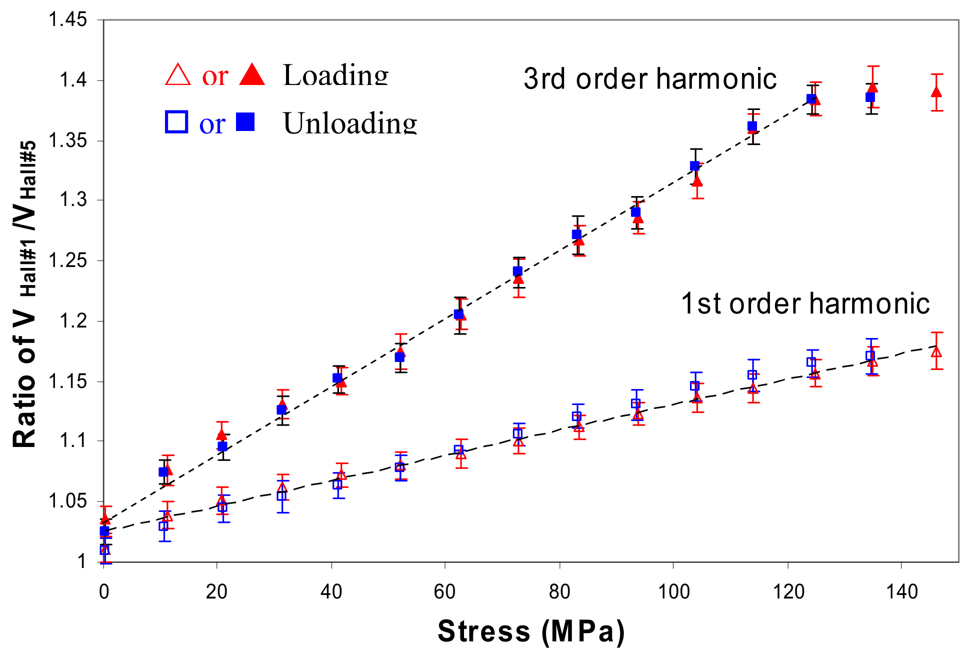

FIGURE 7. Plot of the ratio of the outputs of sensor #1 to sensor #5 as a function of surface stress at the fundamental (open symbols) and third harmonic (solid symbols) frequencies on loading (triangles) and unloading (squares). The dotted lines represent least square linear fits to the data. The error bars correspond to one standard deviation of three repeated measurements at each stress level.

beyond which the ratio tends to level off. Taking into account the average experimental error of about ±3% for the signal ratio, the errors of the estimated stress level were found to be ±28 MPa and ±10 MPa for the fundamental harmonic (Fig. 4) and the third order harmonic signal within the linear regime (Fig. 6), respectively. The present results demonstrate the possibility of determining stress-induced magnetic anisotropy and estimating the stress level by means of stray field measurements with an uncertainty in the estimated stress level comparable to that of the conventional XRD method.

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CONCLUSIONS

A new surface sensor probe comprising an angular array of Hall effect sensors has been developed for detecting magnetic anisotropy as a means to measure residual stresses in ferrous materials. The performance of the probe was evaluated by conducting in situ measurements on an annealed 1018 steel plate subjected to four-point bending stresses. The results indicate the possibility of identifying principal stress axes and estimating residual stress levels by measuring the angular variations of stray fields using a Hall sensor array.

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