Nondestructive evaluation of residual stresses in case hardened steels by magnetic anisotropy measurements

Chester C.H. Lo
Iowa State University, clo@iastate.edu

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Abstract
This paper reports on a recent study aimed at developing the stress-induced magnetic anisotropy (SMA) technique for characterizing residual stresses in case hardened steel components. The results of SMA measurements performed on flat induction hardened steel discs with different case depths confirm the feasibility of detecting principal stress axes by measuring the angular variation of magnetic permeability. The permeability signals along the principal axes were found to vary monotonically with the residual stresses measured by XRD, but the signals are in general smaller for samples with a larger case depth. The magnetomechanical properties of the martensitic case and ferritic/pearlitic core of the induction hardened sample were studied by measuring magnetostriction curves from strip samples that were cut from the case and core regions, respectively. The case strip shows a significantly lower magnetostriction than the core strip, indicating a weaker stress dependence of magnetic properties for the martensitic case than for the ferritic/pearlitic bulk of the case hardened samples.

Keywords
internal stresses, magnetic anisotropy, magnetic permeability measurement, magnetostriction, martensitic steel, nondestructive testing, strips, X-ray diffraction, nondestructive evaluation, QNDE

Disciplines
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Comments
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NONDESTRUCTIVE EVALUATION OF RESIDUAL STRESSES IN CASE HARDENED STEELS BY MAGNETIC ANISOTROPY MEASUREMENTS

C. C. H. Lo

Center for Nondestructive Evaluation, Iowa State University, Ames, IA 50011, USA

ABSTRACT. This paper reports on a recent study aimed at developing the stress-induced magnetic anisotropy (SMA) technique for characterizing residual stresses in case hardened steel components. The results of SMA measurements performed on flat induction hardened steel discs with different case depths confirm the feasibility of detecting principal stress axes by measuring the angular variation of magnetic permeability. The permeability signals along the principal axes were found to vary monotonically with the residual stresses measured by XRD, but the signals are in general smaller for samples with a larger case depth. The magnetomechanical properties of the martensitic case and ferritic/pearlitic core of the induction hardened sample were studied by measuring magnetostriction curves from strip samples that were cut from the case and core regions, respectively. The case strip shows a significantly lower magnetostriction than the core strip, indicating a weaker stress dependence of magnetic properties for the martensitic case than for the ferritic/pearlitic bulk of the case hardened samples.

Keywords: Magnetic Anisotropy, Magnetomechanical Effects, Magnetostriction, Magnetization Curves

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INTRODUCTION

This paper reports on a recent study aimed at investigating the feasibility of exploiting magnetic measurement techniques to detect residual stresses in case hardened steel components. The work was performed as part of an on-going study with a long-term goal of developing magnetic NDE methods for measuring residual stresses in components with complex geometries and limited accesses where the more established techniques, such as x-ray diffraction (XRD), are not applicable. Magnetic methods, including magnetic hysteresis [1], Barkhausen noise [2], nonlinear harmonics [3] and stress-induced magnetic anisotropy (SMA) [4], have been extensively studied with respect to their potential for quantitative residual stress measurements. Among them, SMA has been shown to be useful in determining both the principal stress axes and stress levels [5]. The technique is based on the fact that residual stresses induce anisotropy in magnetic properties and affect the magnetic permeability via the magnetomechanical effect.
Therefore, one can identify the principal stress axes by measuring the angular variation of the magnetic signals, and estimate the residual stress levels from the permeability based on empirical calibrations. The feasibility of detecting biaxial residual stresses by the SMA technique has been demonstrated in our recent study on plain carbon steel plates with a ferritic/pearlitic structure subjected to four point bending stresses [6]. The accuracy was estimated to be ±28 MPa, which is comparable to that of conventional XRD sin²ψ method.

Although the SMA technique has shown promise for characterizing residual stresses in ferritic/pearlitic steels, its potential for inspecting case hardened components is yet to be evaluated. In this work, we studied the feasibility of applying the SMA technique to detect magnetic anisotropy in flat induction hardened discs with different case depths. The results indicate the feasibility of detecting principal stress axes from the SMA signals. Linear correlations were observed between the permeability signals and the residual stress level, which can be exploited for residual stress measurements. The effects of case depth on residual stress measurements were investigated by measuring the magnetostriction curves of the martensitic case and ferritic/pearlitic core of the case hardened samples. The martensitic case shows a substantially weaker magnetomechanical effect than the ferritic/pearlitic core, highlighting the needs of further studies to separate the effects of case hardening on residual stress measurements.

SMA MEASUREMENTS ON INDUCTION HARDENED DISCS

Experimental Details

A set of four induction hardened S45C (0.45wt%C) steel discs with a diameter of 200 mm (8”) and a thickness of 10 mm (0.4”) was used in this study. The discs were induction hardened over a region 95 mm (3.75”) by 146 mm (5.75”) in size (Fig. 1 (a)). The disc samples can be divided into two groups with nominal case depths of 2.0 mm and 2.8 mm. The surface residual stresses along two orthogonal axes (denoted as x- and y-axes in Fig. 1(a)) at multiple positions, both inside and outside the case hardened zone, were measured using the XRD sin²ψ method. An example is given in Fig. 1(b) which shows the residuals stress components at different positions of the sample TP2.8-2 which has a nominal case depth of 2.8 mm.

![Measurement positions (total 11)](image)

**FIGURE 1.** (a) An induction hardened disc used in this study. The darker rectangular region is the induction hardened zone. (b) Residual stress components measured along the x- and y-axes at multiple positions of the disc sample TP2.8-2 (nominal case depth = 2.8 mm) by the conventional XRD sin²ψ method.
SMA measurements were carried out at multiple positions using a surface sensor probe shown in Fig. 2. The probe consists of an electromagnet made of ferrite for applying uniaxial magnetizing field to the sample, and two detection coils aligned along and perpendicular to the field axis to detect the components of the magnetic induction (denoted by $B_{∥}$ and $B_{⊥}$, respectively) in those directions. The longitudinal pickup coil detects the effective permeability signal along the applied field direction, whereas the transverse coil detects the so-called SMA signal perpendicular to the applied field. A third coil was included to monitor probe liftoff by sensing the leakage fields emanating from the arms of the ferrite yoke. During the measurements, a 100 Hz sinusoidal field was applied to the sample. The angular dependence of both the effective permeability and SMA signals was measured by rotating the probe on the sample through $360^°$ in $10^°$ steps.

**Results of SMA Measurements**

The principal stress axes at the measurement positions can be readily determined from the angular variations of the effective permeability and SMA signals. As an example, the signals measured from the disc sample TP2.8-2 are shown in Fig. 3 for comparison. Both the effective permeability and SMA signals vary as a sinusoidal function of the sensor probe orientation $\theta$ (inset of Fig. 1(a)) with a period of $180^°$, and the two signals are separated by $46^°$ in phase. The effective permeability signal shows a maximum along

![Image of experimental setup and probe](image1)

**FIGURE 2.** The experimental setup and the surface sensor probe used for SMA measurements on the induction hardened disc sample.

![Image of effective permeability and SMA signals](image2)

**FIGURE 3.** Plot of the effective permeability and SMA signals as a function of probe orientation $\theta$. Note that the SMA signal peaks at $\theta_{\text{SMA}}^{\text{peak}} = 133.6^°$, which is $46.4^°$ away from the peak of the effective permeability signal. Also shown are the residual stresses measured along the x- and y-axes.
the x-axis (i.e. $\theta = 0^\circ$) where the residual stresses are tensile, and a minimum close to the y-axis (i.e. $\theta = 90^\circ$) under compressive residual stresses. The results can be interpreted by considering the fact that for steels with a positive magnetostriction, magnetic permeability increases under tension but decreases under compression because of the magnetomechanical effect.

Figure 4 shows the permeability signals measured at multiple locations of two disc samples with nominal case depths of 2 mm and 2.8 mm. In all cases, the permeability signals attain the maximum values along the x-axis where the residual stresses are tensile, and the peak value tends to increase with the tensile residual stress level. Of special note is that the permeability measured from the sample with a smaller case depth (2 mm) is consistently larger than those found in the sample with a larger case depth (2.8 mm) with similar residual stress levels, indicating that the detected permeability signals depend not only on the residual stress level but also on the case depth.

In order to evaluate the stress sensitivity of the SMA technique, the peak positions and signal amplitudes of the permeability signals measured at different positions were determined by fitting the data (e.g. plots in Fig. 4) using

![Graphical data](image)

**FIGURE 4.** Plot of the effective permeability signals (all in the same vertical scale) measured at different positions on disc samples TP2-2 and TP2.8-2, which have nominal case depths of 2.0 mm and 2.8 mm, respectively. In each plot the residual stresses measured at that position along the x- and y-axes are also shown. The arrows indicate the maximum permeability which tends to increase with the level of the tensile residual stresses along the x-axis.
where $V_{avg}^\mu$ is the mean effective permeability signal averaged over 360°, $A^\mu$ is the amplitude characterizing the strength of magnetic anisotropy and $\theta_0^\mu$ is the probe orientation when the signal is maximum.

Figure 5 summarizes the stress dependence of the effective permeability signal. For samples with nominally the same case depth (e.g. TP2-1 and TP2-2), the effective permeability signals measured along the principal stress axes (i.e. x- and y-axes) were found to vary approximately linearly with the principal residual stresses, and the signals are in general smaller for samples with a larger case depth (c.f. TP2-1 and TP2.8-1). This is attributed to the fact that the detected signals represent the magnetic responses of both the surface martensitic case and the ferritic/pearlitic core to the excitation field which could penetrate to a depth (i.e. skin depth) estimated to be 2 mm at 100 Hz. A larger case depth is therefore expected to result in a smaller permeability signal, due to the presence of a high density of defects in the martensitic case, which act as strong pinning sites for magnetic domain walls and in turn reduces the permeability. While the present results indicate the possibility of locating principal stress axes in case hardened components by measuring the stress-induced magnetic anisotropy, further studies are needed to characterize the magnetomechanical effect of the martensitic case, and to identify means to separate the effects of case hardening on residual stress measurements.

STUDY OF THE MAGNETOMECHANICAL EFFECTS IN MARTENSITE AND FERRITE/PearlitE

The magnetomechanical properties of martensitic case and ferritic/pearlitic core of the case-hardened steel samples were measured in order to elucidate the effects of case hardening on the stress dependence of the magnetic properties. Two rectangular strips

![Graph showing magnetic permeability signals versus residual stress components](image)
samples of dimensions 87 mm (l) × 2 mm (h) × 2 mm (w) were cut from the case and core regions of a S45C induction hardened steel rod by EDM to obtain samples with a purely martensitic structure and a ferritic/pearlitic structure, respectively. Ideally, it is preferable to directly measure the changes in magnetic properties of the samples under applied stresses. This proved to be very difficult task, however, as the experimental setup suitable for tensile tests on the strip samples was not available due to the small sample size. Therefore, the magnetomechanical properties of the samples were characterized indirectly by measuring the sample magnetostriction (i.e. the sample strains induced by a magnetic field) based on the Le Châtelier's principle. It states that for small reversible changes, the stress sensitivity of magnetic induction $B$ under a constant field is equal to the rate of change of magnetostriction $\lambda$ with respect to an applied field $H$ under a constant stress [7], i.e.

$$\left(\frac{dB}{d\sigma}\right)_H = \left(\frac{d\lambda}{dH}\right)_\sigma.$$  (2)

Therefore, instead of measuring the induction signal under applied stresses, one can measure the magnetostriction curve $\lambda(H)$ and estimate the stress sensitivity of magnetic induction $(dB/d\sigma)_H$ from the strain derivative $(d\lambda/dH)_\sigma$ using equation (2).

The experimental setup for magnetostriction measurements is shown in Fig. 6. During the measurements, a strip sample was magnetized inside a solenoid using a 0.1 Hz excitation field with a triangular waveform. The sample magnetization was measured using an encircling detection coil with 3000 turns. The sample strain along the field direction was measured using an extensometer with a gage length of 10 mm.

The magnetostriction curves measured from the case and core strips are shown in Fig. 7 for comparison. The case strip shows a substantially smaller magnetostriction than the core strip. The maximum values of the strain derivative were found to be $0.2 \times 10^{-8}$ m/A and $1.2 \times 10^{-8}$ m/A for the case and core strips, respectively, indicating a much weaker magnetomechanical effect in the martensitic case than in the ferritic/pearlitic core of the induction hardened samples. The present results highlight the need to improve stress sensitivity of the SMA technique for measuring residual stresses in deeply hardened components, and to compensate for the effects of case hardening on the measurement parameters before they can be reliably used to estimate the residual stress levels.

**FIGURE 6.** Experimental setup for magnetostriction curve measurements on the strip samples cut from the case and core regions of an induction hardened steel rod. The sample strain under applied field was measured using an extensometer with a gage length of 10 mm.
CONCLUSIONS

The feasibility of applying the stress-induced magnetic anisotropy technique to detect residual stresses in induction hardened steel components has been studied. The results show that the principal stress axes can be readily determined by measuring the angular variation of the effective permeability signal. The permeability signals measured along the principal stress axes correlate with the residual stress levels, but the correlation was found to depend on the case depth of the samples. The magnetomechanical properties of the martensitic case and ferritic/pearlitic core of the material were studied by measuring the magnetostriction curves from the strip samples obtained from the hardened case and unhardened core regions of the induction hardened samples. The martensitic case shows a substantially weaker magnetomechanical effect than the ferritic/pearlitic core. The results highlight the need of further studies to compensate for the effects of case depth on the measurement parameters before they can be used for characterizing residual stresses in case hardened steel components.

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