AIP Journal of Applied Physics

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Citation: Journal of Applied Physics **115**, 17E305 (2014); doi: 10.1063/1.4862095
View online: http://dx.doi.org/10.1063/1.4862095
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/115/17?ver=pdfcov
Published by the AIP Publishing

JOURNAL OF APPLIED PHYSICS **115**, 17E305 (2014)

Barkhausen spectroscopy: Non-destructive characterization of magnetic materials as a function of depth

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(Presented 5 November 2013; received 23 September 2013; accepted 18 October 2013; published online 22 January 2014)

In this study, we conceptually divided a ferromagnetic specimen into layers along its depth. For each layer, we derived a non-linear integral equation that describes the attenuation with frequency and distance of magnetic Barkhausen emissions coming from that layer. We postulate that the Barkhausen spectrum measured at the surface by an induction coil can be expressed as the sum of the individual layer spectra. We show how a non-linear least squares algorithm can be used to recover the properties in individual layers. These are related to stress using an extension to the theory of ferromagnetic hysteresis. We found that the quality of the fit is influenced by the sensitivity of the ferromagnetic material to strain, as well as by the sensor-specimen coupling. The proposed method can be used for the non-destructive characterization of stress as a function of depth in magnetic materials. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4862095]

I. INTRODUCTION

The magnetic Barkhausen noise method is popular for its reliability[1–8] in assessing stress levels in ferromagnetic components when other non-destructive evaluation methods cannot be used to evaluate the specimen under test. The method relies on detecting the magnetic Barkhausen signals, which are electromagnetic noise-like emissions with energy contained mostly in the 20 kHz to 2 MHz range. These emissions are a by-product of discontinuous magnetization changes, which occur when the specimen is subjected to an applied, time-varying magnetic field. The presence of magnetoelastic energy in the lattice, as a result of strain, alters the magnetic permeability and thus the Barkhausen signal. This makes it possible to measure the amplitude of the Barkhausen signals and obtain an estimate of mechanical stress, based on a calibration curve calculated from a series of reference measurements.

Despite the method's success in assessing average stress levels in a structure, there is still a need for the ability to determine depth-specific stress information; this is currently done using a combination of x-ray diffraction and electropolishing, which is, however, destructive. Such an advance would extend the existing Barkhausen technique and thus provide industry with a rapid, non-destructive, cost-effective stress evaluation tool.

In this study, we formulate a system of non-linear integral equations that describe the spectra of Barkhausen signals emanating from different depths inside a specimen. An expression for the resultant signal measured at the surface was derived, and a least-squares fitting algorithm was used to extract stress-related parameters for each depth.

II. THEORY

Consider a specimen of ferromagnetic material with homogeneous and isotropic resistivity ρ. Barkhausen emissions occur over the entire volume that is magnetized by an externally applied magnetic field. They are collectively assumed to have a flat frequency spectrum, such that their average amplitude at the origin V_{orig} is independent of frequency; this is the white noise assumption. Assuming plane wave propagation, as emissions travel towards the surface, they attenuate as a function of both distance and frequency, such that $x = \sqrt{2\rho/\omega\mu}$; where x is the distance at which the amplitude reduces to $1/e$ of its value at the origin, μ is the magnetic permeability seen by emissions as they travel towards the surface, and ω is the angular frequency. In our treatment, we have ignored the phase of Barkhausen emissions and considered only their magnitude. It is possible to conceptually divide the specimen into layers along its depth, with each layer having a unique value of permeability μ and emission amplitude V_{orig}, associated with a certain magnitude of mechanical stress σ present in that layer. As emissions propagate, they attenuate at a rate unique to each layer (in previous treatments and to simplify the problem, we assumed that permeability remained invariant[1,3]).

A. Single emission

It is possible to express the measured emission at the surface, in terms of its amplitude at the origin[1,3]

$$V_{att1}(\omega) = V_{orig1} e^{-\zeta_1 x\sqrt{\omega}}, \tag{1}$$

where $\zeta_1 = \sqrt{\mu/2\rho}$. The above emission occurs in the first layer and thus only passes through that layer, attenuating at an exponential rate proportional to ζ_1. For an emission originating in the second layer, in a similar manner, one can write

$$\begin{aligned} V_{att2}(\omega) &= V_{orig2} e^{-\zeta_2(x-\Delta x)\sqrt{\omega}} e^{-\zeta_1 \Delta x\sqrt{\omega}} \\ &= V_{orig2} e^{-\sqrt{\omega}(\zeta_2(x-\Delta x)+\zeta_1\Delta x)}, \end{aligned} \tag{2}$$

as the emission attenuates at a rate proportional to ζ_2 while it passes through the second layer. The layer thickness is denoted by Δx.

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B. Multiple emissions

Since multiple emissions occur in a layer, by taking the integral over a certain depth range, the combined spectra of all emissions within that range are considered. That gives $V_{att1}(\omega)$ as the component of the signal detected at the surface[1,3]

$$V_{att1}(\omega) = V_{orig1}\int_{x_0}^{x_1} e^{-\zeta_1 x\sqrt{\omega}}dx = -\frac{V_{orig1}}{\zeta_1\sqrt{\omega}}\left(e^{-\zeta_1 x_1\sqrt{\omega}} - e^{-\zeta_1 x_0\sqrt{\omega}}\right). \quad (3)$$

Similarly, for emissions originating in the second layer,

$$V_{att2}(\omega) = V_{orig2}\int_{x_1}^{x_2} e^{-\sqrt{\omega}(\zeta_2(x-\Delta x)+\zeta_1\Delta x)}dx = -\frac{V_{orig2}}{\zeta_2\sqrt{\omega}}\left(e^{-\sqrt{\omega}(\zeta_2 x_2-(\zeta_2-\zeta_1)\Delta x)} - e^{-\sqrt{\omega}(\zeta_2 x_1-(\zeta_2-\zeta_1)\Delta x)}\right). \quad (4)$$

Uncorrelated white noise has a uniformly distributed phase between $-\pi$ and π; we can therefore use the assumption that at the origin the phase is zero (mean value) such that, since dispersive effects are ignored, the resulting phase at the surface is also zero, leading to only constructive interference when all attenuated spectra are summed. By summing the emissions in separate layers, we are also implicitly assume that they are statistically independent. This summation yields the measured spectrum at the surface $V_{meas}(\omega)$, such that

$$V_{meas}(\omega) = \sum_i V_{att_i}(\omega), \quad (5)$$

where V_{att_i} is the Barkhausen signal from the ith layer. One can retrieve the stress state of the material, by fitting the above expression to Barkhausen spectra measured at the surface of a specimen and extracting the value of stress-related parameters ζ and V_{orig}. With this approach, for n total layers, one obtains $2n$ parameters. It is possible to reduce the number of fitting parameters by incorporating a Barkhausen-stress calibration relationship[2,9] into our model for the spectrum.

C. Reducing the number of fitting parameters

It was shown previously[10] that the reciprocal of the peak differential susceptibility $1/\chi'$ varies linearly with stress, via the following relation:

$$\frac{1}{\chi'(0)} - \frac{1}{\chi'(\sigma)} = \frac{3b\sigma}{\mu_0}, \quad (6)$$

where σ denotes stress and b is a magnetostrictive coefficient with units m^2A^{-2}, which connects magnetostriction with magnetization,[11] associated with a quadratic approximation to the $\lambda - M$ curve, and can be obtained using a quasi-static magnetostriction measurement. The above relation can also be used to relate the reciprocal of the peak Barkhausen voltage to stress,[2] such that

$$\frac{1}{V_{orig}(0)} - \frac{1}{V_{orig}(\sigma)} = \frac{3b'\sigma}{\mu_0}, \quad (7)$$

where b' is a modified magnetostriction coefficient with units $m^2V^{-1}A^{-2}$. Its value depends on the frequency of magnetization, strength of magnetizing field and sensitivity of the Barkhausen probe, and is, thus, not easily determinable. By dividing (6) by (7), we yield

$$\frac{\dfrac{1}{\chi'(0)} - \dfrac{1}{\chi'(\sigma)}}{\dfrac{1}{V_{orig}(0)} - \dfrac{1}{V_{orig}(\sigma)}} = \frac{b}{b'}. \quad (8)$$

Solution for $V_{orig}(0)$ yields

$$V_{orig}(\sigma) = -\frac{b}{b'}\frac{1}{\dfrac{1}{\chi'(0)} - \dfrac{1}{\chi'(\sigma)} - \dfrac{b}{b'}\dfrac{1}{V_{orig}(0)}}, \quad (9)$$

where b, $\chi'(0)$, and $V_{orig}(0)$ can be experimentally determined. The differential susceptibility at some value of unknown stress $\chi'(\sigma)$ is related to μ_r and ζ such that

$$\chi'(\sigma) \cong \mu_r'(\sigma) = 2\rho\zeta^2(\sigma)/\mu_0. \quad (10)$$

By substituting (9) into (3) and (4) (and consequently (5)), we are reducing the number of fitting parameters from $2n$ to $n+1$.

III. SIMULATION OF BARKHAUSEN SPECTRA EMANATING FROM VARIABLE STRESS-DEPTH PROFILES

To establish a relationship between stress and relative permeability, an extension to the theory of ferromagnetic hysteresis[10] was used

$$\mu_r' \cong \chi' = \frac{M_s}{3a - \left(\alpha + \dfrac{3b(\sigma + \sigma_{offset})}{\mu_0}\right)M_s}, \quad (11)$$

where a is a parameter which characterizes the shape of the anhysteretic magnetization, α is a mean field term that quantifies interdomain coupling, σ is the stress present in the sample, and M_s is the saturation magnetization. Plots of μ_r' and its reciprocal versus stress can be seen in Fig. 1.

To simulate non-uniform strain, each layer was assigned a different value of stress, by modulating the value of the differential permeability and thus the parameter ζ, which was defined in Sec. III. Different values of stress lead to different y-axis intercepts and spectrum shapes, as shown in Fig. 2. To simulate a practical measurement and thus make the treatment more realistic, Gaussian random noise was added to the simulated spectra. A least squares algorithm was used to obtain the estimates $\hat{\zeta}_1$ and $\hat{\zeta}_2$, from which the stress can be calculated, using the linear relationship shown in Fig. 1.

IV. DISCUSSION

From the results of Fig. 1, it is evident that tensile stress leads to an increase in the Barkhausen signal amplitude at

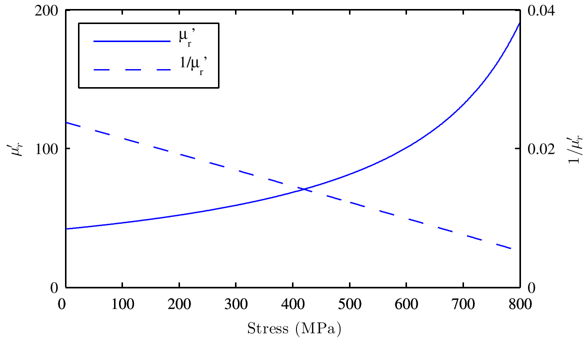

FIG. 1. Calibration relationship, relating relative differential permeability, and its reciprocal to stress. We set $a = 2019.620\,\mathrm{Am^{-1}}$, $M_s = 2.485 \times 10^5\,\mathrm{Am^{-1}}$, and $\alpha = 1.9119 \times 10^{-2}$, which are typical values for a soft steel. The values of b and σ_{offset} were set to $1 \times 10^{-17}\,\mathrm{m^2A^{-2}}$ and -800 MPa, respectively.

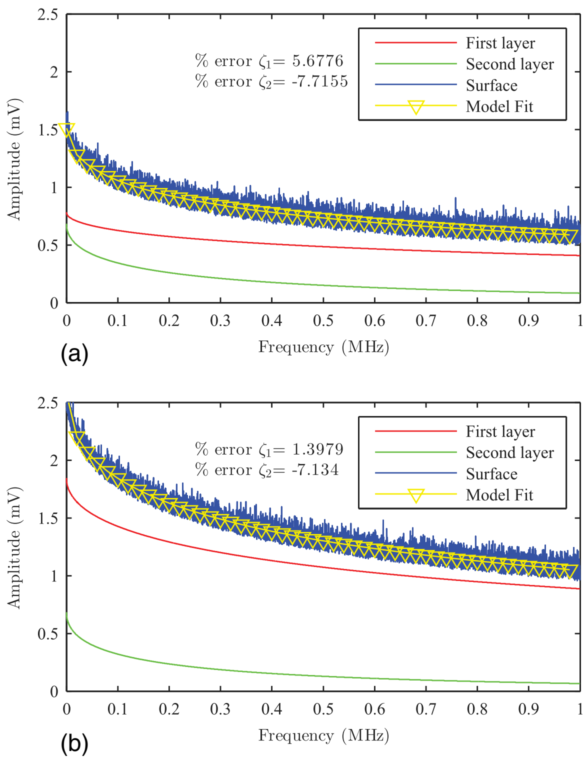

FIG. 2. Least-squares fit to simulated Barkhausen spectra, of the non-linear expression of (5) combined with the relationship in (9), for different stress magnitudes in the first and second layer. The value of b', which quantifies the sensitivity of the sensing element, was set to $1 \times 10^{-22}\,\mathrm{m^2V^{-1}A^{-2}}$. The parameters $\chi'(0) \cong \mu_r'(0)$, ρ, and $V_{orig}(0)$ were set to 42, 0.22 $\mu\Omega$m, and 10 V, respectively. The layer thickness Δx was set to 50 μm.

the origin. This is true for steels with positive magnetostriction, while in the case of negative magnetostriction, the converse is true. While the parameter b solely relies on the magnetomechanical coupling within the specimen and therefore can be accurately determined via a quasi static magnetostriction measurement, b' relies also on the probe-specimen coupling and amplification factor of the sensing equipment. The magnetization in a material with a higher value of b is more sensitive to changes in strain, and, as a result, the Barkhausen amplitude at the origin becomes larger. The amplitude of the signals at their origin also affects the accuracy of the fitting algorithm. It follows that detection of stress becomes easier and more reliable when using a well-coupled, sensitive sensing element on steels with relatively high magnetostriction.

V. CONCLUSION

In this work, we derive the theoretical framework for a magnetic spectroscopy method that can be used to nondestructively assess the local stress state by separating the Barkhausen signals originating in different regions inside a ferromagnetic specimen. This is particularly useful in aerospace applications where tensile stresses on component surfaces may initiate crack formation, possibly leading to failure and loss of human life.

ACKNOWLEDGMENTS

This research was undertaken with support of a Graduate Fellowship for O. Kypris from the Takano Foundation and was also supported by the James and Barbara Palmer Endowment in the Department of Electrical and Computer Engineering at Iowa State University.

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