Analysis of Barkhausen effect signals in surface-modified magnetic materials using a hysteretic-stochastic model

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The effects of microstructural variations with depth on Barkhausen effect (BE) signals in surface-modified ferrous materials have been studied through measurements and simulations based on a hysteretic-stochastic model. The BE signals measured from an unhardened sample show a peak near zero field. In contrast, the BE signals in surface-hardened samples with different case depths exhibit low-amplitude pulses near zero field and a peak at a high reverse field, which are attributed to irreversible magnetization processes in the soft core and the hardened surface layer, respectively. Theoretical analysis showed that the model parameters k and ξ, which describe the domain-wall pinning strength and the range of interaction of a domain wall with pinning sites, respectively, are related to each other as $\xi = a \, \rho^{-1/2} = b/k$ via the pinning site density ρ, where a and b are constants. The relationship was used to simulate BE signals of the surface-hardened samples as a sum of signals generated at different depths by taking into account signal attenuation due to eddy current shielding. The simulated results were found to exhibit the general features observed in the experimental results. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2163272]

I. INTRODUCTION

In this work, a model description of Barkhausen effect (BE) signals based on the hysteretic-stochastic model was presented for simulation and analysis of BE signals in surface-modified magnetic materials. Barkhausen effect measurements have long been recognized as one of the promising techniques for evaluation of surface conditions of magnetic materials such as surface-hardened steels. Widespread applications of the technique have, however, been hampered by the complexity of the phenomenon that made quantitative analysis of experimental BE data for information on structural conditions (e.g., defect density or grain size) a difficult task. The stochastic process model of domain wall dynamics[1,2] recently developed offers a mathematical description of the intrinsically random nature of Barkhausen emissions. The model has been extended by combining it with the theory of magnetic hysteresis so that it becomes possible to simulate BE signals over an entire hysteresis cycle.[3] The resulting model provides a platform for developing theoretical description of the dependence of BE signals on material conditions such as microstructure (e.g., dislocation density[4]) or stress state.[5]

Despite the advances in theoretical modeling, quantitative analysis of BE in surface modified materials remains a challenge for two reasons. BE signals in general show complex dependence on microstructure. The situation is further complicated in the case of surface-modified materials because of the variations in microstructure with depth. Also, the detected BE signals comprise signals generated at different depths below the surface, which are increasingly attenuated with depth due to eddy current shielding. This needs to be considered when analyzing BE signals in surface-modified materials such as induction or case hardened steels, which consist of a hardened surface layer and a soft core with different magnetic properties.

In this work, the BE signals in a series of induction-hardened steel rods with different case depths were studied. For each hardened rod, magnetic hysteresis and BE signals were measured from samples obtained at different depths, and the results were analyzed by comparison with model simulations to obtain depth profiles of domain wall pinning strength. Such information was used to simulate BE signals in the hardened steel rods based on a model that takes into account the attenuation of BE signals with depth.

II. EXPERIMENTAL DETAILS

A series of Fe-C rods was induction-hardened to produce a microstructure consisting of a hardened surface layer of martensite and a soft ferrite/pearlite core. The thicknesses of the hardened surface layer of the rods were characterized by measuring the microhardness as a function of depth below surface. The measured nominal case depths (the depth corresponding to hardness of 50 in the Rockwell C scale) and the midpoints of the hardness depth profiles (determined by fitting an error function to the hardness depth profiles) are shown in Table I. Hysteresis loops and BE signals were measured from the rods using a 2 Hz sinusoidal field of amplitude 27.9 kA/m (350 Oe). An encircling induction coil was used to detect the magnetic signals. The induced emf was either integrated to obtain the hysteresis loop, or filtered (frequency passband: $10-100$ kHz) and amplified (total gain: 50 dB) to obtain BE signals.

Rectangular strip samples that are 20 mm long, 1 mm wide, and 0.4 mm thick were cut from each rod at different depths using an electric discharge machine (EDM). Hyster-

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TABLE I. Normal case depth d_N, midpoint of hardness depth profile d_{mid}, coercivity H_C, hysteresis loss W_H, normalized rms values of BE signals from measurements V_{BE}^{exp} and model simulations V_{BE}^{sim} for an unhardened (case depth=0) and a series of induction-hardened steel rods.

d_N (mm)	d_{mid} (mm)	H_C (A/m)	W_H (J/m^3)	V_{BE}^{exp}	V_{BE}^{sim}
0.00	0.0	828	8897	1.000	1.000
0.36	0.38	1114	10458	0.693	0.659
1.07	1.03	1162	15945	0.681	0.648
1.47	1.49	1345	16246	0.664	0.649
1.88	1.90	1966	16807	0.661	0.649

esis loop and BE measurements were performed on the strip samples to obtain depth profiles of magnetic properties of the hardened rods.

III. MODEL DESCRIPTION OF THE BARKHAUSEN SIGNAL

The BE signals in surface-hardened steel rods were simulated based on the hysteretic-stochastic process model,[3] which was modified in this work to take into account the variations of pinning strength and signal attenuation with depth due to eddy current damping. According to the model, the characteristics of BE signals are determined by two model parameters, A and ξ, which correspond to the intensity of the short-range fluctuation of the local pinning field experienced by a moving domain wall and the range of interaction of a domain wall with pinning sites, respectively. For materials with a high density of pinning site, the interaction range ξ is determined by the average spacing between pinning sites given by $\rho^{-1/2}$, i.e., $\xi = a\,\rho^{-1/2}$, where ρ is the density of linear pinning sites (e.g., dislocations) defined to be number of pinning sites per unit area, and a is a proportional constant. It has been proposed in a recent theoretical study of magnetic hysteresis that the pinning coefficient k, which characterizes average domain wall pinning strength, depends on grain size d and dislocation density ρ as $k = (m + n/d)\rho^{1/2}$, where m and n are constants.[4] It follows that ξ is proportional to $1/k$, and k can be extracted from hysteresis loops measured at different depths to determine the depth profile of ξ so that BE signals $V_{BE}(H,x)$ as a function of applied field H at different depths x can be simulated. The BE signals V_{BE}^{total} detected from the entire hardened rod can then be calculated as

$$V_{BE}^{total}(H) = A \int_0^R 2\pi(R - x)$$

$$\times \left(\int_{f_1}^{f_2} V_{BE}(H,x) e^{-\sqrt{\pi\sigma\mu_0\mu_r f}x} df \right) dx, \qquad (1)$$

where the factor $e^{-\sqrt{\pi\sigma\mu_0\mu_r f}x}$ accounts for signal attenuation with depth x, σ is the conductivity, μ_r is the relative permeability, which varies with depth for surface-modified materials, R is the radius of the steel rods, f is the frequency, f_1 and f_2 are the lower and upper cutoff frequencies used for filtering the detected BE signals, and A is the voltage amplification used in BE measurements.
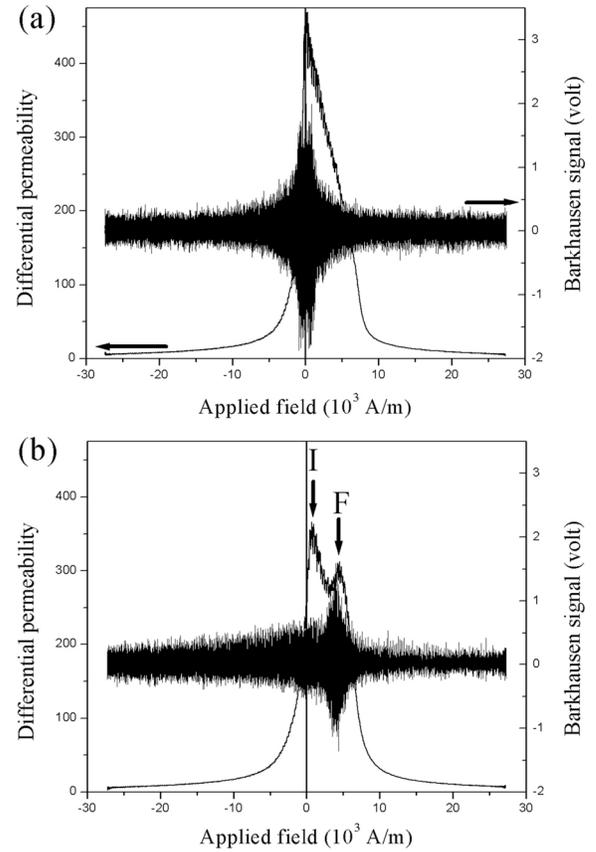

FIG. 1. Plots of the differential permeability and BE signal as a function of applied field for the (a) unhardened sample, and (b) surface hardened sample with a nominal case depth of 0.38 mm.

IV. RESULTS AND DISCUSSION

As shown in Table I, the coercivity and hysteresis loss of the hardened rods increase with case depth. It was found from the plots of differential permeability and BE signal as a function of applied field that there are systematic changes in the magnetization reversal processes as a result of surface hardening. The permeability of the unhardened rod shows a sharp peak near zero applied field where the Barkhausen signal also shows a maximum [Fig. 1(a)]. In contrast, the permeability profiles of all the surface hardened rods consist of two peaks. An example is given in Fig. 1(b), which shows the permeability and BE signals for the sample with a nominal case depth of 0.36 mm. The initial peak position (labeled I) coincides with the coercivity of the unhardened rod (828 A/m), whereas the final peak (labeled F) occurs at a higher reverse field (3980 A/m). As the case depth increases, the initial peak of the permeability profiles gradually shifts to a higher field and decreases in magnitude, while the final peak height increases. The BE signals of all surface hardened rods show low-amplitude pulses near zero field and a narrow peak [e.g., Fig. 1(b)] that coincides with the final peak of the permeability profile.

The rms BE signal voltage measured from the strip samples that were cut from the rods at different depth are shown in Fig. 2 for comparison. All the hardened rods show weak BE signals in the case layer due to the high densities of defects (e.g., dislocations) which act as pinning sites for domain walls. The BE signal levels increase significantly near
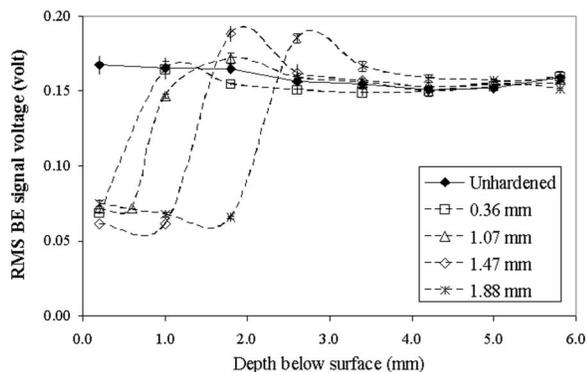
FIG. 2. Variation of the rms BE signal voltage with depth for the unhardened and surface-hardened samples with different case depths.

FIG. 4. Simulated BE signal for the hardened steel sample with a nominal case depth of 0.36 mm.

the case depths of the samples where the samples' microstructure transformed from martensite to ferrite/pearlite with a substantially lower dislocation density. Variation in domain wall pinning strength with depth was studied by analyzing the measured hysteresis loops of the strips using a hysteresis model to extract the pinning coefficient k.[6] As shown in Fig. 3, the pinning coefficient k closely follows the coercivity, and they both decrease substantially near the nominal case depths of the samples to low values in the core that are comparable to the coercivity (828 A/m) of the unhardened rod.

The effects of surface hardening on BE signals can be interpreted as follows. For the unhardened rod, which has a ferrite/pearlite structure, magnetization reversal proceeds mainly by irreversible domain wall processes near the coercive field, giving rise to a sharp peak in the permeability profile and strong BE signals in the low field region [<1.5 kA/m, Fig. 1(a)]. In the hardened rods, magnetization reversal first takes place in the ferrite/pearlite core, and then in the martensitic surface layer at a higher reverse field due to a higher pinning site density. This accounts for the formation of the initial and final peaks of the permeability profile [Fig. 1(b)]. The low-amplitude BE pulses in the low field region and the strong BE signals observed at higher reverse field [Fig. 1(b)] are attributed to irreversible domain wall processes in the core and the surface layer, respectively. The relatively small contribution of the BE signals from the core
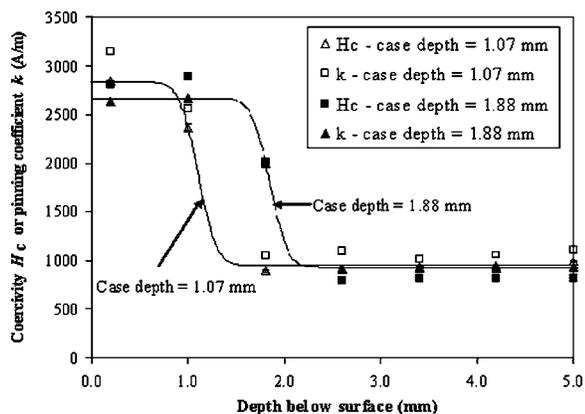
is attributed to the fact that the signals are more attenuated by eddy current damping than those generated in the surface layer.

This interpretation is supported by simulating BE signals for the hardened rods using Eq. (1). Values of the relative permeability μ_r and pinning coefficient k at different depths were extracted from the hysteresis loops measured from the strips to simulate BE signals $V_{BE}(H, x)$ at different depths x. The total BE signals V_{BE}^{total} were then calculated for the entire rod. As shown in Fig. 4, the simulated BE signals contain low-amplitude pulses near zero field, and a peak at high reverse field as observed in the experimental results [Fig. 1(b)]. The rms values of the simulated BE signals exhibit a similar dependence on case depth as the experimental data (Table I). The measured BE signals of the hardened samples are significantly lower than the unhardened samples, and decrease only modestly with increasing case depth. This can be understood in terms of the small information depth associated with the frequency range (10 − 100 kHz) used in the BE measurements. It was estimated that the skin depth at 10 kHz is 0.29 mm (for $\sigma = 5 \times 10^6$ Ωm and $\mu_r = 60$) and that according to Eq. (1) for the sample with a case depth of 0.38 mm the BE signals generated in the core (which occupies 87 volume percent of the whole rod) only contributed to 5% of the total signal. This suggests that the detected BE signals from the hardened rods came primarily from a surface layer thinner than the nominal case depths of the hardened rods and therefore the signals only decrease slightly with case depth.

FIG. 3. Coercivity and pinning coefficient k vs depth for the surface-hardened samples with nominal case depths of 1.07 mm and 1.88 mm.

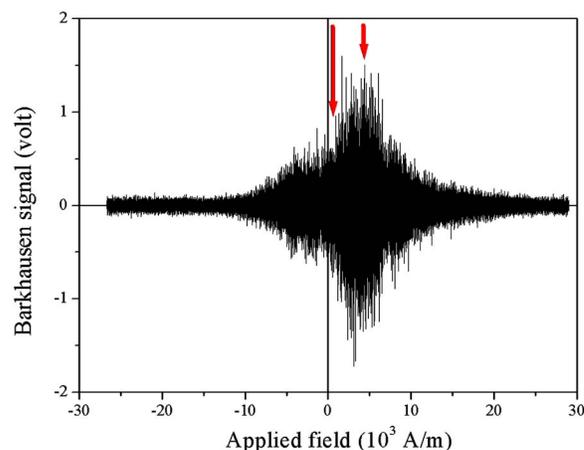[1]G. Bertotti, Phys. Rev. B **39**, 6737 (1989).
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