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Modeling the interrelating effects of plastic deformation and stress on magnetic properties of materials

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A model has been developed that describes the interrelating effects of plastic deformation and applied stress on hysteresis loops based on the theory of ferromagnetic hysteresis. In the current model the strength of pinning sites for domain walls is characterized by the pinning coefficient k_{eff} given by $k_{\mathrm{eff}}=k_0+k'\sigma$. The term k_0 depicts pinning of domain walls by dislocations and is proportional to ρ^n, where ρ is the number density of dislocation which is related to the amount of plastic strain, and the exponent n depends on the strength of pinning sites. The second term $k'\sigma \propto -3/2\lambda_s/2m\sigma$, where m is magnetization and λ_s is magnetostriction constant, describes the changes in pinning strength on a domain wall induced by an applied stress σ. The model was capable of reproducing the stress dependence of hysteresis loop properties such as coercivity and remanence of a series of nickel samples which were pre-strained to various plastic strain levels. An empirical relation was found between the parameter k_0 and the plastic strain, which can be interpreted in terms of the effects on the strength of domain wall pinning of changes in dislocation density and substructure under plastic deformation.
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I. INTRODUCTION

A model description of the effects of plastic deformation and applied stress on hysteresis loop has been developed based on the theory of ferromagnetic hysteresis.[1] It is well established that the magnetic properties of materials such as coercivity and remanence are sensitive to both microstructure and stress state of the materials,[2,3] and that a material can exhibit different stress dependence of magnetic properties depending on the structural conditions (e.g., hardness) of the material.[4,5] Several models have been developed to account for the effects on magnetic properties of either applied stresses[6] or microstructure such as dislocation density or grain size.[7] In this work experimental and theoretical studies were performed to investigate the stress dependence of magnetic properties in materials subjected to different amounts of plastic deformation. A model was developed by incorporating the effects of plastic deformation and applied stress on domain wall pinning into the theory of magnetic hysteresis.[1] The extended model was found to be capable of reproducing the stress dependence of the magnetic properties of nickel samples which were pre-strained to various plastic strain levels.

II. EFFECTS OF MICROSTRUCTURE AND APPLIED STRESS ON DOMAIN WALL PINNING

The model description of the effects of stress and microstructure on magnetic properties was developed based on the theory of ferromagnetic hysteresis,[1] which provides the basis for linking macroscopic magnetic properties to microscopic magnetization processes such as domain wall motion. According to the theory the energy E_{pin} dissipated through pinning and unpinning of a domain wall is proportional to the change in magnetization m and the pinning coefficient $k_0 = n_0\langle\varepsilon_0\rangle/2m$, where n_0 is the pinning site density and $\langle\varepsilon_0\rangle$ is the average pinning energy. It has been shown in a previous study[8] that the average pinning energy $\langle\varepsilon_0\rangle$ can be influenced by an applied stress which induces changes in the anisotropy energies of the domains on either side of the domain wall due to the magnetoelastic coupling. This in turn alters the local energy barrier that a domain wall needs to overcome before it moves irreversibly from one pinning site to another. The pinning coefficient k_{eff}, which characterizes the strength of the pinning site, becomes dependent on the applied stress σ and is given by

$$k_{\mathrm{eff}}=k_0+k'\sigma, \tag{1}$$

where $k'=-3/2b\lambda_s$, b is a constant factor, and λ_s is the magnetostriction constant. The first term k_0 characterizes the strength of domain wall pinning by structural defects such as dislocations. The second term $k'\sigma$ describes the stress-induced changes in pinning strength on a domain wall, where the factor b is dependent on the material conditions such as microstructure. According to Eq. (1), k_{eff} decreases with tension but increases with compression for materials with positive λ_s (e.g., iron at low field strengths). Such stress dependence of k_{eff} has been found in a previous study.[8]

The structural effects can be incorporated into the hysteresis model through the model parameter k_0. For single-phase magnetic materials the most important microstructural factors affecting magnetic properties are grain size and number density of dislocations, since grain boundaries and dislocations act as pinning sites for domain walls. Empirical relationships between these microstructural features and hysteresis loop properties have been reported in previous studies,[9,10] and the general consensus is that coercivity H_c is inversely proportional to grain size[9] and is proportional to

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the square root of dislocation density.[10] Since the pinning coefficient is approximately equal to coercivity for soft magnetic materials,[11] it is reasonable to assume that k_0 has the same dependence as H_c on grain size and dislocation density ρ, i.e.

$$k_0 \propto \rho^{1/2}. \tag{2}$$

This equation has been adopted in a recent modeling study of the effect of grain size and dislocation density on magnetic properties of steels.[7] In this approach, the pinning strength parameter k_0 can be correlated with the macroscopic material conditions such as the amount of plastic deformation ε, which is related to the dislocation density. In this case, one can write

$$k_0 = a\varepsilon^n, \tag{3}$$

where a is a constant factor and n is the index characterizing how domain wall pinning varies as dislocations multiply and evolve into dislocation substructures under plastic deformation.

III. PROCEDURES

A series of pure nickel samples were first annealed at 500 °C for 2 h. One sample was kept in the annealed condition while the others were pre-strained to various plastic tensile strain levels ε_p using a servo-hydraulic mechanical testing system. *In situ* hysteresis loop measurements were made on the pre-strained samples under various tensile stresses within the elastic limits of the samples. During the measurement a 2 Hz sinusoidal magnetizing field was applied to the sample using a solenoid. A Hall effect sensor was used to measure the tangential magnetic field H at the sample surface. The output of a search coil encircling the sample was integrated to obtain the hysteresis loop.

Using model calculations, hysteresis loops were simulated for various stress levels using the following values for the model parameters: $M_s = 5.04 \times 10^5$ A/m, $c = 0.1$, $a = 1300$ A/m, and $\alpha = 0.006$. The values of k_{eff} were determined by obtaining the best fit to the experimental hysteresis loops.

IV. RESULTS AND DISCUSSION

It was found that the effects of plastic deformation and applied stress on the hysteresis loops of the nickel samples can be reproduced using the extended hysteresis model. Examples are given in Fig. 1, which shows the measured and modeled hysteresis loops for the sample pre-strained to $\varepsilon_p = 736 \times 10^{-6}$ at $\sigma = 0$ and 50 MPa. The modeled hysteresis loops were found to agree with the experimental data in the low field regime (i.e., at field strengths below the coercive field). Discrepancies between the modeled and measured results were nevertheless observed at the knee of the hysteresis loops, in particular when the samples were under tensile stresses (Fig. 1). The shape of the measured hysteresis loops in the high field regime suggests that the magnetization reversal processes involved mainly reversible rotation of domain magnetization towards the applied field against the

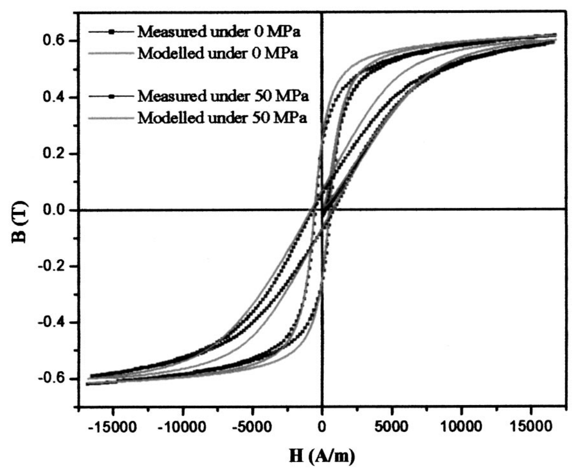

FIG. 1. Measured and modeled hysteresis loops under 0 and 50 MPa for the nickel sample pre-strained to 736×10^{-6}.

stress-induced anisotropy. This process is not accounted for in the previous model equation, which is based primarily on the consideration of domain wall motion.

As shown in Fig. 2, the coercivity of all samples increased while the remanence decreased with tensile stress, except for the sample with $\varepsilon_p = 0$ where the remanence increased initially and then decreased as the applied stress was further increased. The stress dependence of coercivity and

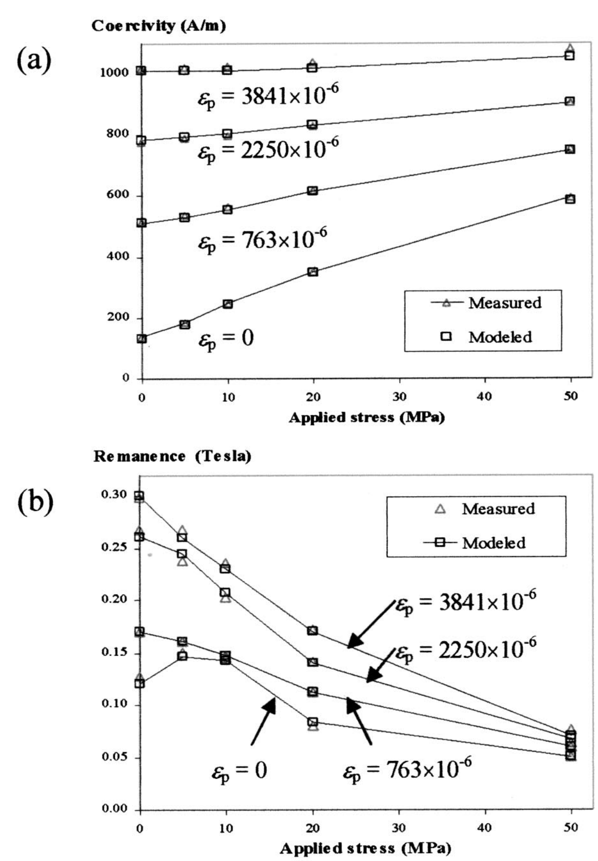

FIG. 2. Variations in (a) coercivity and (b) remanence with applied stress for the nickel samples plastically deformed to various plastic strain levels ε_p prior to the *in situ* hysteresis measurements under applied stresses.

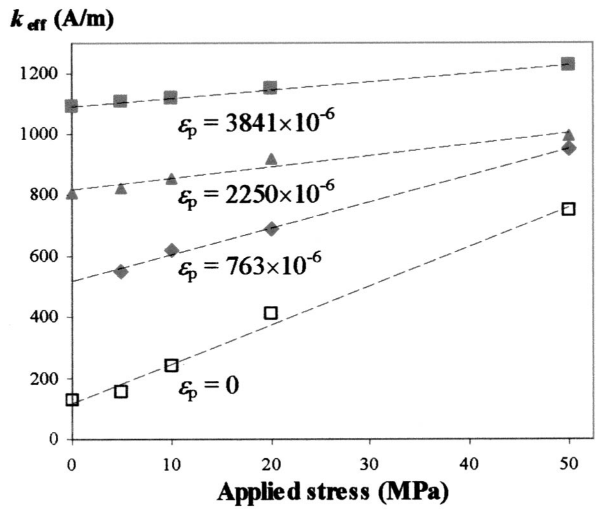

FIG. 3. Dependence of the pinning coefficient k_{eff} on applied stress for samples pre-strained to different plastic strain levels. The dotted lines represent least-square linear fits to the data.

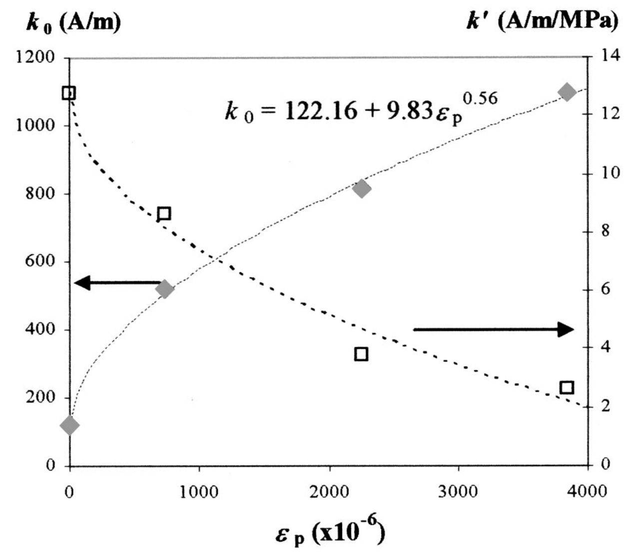

FIG. 4. Plot of the model parameters k_0 and k' as a function of the initial plastic strain ε_p of the samples. The dotted curves were obtained by empirical curve fitting to the data.

remanence was reproduced in the simulated hysteresis loops for all samples. Samples pre-strained to higher plastic strain levels in general showed larger values of coercivity and remanence. This is attributed to the multiplication of dislocations caused by plastic deformation. Dislocations are associated with localized strain field which interacts with domain walls via the magnetoelastic coupling. Increase in dislocation density therefore results in stronger domain wall pinning and hence higher coercivity and remanence.

The pinning coefficient k_{eff} exhibits dependence on applied stress and plastic deformation similar to that of the coercivity. It is evident in Fig. 3 that the pinning coefficient k_{eff} increases linearly with applied stress, in agreement with Eq. (1) which indicates that the pinning strength increases with tensile stress for materials with negative magnetostriction constant such as nickel. The effects of plastic deformation on domain wall pinning strength were studied by examining the relation between the plastic strain level and the factors k_0 and k', which characterize the strength of domain wall pinning at structural defects and the stress dependence of domain wall pinning strength, respectively. The values of k_0 and k' were determined by least-squares fitting of Eq. (1) to the results in Fig. 3. As shown in Fig. 4, the parameter k_0 increases while k' decreases with the amount of plastic deformation. It was found by empirical curve fitting that the factor k_0 is related to the plastic strain level ε_p by $k_0 \propto \varepsilon_p^{0.56}$. Comparing this relationship with Eq. (2), the present result seems to suggest that the number density of dislocations increases approximately linearly with plastic strain ε_p within the range of the plastic deformation investigated in this study. Similar relations between strain and dislocation density have been observed during the early stages of deformation in materials such as lithium fluoride.[12]

The dependence of the model parameter k' on plastic deformation found in the present study suggests that the effects of applied stresses and microstructure on domain wall pinning are interrelated. The effect of an applied stress on magnetization can be treated as an effective field which, in the presence of an externally applied field, may induce irreversible domain wall motion if the total internal field is large enough to overcome the pinning force. When a material is subjected to plastic deformation, the dislocations rapidly multiply, which then develop into substructures such as dislocation tangles and cells if the material has a high stacking fault energy (e.g., nickel). These deformation substructures consist of highly dense dislocations, and they are therefore stronger pinning sites for domain walls than the individual dislocations. As a result the coercivity increases. This also results in a decrease in the influence of the applied stress on domain wall pinning, since the stress-induced changes in local energy barrier to domain wall motion become less significant compared to the pinning energy of the existing dislocation substructures.

ACKNOWLEDGMENT

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