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Abstract
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Keywords
Ames Laboratory, CNDE, Magnetic films, Coercive force, Magnetic moments, Magnetization reversals, Metallic thin films

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Micromagnetic modeling of the effects of stress on magnetic properties

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A micromagnetic model has been developed for investigating the effect of stress on the magnetic properties of thin films. This effect has been implemented by including the magnetoelastic energy term into the Landau–Lifshitz–Gilbert equation. Magnetization curves of a nickel film were calculated under both tensile and compressive stresses of various magnitudes applied along the field direction. The modeling results show that coercivity increased with increasing compressive stress while remanence decreased with increasing tensile stress. The results are in agreement with the experimental data in the literature and can be interpreted in terms of the effects of the applied stress on the irreversible rotation of magnetic moments during magnetization reversal under an applied field. [DOI: 10.1063/1.1363604]

I. INTRODUCTION

Magnetic thin films find application in the areas of information storage and sensor devices. Computational micromagnetics has proven to be a useful tool since it leads to a deeper understanding of magnetization processes in thin films through visualization of the simulated reversal processes for the magnetic moments.

Although stress has an important role in magnetism,[1] it is surprising that modeling of magnetization processes in thin films in the presence of external stresses has received little attention. A magnetomechanical model has been developed by Sablik *et al.*[2] and by Jiles[3] to describe the stress effect on magnetic properties of bulk materials. However, recent experimental results obtained from nickel thin films[4] showed stress dependence of the hysteresis loop properties different from the predictions of that model. Such differences can be attributed to the different mechanisms of magnetization reversal in thin films and bulk materials.[4] In order to investigate the stress effect in magnetic thin films, a stress dependent micromagnetic model based on the Landau–Lifshitz–Gilbert (LLG) equation[5] has been developed. The magnetoelastic energy term[6] induced by external stress was included in the Gibb's free energy of the material. The magnetic moment configuration was calculated by solving the LLG equation. The modeling results show that the hysteresis loop properties, such as coercivity and remanence, change with applied stress in a way which is different from that observed in bulk magnetic materials. These results are in agreement with experimental data on nickel thin films reported in the literature.[4]

II. MICROMAGNETIC MODEL OF STRESS EFFECT

In the micromagnetics approach an equilibrium magnetization configuration of a ferromagnetic body can be found by minimizing its total Gibbs free energy E_{tot} which can be written as a sum of several energy contributions:

$$E_{\mathrm{tot}}=E_{\mathrm{field}}+E_{\mathrm{exch}}+E_{\mathrm{anis}}+E_{\mathrm{demag}}+E_{\mathrm{me}}, \tag{1}$$

where E_{field} is the energy contribution due to an external field (the Zeeman energy term), E_{exch} is the exchange energy, E_{anis} is the magnetocrystalline anisotropy energy, E_{demag} is the demagnetizing or stray field energy, and E_{me} is the magnetoelastic energy. In general, the effective field H_{eff} acting on a given magnetic moment can be defined as the derivative of energy with respect to magnetization,

$$H_{\mathrm{eff}}=-\frac{1}{\mu_0}\frac{\partial E}{\partial M}. \tag{2}$$

Differentiating Eq. (1) gives an effective field H_{eff} which consists of several components:

$$H_{\mathrm{eff}}=H_{\mathrm{field}}+H_{\mathrm{exch}}+H_{\mathrm{anis}}+H_{\mathrm{demag}}+H_{\mathrm{me}}, \tag{3}$$

where each term on the right-hand side of Eq. (3) represents a field which is the derivative of the corresponding energy terms in Eq. (1) with respect to magnetization. At equilibrium, the magnetization vector M is parallel to H_{eff} and the total free energy reaches a minimum. The magnetization configuration satisfying this condition is usually computed by integration of the LLG equation which is given by

$$\frac{dM}{dt}=-\gamma M\times H_{\mathrm{eff}}-\frac{\alpha}{M_s}M\times(M\times H_{\mathrm{eff}}), \tag{4}$$

where M_s is the saturation magnetization, γ is the gyromagnetic ratio, and α is a damping coefficient.

When the magnetic material is under applied stress, the magnetoelastic energy E_{me} induced by the stress has to be included in the Gibbs free energy. For cubic materials, the magnetoelastic energy E_{me} under applied uniaxial stress σ is given by[6]

$$E_{\mathrm{me}}=-\tfrac{3}{2}\lambda_{100}\sigma(\alpha_1^2\gamma_1^2+\alpha_2^2\gamma_2^2+\alpha_3^2\gamma_3^2)-3\lambda_{111}\sigma \times(\alpha_1\alpha_2\gamma_1\gamma_2+\alpha_2\alpha_3\gamma_2\gamma_3+\alpha_3\alpha_1\gamma_3\gamma_1), \tag{5}$$

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where λ_{100} and λ_{111} are the magnetostriction coefficients of the material along the $\langle 100 \rangle$ and $\langle 111 \rangle$ directions, respectively, α_1, α_2, and α_3 are the direction cosines of M, and γ_1, γ_2, and γ_3 are the direction cosines of the uniaxial stress axis with respect to the crystal axes. The corresponding effective field H_{me} can be calculated from Eq. (2) and then incorporated into Eq. (4) to determine how the magnetic moments change under the magnetic field in the presence of applied stress according to this model.

III. RESULTS AND DISCUSSION

The model system is a two-dimensional grid of width a (x direction) and height b (y direction). The grid is divided into a number of square cells. The magnetic moments are positioned at the center of each cell. Each of these magnetic moments is free to rotate in three dimensions but its magnitude is kept constant. The Von Neumann type boundary condition ($\partial M/\partial n = 0$) is assumed in the calculation.

The magnetic simulation is based on the algorithm provided by the National Institute of Standards and Technology (NIST)[7] and the material parameters of nickel ($M_s = 0.48 \times 10^6\ \mathrm{A\,m}^{-1}$, $K_1 = -5.7 \times 10^3\ \mathrm{J\,m}^{-3}$, $\lambda_{100} = -46 \times 10^{-6}$, $\lambda_{111} = -24 \times 10^{-6}$) were used. A 2 μm wide, 0.5 μm high, 20 nm thick rectangular element with cell size of 20 nm was used in the present study. The demagnetizing field was obtained by calculating the average field in each cell[7] under the assumption that the magnetization in each cell is constant.[8]

The initial pattern of magnetic moments contained seven domains arranged in a flux closure configuration so that the net magnetization of the model system was zero. Such a domain configuration was chosen arbitrarily and it should not affect the modeled hysteresis loops because the magnetic field amplitude used in the simulation was found to be sufficient to magnetize the system to saturation. Both the stress and the magnetic field were applied along the long axis of the rectangular element (the x direction). The applied field amplitude was 80 kA/m. When calculating the magnetization curves the applied field was incremented (step size = 1600 A/m) in a linear manner. At the end of each field increment, when the magnetic moments attained an equilibrium configuration, the x components of the magnetic moments were summed over the grid to obtain the magnetization component of the entire model system in the x direction which was plotted against the applied field to obtain the hysteresis loop.

Figures 1 and 2 show the simulated hysteresis loops for a nickel thin film under different levels of tensile and compressive stress. The hysteresis loops displayed systematic changes under different levels of applied stress. Figure 3 shows the variations of coercivity with applied stress. The results show that the coercivity increased significantly with increasing compressive stress and decreased slightly with increasing tensile stress. The modeling results are in good qualitative agreement with the experimental data on nickel film found in the literature[4] but are quite different from those reported on bulk nickel samples.[9] Such differences can be attributed to the different effects of applied stress on two different mechanisms of magnetization reversal, namely, irreversible domain rotation and domain wall movement.[10] It has been pointed out that when the reversal process is dominated by irreversible domain rotation, the field required to switch the domain magnetization (i.e., the coercivity) will increase if the easy axis induced by the external stress is parallel to the applied field (e.g., compressive stress applied to nickel along the field direction).[10] This can be explained by considering the coherent rotation of domain magnetization against the stress-induced uniaxial anisotropy under an applied field. As described by other anisotropic models, such as the Stoner–Wolfarth model,[11] the critical field at which the domain magnetization switches abruptly increases with the anisotropy. Therefore it was expected that the coercivity of the model system, for which the magnetization reversal process involved is essentially irreversible rotation of magnetic moments, would increase with increasing compressive stress along the field direction. Similarly the coercivity was expected to decrease when the easy axis induced by the external stress was perpendicular to the applied field (e.g., tensile stress on nickel along the field direction). On the other hand, for bulk materials, the predominant mechanism is do-

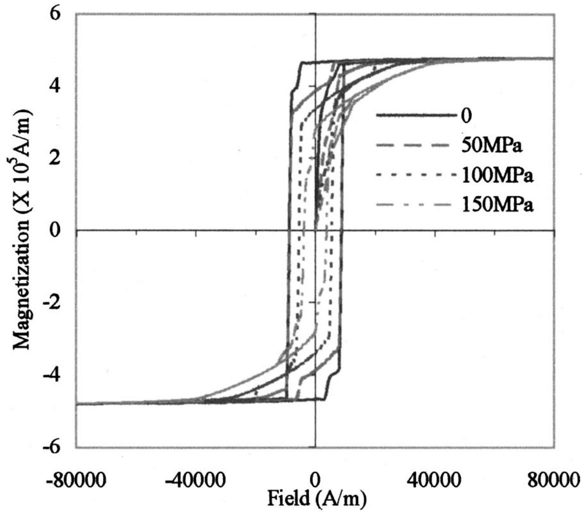

FIG. 1. Hysteresis loops modeled under tensile stress.

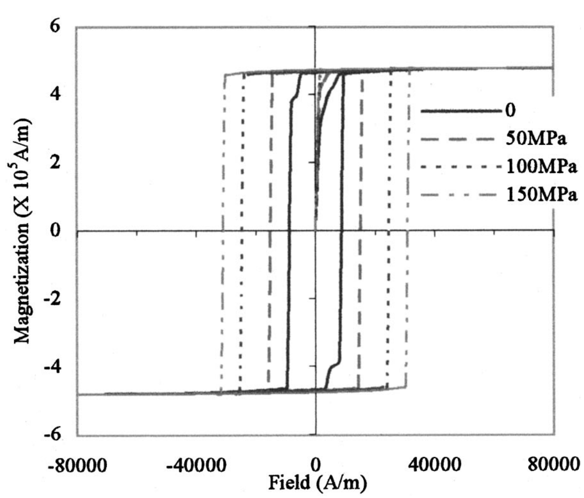

FIG. 2. Hysteresis loops modeled under compressive stress.

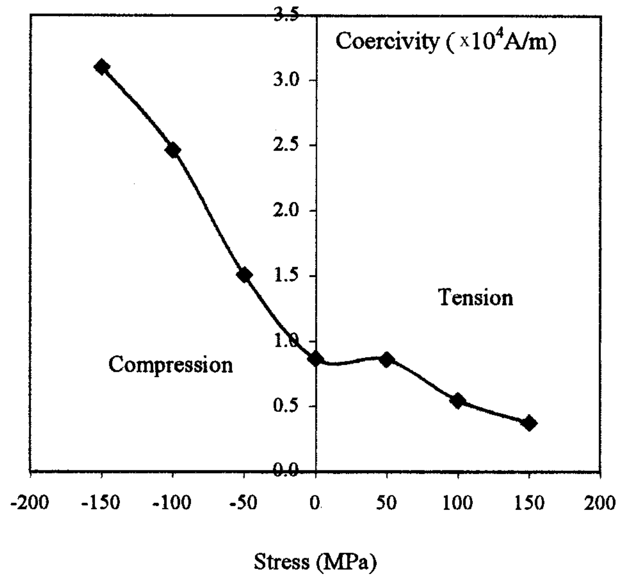

FIG. 3. Plot of coercivity of the Ni film as a function of applied stress.

main wall movement. Quantitative predictions of the effects of stress on magnetic properties of bulk materials has been given by Sablik *et al.*[2] and by Jiles[3] and were found in good agreement with experimental results.[9]

Figure 4 shows the changes in remanence under applied stress. The results show that the remanence decreased with increasing tensile stress but was much less sensitive to compressive stress. This can be interpreted based on the argument given above. Specifically, tensile stress in the field direction induced anisotropy perpendicular to the applied field. As the applied field was reduced from saturation, due to the stress-induced anisotropy the domain magnetization partially rotated away from the field direction in a reversible manner, before it suddenly switched irreversibly and discontinuously into the opposite direction. The effect of reversible rotation became more pronounced as the stress-induced anisotropy increased. As a result the remanence decreased with tensile stress. Compressive stress did not change the remanence so much because the remanence in the unstressed state was very close to the saturation value, as shown in Fig. 2.

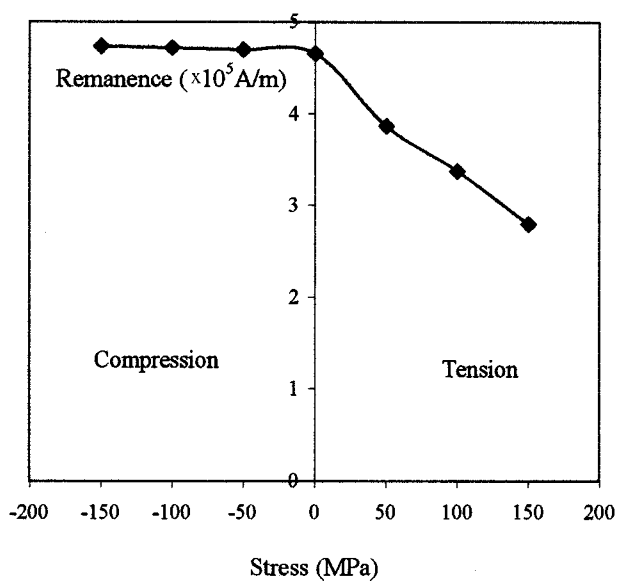

FIG. 4. Plot of remanence of the Ni film as a function of applied stress.

IV. CONCLUSIONS

Micromagnetic modeling of the effect of stress on magnetic properties of thin films has been carried out by including a magnetoelastic energy term in the Landau–Lifshitz–Gilbert equation. Magnetization curves of a nickel thin film were calculated and the modeling results showed that the shape of the hysteresis loop and the magnetic properties (e.g., coercivity and remanence) changed systematically under applied stress in a manner which was in agreement with experimental results of others. The variation of the coercivity with applied stress can be attributed to the effects of stress-induced anisotropy on the irreversible rotation of magnetic moments which is the dominant mechanism of magnetization reversal in the model system used in the present study.

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[1] R. M. Bozorth, *Ferromagnetism* (Van Nostrand, New York, 1951).
[2] M. J. Sablik, H. Kwun, G. L. Burkhardt, and D. C. Jiles, J. Appl. Phys. **61**, 3799 (1987).
[3] D. C. Jiles, J. Phys. D **28**, 1537 (1995).
[4] L. Callegaro and E. Puppin, Appl. Phys. Lett. **68**, 1279 (1996).
[5] T. L. Gilbert, Phys. Rev. **100**, 1243 (1955).
[6] B. D. Cullity, *Introduction to Magnetic Materials* (Addison–Wesley, Reading, MA, 1972).
[7] M. J. Donahue, OOMMF User's guide 1.1b0, 2000.
[8] A. J. Newell, W. Williams, and D. J. Dunlop, J. Geophys. Res. **98**, 9551 (1993).
[9] D. C. Jiles, T. T. Chang, D. R. Hougen, and R. Ranjan, J. Appl. Phys. **64**, 3620 (1988).
[10] I. J. Garshelis, J. Appl. Phys. **73**, 5629 (1993).
[11] E. C. Stoner and E. P. Wohlfarth, Philos. Trans. R. Soc. London, Ser. A **240**, 599 (1948).