Stress dependence and effect of plastic deformation on magnetic hysteresis and anhysteretic magnetization of FeNi32% films

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The magnetic hysteresis and anhysteretic magnetization of FeNi32% films were investigated as a function of isotropic stress. The magnetostriction contribution to dc magnetization under elastic stress and the effect of the plastic strain on the hysteresis loops are discussed. Also, a role of the plastic deformation interrelated with the elastic stress in the magnetization process is established. An experimental system based on a conventional vibrating sample magnetometer equipped with a specially designed loading fixture and optical resonant spectroscopy tension monitoring technique are used to measure anhysteretic permeability and magnetization curve as a function of stress. Measurements of magnetostriction as a function of magnetic field were shown to be also possible using this fixture. Stresses are deduced from the characteristic resonant frequency of the sample in the fixture and verified via pulse propagation velocity measurement. Both indirect stress measurements are contactless, relying on remote vibration measurement using a laser Doppler vibrometer. Uniaxial stresses up to 1 GPa can be applied for samples down to 50 μm specimens. Anhysteretic permeability was extracted from the anhysteretic *B-H* curves constructed by degaussing the sample at the given longitudinal (parallel to the stresses) dc field. The large positive magnetostriction constant leads to higher susceptibility and lower coercivity with tensile stress while the large volume magnetostriction results in reduced saturation magnetization. Large stresses imposed on the sample result in plastic strain of the sample which induces increase in dislocation density and domain wall pinning. This causes the gain in hysteresis loss and coercivity to increase at the highest stresses. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2709497]

I. INTRODUCTION

Because of the relatively high magnetostriction and low saturation field, FeNi alloys are still considered to be a very promising material for sensor and switch applications, making them suitable for many technological applications where high permeability μ and low losses and coercivity *Hc* are required. However, intrinsic magnetic anisotropy of these ferromagnetic materials is linked with magnetostriction and makes magnetic properties extremely sensitive to stress and strain. Study of their magnetic properties had attracted much attention, especially as a function of applied stress.[1] Adequate characterization very often depends on the anhysteretic permeability μ of the material. Often it is very important to know how anhysteretic magnetic properties vary as a function of applied tensile stress, since the magnetic characteristics are invariably affected by stress via magnetoelastic coupling. While the stress dependence of the magnetization can be measured by ac techniques,[2] heretofore there has been no method to measure the static anhysteretic magnetization, which can be rather different from the frequency dependent susceptibility. Also, ac methods require specially shaped samples, which present problems in studying the effect of stress on magnetic properties. In our previous work[3] we developed a method to measure the anhysteretic magnetization of thin samples under tensile stress, using a conventional vibrating sample magnetometer (VSM) and a specially designed loading fixture.

The goal of this work is to further demonstrate this method and investigate stress effect on magnetization curve magnetoelastic properties of 10–100 μm thick FeNi32% sample by measuring magnetization and magnetostriction as a function of applied tensile stress and magnetic field. In this work we present the results of our study on the effect of the magnitude of isotropic in-plane stress on magnetic static hysteresis curve and on anhysteretic susceptibility and discuss the threshold of a plastic deformation on magnetic properties

II. EXPERIMENTAL TECHNIQUE

The fixture used with vibration sample magnetometer is shown in Fig. 1. More details on the fixture design can be found in Ref. 2. Briefly, the sample is clamped between two sets of brass bars with screws. The stress is applied by a pair of nonmagnetic beryllium copper compression springs. Two support bars, which hold the springs in place, also serve to ensure that the amplitude of the sample vibration is the same as that of the VSM rod.

The isotropic tensile stress σ in the sample is controlled by adjusting the nut and by the compression of the spring.

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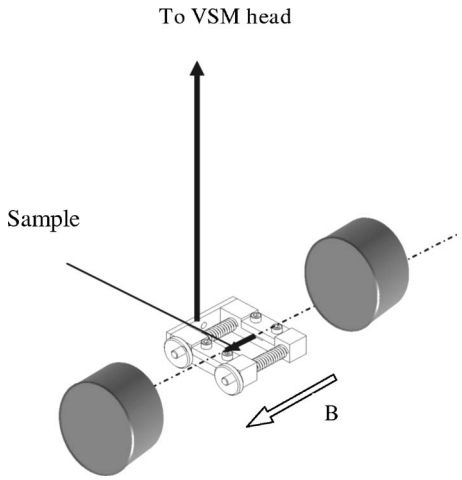

FIG. 1. Schematic of the stress-loading fixture for magnetization measurements in VSM. The VSM connecting rod and degaussing coils are omitted for clarity.

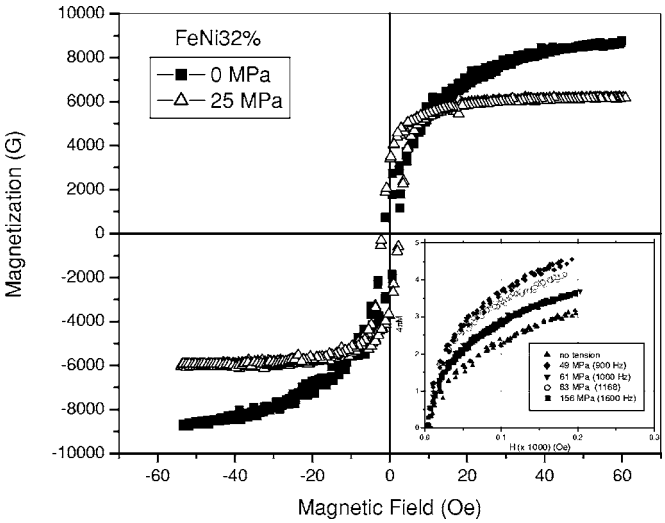

FIG. 2. Magnetization curves as a function of stress for FeNi32%. The inset shows stress and field dependence of anhysteretic magnetization for various stresses.

The fundamental oscillation frequency f of the sample is determined using an optical Doppler vibrometer and performing a fast Fourier transform (FFT) of the signal excited by a piezotransducer by sweeping the frequency of the external sine wave generator.

From this, σ is determined via $\sigma=4L^2f^2\rho$, where L is the length and ρ the density of the sample material. As the sample size (length) is limited by the VSM pole gap, care must be taken to ensure that the demagnetizing effect is accounted for. It is important, in particular, if the permeability μ is high, i.e., the demagnetizing field H_d resulting from the finite sample size must be much smaller than the applied field H_{app}. The true magnetic field H is $(H_{\text{app}}-H_d)$; $H_d=DM$ where D is the demagnetizing factor and M the magnetization. D depends only on sample shape and direction of the applied magnetic field. For a long ribbon,[4,5]

$$D=\frac{4\pi}{m^2}(\ln 2m-1),$$

where $m=c/d$, the ratio of the length c to the effective diameter $d=1.12(ab)^{1/2}$, with a and b being the width and thickness of the sample, respectively.

In a conventional VSM, the coils are separated by about 25–100 mm. The demagnetizing factor, for example, of the 500 μm thick sample is $D=0.0014$. If $\mu>\sim 40$ for this sample, the measured magnetization is completely dominated by demagnetizing effects. Since commonly used ferromagnetic materials possess μ greater than 2000, D must be accounted for.[6] This can be accomplished by increasing m, by either reducing the cross sectional area or increasing the sample length. Sample length is limited by the size of the VSM magnet gap and separation of the pickup coils. In our case, the pickup coils are separated by 60 mm in a wide gap magnet. The calibration of the VSM is a two-step procedure. First a Ni sphere is used as a standard to determine the magnetization of a short section ($\sim$10 mm) of a strand. Next, the signal from a long ($\sim$60 mm) strand of the sample under no stress is measured and used for the calibration. This last step is required because the sample is approximately the size of the coil separation and can no longer be considered as a simple point dipole as in the case of the short strand.

The anhysteretic curve was obtained by ac demagnetization of the sample and measuring the subsequent magnetization at a given value of H. The anhysteretic permeability μ_{anh} is defined as the derivative of magnetic induction, $B(H)$, at a given applied dc field H on which has been superimposed a large alternating field, the magnitude of which is steadily reduced to zero. This ac demagnetization process does not produce the static B-H curve. For true anhysteretic measurements, the ac degaussing field must be sufficient to saturate the magnetization. A set of degaussing coils, operating at 60 Hz, is brought near the sample (Fig. 1, not shown for clarity), and the maximum degaussing ac field is about 300 Oe, much greater than the saturation field. After degaussing at the given dc field, the dc magnetization is measured. The degaussing process was repeated several times to minimize errors. From these data, the anhysteretic B-H curves were constructed.

III. RESULTS AND DISCUSSION

Figure 2 shows magnetization hysteresis loops of the FeNi32% sample at various stress levels. As it can be seen the magnetization exhibits a very strong dependence on stress. Anhysteretic magnetization curves for several stress levels are shown in the insert. Figure 3 shows stress dependent anhysteretic magnetization and coercivity. As it can be seen the magnetization of the sample exhibits a very strong dependence on stress with well pronounced saturation at approximately 70 MPa, while permeability increases monotonically with increasing stress up to this stress level. Above 70 MPa, the permeability saturates and practically does not change with increasing stress. Coercivity decreases with stress at low stress levels, while it increases at higher stress levels.

The large positive magnetostriction constant of FeNi (Ref. 4) leads to higher susceptibility and lower coercivity with tensile stress while the large volume magnetostriction

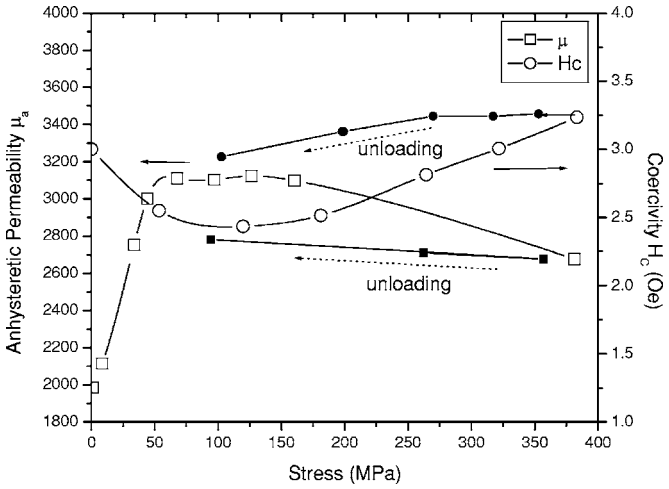

FIG. 3. Stress dependence of the anhysteretic permeability and coercivity of FeNi32% sample between 0 and 400 MPa. There is a clear saturation in the coercive field and permeability above 70 MPa. Dashed line depicts the unloading cycle, showing very little difference for unloading stresses, denoting the effect of plastic deformation.

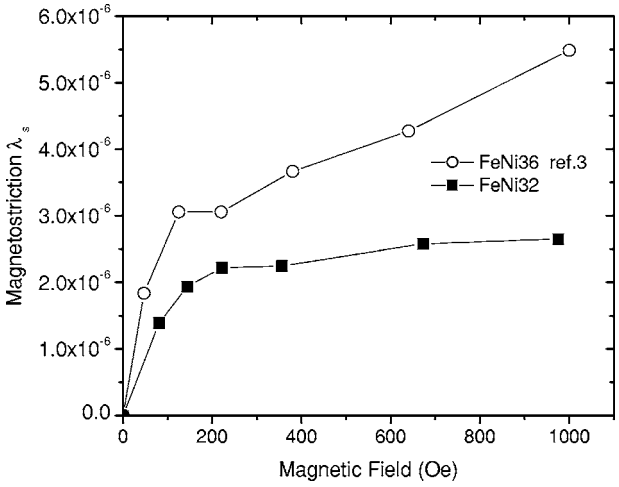

FIG. 4. Magnetostriction of FeNi32% as a function of magnetic field.

results in reduced saturation magnetization. As it was expected, large stresses result in plastic deformation of the sample which produces structural defects. These defects act as pinning centers for domains, which causes the coercive field to increase at the highest stresses. After stresses exceeded 150 MPa (which is approximately 75% of the yield stress for the FeNi32% alloy), the magnetic susceptibility and coercivity of the sample on the consequent unloading cycle (Figs. 3 and 4) became essentially insensitive to stress. This effect of the irreversibility of magnetic properties is related to the cold working, which introduces defects and local strains that cannot be affected without very large stresses.[6]

Figure 4 shows the field dependence of the forced magnetostriction coefficient $\lambda(H)$ of the $Ni_{32}Fe$ sample calculated by measuring the corresponding resonance frequency of the sample clamped and held in place in the fixture in a prestressed condition as a function of magnetic field.[3] As expected, $\lambda(H)$ is low for the Ni concentration below the invariable state (FeNi36%).

IV. CONCLUSION

In conclusion, we measured the stress dependent magnetization and anhysteretic permeability of FeNi32% thin film using a vibrating sample magnetometer and utilizing a specially designed loading fixture. Using this fixture we showed plastic deformation due to isotropic stresses exceeding 150 Mpa. For thin samples, the fixture can be used without worrying about demagnetization; however, for high permeability samples, one needs to use a large coil separation and a separate calibration. Measurements on FeNi32% samples demonstrated that this method is useful in investigating anhysteretic magnetization and magnetostriction. The large positive magnetostriction constant of FeNi32% leads to higher susceptibility and lower coercivity with tensile stress while the large volume magnetostriction results in reduced saturation magnetization.[7] High stresses result in plastic deformation of the sample which produces structural defects, which act as pinning centers for domains, resulting in increased coercive fields at the highest stresses.

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