Dynamic scaling of magnetic hysteresis in micron-sized $Ni_{80}Fe_{20}$ disks

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The scaling of the magnetic hysteresis loop area of permalloy disks (20–400 μm diam) has been studied as a function of applied field amplitude H_0 and frequency Ω using scanning Kerr microscopy. An increase in the dynamic coercivity with reduced size is observed for $d<100\ \mu$m in the frequency range studied (0.1–800 Hz). However, the loop area A follows the scaling relation $A \propto H_0^\alpha \Omega^\beta$, with $\alpha \approx 0.14$ and $\beta \approx 0.50$ throughout the entire size range studied. Our results demonstrate that the dynamic scaling behavior is universal even though the lateral size influences the domain structure and magnetic reversal behavior. © *1999 American Institute of Physics.* [S0003-6951(99)02411-0]

The magnetic properties of micron- and nanometer-scale patterned structures have recently attracted considerable interest both due to the possibility of data storage applications and fundamental magnetism studies, e.g., the domain structures and magnetization reversal behavior.[1–4] The dynamic hysteresis scaling behavior in such structures provides an opportunity to test universality hypotheses and to search for scale-invariant descriptions of the energy-loss per cycle (area of the hysteresis loop) as a function of external parameters, e.g., applied magnetic-field strength H_0 and frequency Ω, and intrinsic system parameters, such as dimensionality and magnetic anisotropy.[5–13] The scaling behavior for the variation of the hysteresis loop area A has been shown to reduce to a power-law function of the form[5]

$$A \propto H_0^\alpha \Omega^\beta, \tag{1}$$

where α and β are exponents that depend on the dimensionality and symmetry of the system. Specific values of the exponents are predicted for the various models, such as $\alpha = \beta = 1/2$ (Refs. 7 and 8) or $\alpha = 2/3, \beta = 1/3$ (Ref. 5) in a continuous spin system and $\alpha = \beta \approx 2/3$ in a mean-field Ising model.[9] Even though there have been a few recent efforts to describe the scaling behavior observed in ultrathin ferromagnetic films, e.g., Fe/Au(001),[10] Co/Cu(001),[11] and Fe/W(110),[12] based on the continuous spin system and two-dimensional (2D) Ising spin model, the determination of universal dynamic exponents still remains controversial.[12,13] However, to date, studies have focused on continuous films, and to the best of our knowledge the dynamic scaling behavior in micron- and nanometer-scale patterned structures has not been studied. Patterned structures are of particular interest in this context since the presence of edges introduces dipolar fields which modify the magnetic anisotropy and magnetization reversal process behavior. Permalloy disks with $d \geq 50\ \mu$m are reported[1,2] to have a multidomain or a three-domain structure according to the strength of the stress-induced uniaxial anisotropy. By contrast, a vortex state becomes predominant in smaller-sized disks as the edge-induced anisotropy favors a concentric magnetization state where the magnetization vector rotates around a singular point at the disk center. Thus, permalloy disks provide an ideal system for dynamic studies in which the effects of domain structure can be investigated.

In this letter, we report the dynamic response of micron-sized permalloy ($Ni_{80}Fe_{20}$) disks to a sinusoidal external magnetic field within the frequency range 0.1 to 800 Hz at room temperature. Our results demonstrate that the dynamic scaling behavior is indeed described by size-invariant exponents, although the lateral size profoundly influences the magnetic anisotropy, coercivity, and magnetization reversal process.

Micron-sized polycrystalline permalloy disks with a thickness of 200 Å and diameter (d) varied from 400 μm down to 20 μm were fabricated by electron-beam lithography and a lift-off process. Before pattern transfer, a permalloy film was deposited on the GaAs (001) substrate at room temperature with a base pressure of 5×10^{-10} mbar. The $Ni_{80}Fe_{20}$ was deposited at a rate of 2.5 Å/min and the pressure during growth was 5×10^{-9} mbar. After deposition of $Ni_{80}Fe_{20}$, the film was capped with a Au layer of 30 Å thickness. Hysteresis loops was obtained *ex situ* by scanning Kerr microscopy.[14] An objective lens (×20, numerical aperture: 0.55) were used to focus the probing laser beam (~2 μm spot size) on the center of the disks. The magnetic field was driven by a time-varying current up to 800 Hz.

Figure 1 presents hysteresis loops of the disks with $d = 400$ and 20 μm measured by applying a dc magnetic field along the easy and hard directions, respectively. A clear size dependence in the hysteresis loops was found. The data [Figs. 1(a) and 1(b)] for the disk with $d = 400\ \mu$m indicate the presence of a uniaxial anisotropy. The uniaxial anisotropy is attributed to strain during the growth of the film.[1] The coercive field along the easy direction is ~3 Oe and the saturation field, approximately corresponding to the anisotropy field ($H_a = 2K_u/M$, where K_u is the uniaxial anisotropy and M_s the saturation magnetization) along the hard direction is ~10 Oe. All disks of $d > 50\ \mu$m reveal identical anisotropic behavior, while the disk of $d = 20\ \mu$m shows a

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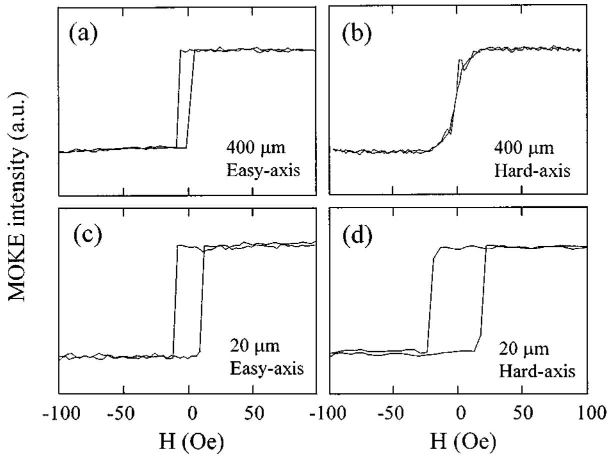

FIG. 1. Hysteresis loops for the $d = 400\ \mu$m (a,b) and 20 μm (c,d) disks along the easy and hard directions under a dc magnetic field.

different dependence of the $M-H$ loop on the field direction accompanied by an enhancement in the coercivity ($H_c \approx 10-20$ Oe) [Figs. 1(c) and 1(d)]. We attribute the observed behavior to a size dependence of the domain configurations and magnetization reversal process within the disks.[1–3] As reported in previous studies using Kerr microscopy,[1,2] the disks with $d \geqslant 50\ \mu$m are composed of multidomains or a three-domain structure according to the strength of the stress-induced uniaxial anisotropy. By contrast, a vortex state becomes predominant in the smaller-sized disks as the edge-induced anisotropy favors a concentric magnetization configuration, where the magnetization vector rotates around a single point at the disk center. The edge-induced anisotropy is due to the dipolar fields associated with the edges of the disks. The lateral size effect is also well demonstrated in measurements of the frequency-dependent coercive field or dynamic coercivity H_c^* shown in Fig. 2, where H_c^* is represented as a function of the disk diameter at a fixed applied magnetic-field strength of 152 Oe. It is seen that H_c^* for $d = 20\ \mu$m is higher than that of the other disks. With increasing diameter the coercivity becomes smaller, and for the disks with $d > 100\ \mu$m the values of H_c^* are almost the same, indicating that disks of these sizes have identical magnetic switching behavior. From the anisotropic behavior and coercive field values at dc, which are comparable with those of the continuous films,[1,2] we infer that the disks with $d > 100\ \mu$m have the magnetic properties of the continuous films.

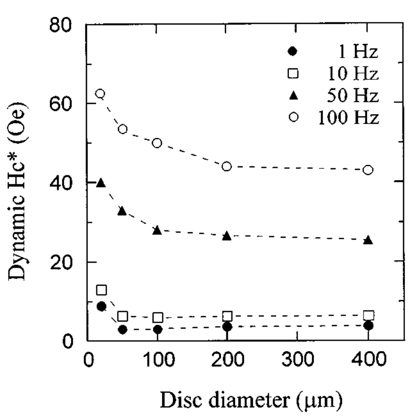

FIG. 2. Dynamic coercive field H_c^* as a function of the disk diameter d. H_c^* of $d = 20\ \mu$m is comparatively higher than that of the other disks. With increasing diameter H_c^* becomes smaller, and for the disks with $d > 100\ \mu$m H_c^* are almost the same, indicating that the disks of these sizes have identical magnetic switching behavior.

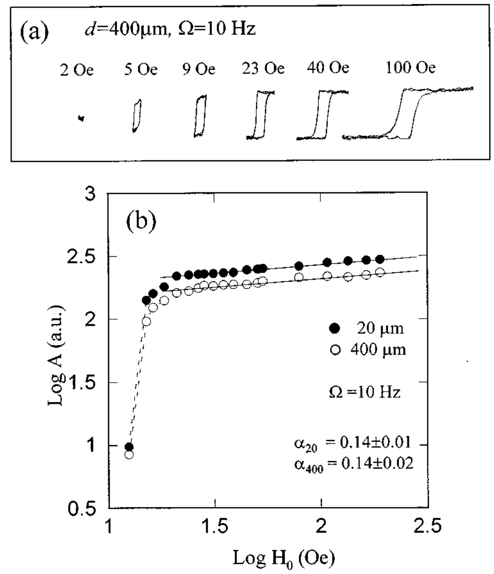

FIG. 3. Evolution of hysteresis loops (a) and loop area (b) for the disk of $d = 400\ \mu$m as a function of magnetic-field amplitude H_0 at a fixed frequency of 10 Hz. After the initial abrupt change, the area increases slowly with H_0, and the slopes of the straight lines after the threshold field, i.e., $H_0 > H_c^*$, yield the same exponents ($\alpha \approx 0.14$) within error for both disks with $d = 20$ and 400 μm.

Now, it is of importance to study how the size-dependent domain structures, i.e., multidomain and vortex structures, influence the dynamic scaling behavior in the small-patterned structures. Figure 3(a) shows the hysteresis loops for the 400 μm disk measured as a function of magnetic-field amplitude (H_0) at a fixed frequency of 10 Hz for the field applied along the easy-axis direction. A similar sequence of loops is also observed from the other disks. It is clearly seen that a critical threshold field (H_t) exists corresponding to the dynamic coercive field (H_c^*), beneath which minor loops are observed, i.e., $M < M_s$ for all applied field strengths. Once the applied field strength exceeds the threshold field, hysteresis loops which reach the saturation magnetization are obtained, as shown with the loop at 23 Oe. The evolution of the loops is demonstrated in Fig. 3(b), where a log–log plot of the hysteresis loop area A is represented as a function of the applied field amplitude (H_0) for disks with $d = 20$ and 400 μm, respectively. An abrupt transition occurs at the threshold field after which the area increases slowly with H_0 for both disks. The slopes of the straight lines after the threshold, i.e., $H_0 > H_t$, yield the same exponents of $\alpha \approx 0.14$ within error, as observed in previous work.[10–12] First, this result is at odds with theoretical studies,[5,6] which presume that the scaling relation reflects the magnetization reversal mechanism induced by a time-varying magnetic field. In our case, it is clearly seen that the exponents governing the scaling behavior are the same in spite of the distinct magnetization reversal mechanisms corresponding to the distinct domain structures, i.e., vortex and multidomain, as described above. Second, the determined exponents depart from the theoretical value of $\alpha = 0.66$ predicted by Rao *et al.*[5] for the

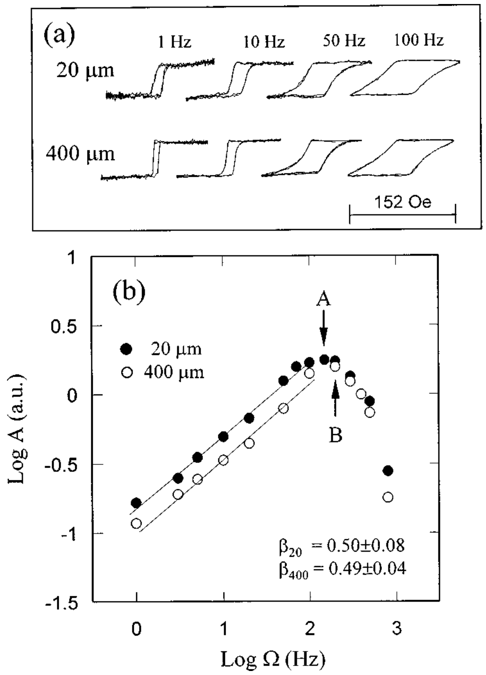

FIG. 4. Frequency-dependent hysteresis loops (a), and hysteresis loop area as a function of field frequency (b). The field amplitude was fixed at 152 Oe. The frequencies at which the disks are no longer saturated are indicated with the arrows A and B in (b). In the frequency range up to ~100 Hz, the initial rise of A follows the scaling relation of the form of $A \propto \Omega^{\beta}$, where the exponents β for the 400 and 20 μm disks are $\beta_{400} = 0.49 \pm 0.04$ and $\beta_{20} = 0.50 \pm 0.08$, respectively.

continuous spin system and $\alpha \approx 0.7$ by Acharrya and Chakrabati[6] for the 2D Ising system. Our values of the exponents are also different from those previously found in continuous ultrathin ferromagnetic films in the field range ($H_0 > H_c^*$), e.g., $\alpha = 0.59 \pm 0.07$ in the Fe/Au(001),[10] $\alpha = 0.67 \pm 0.01$ in the Co/Cu(001),[11] and $\alpha = 0.254 \pm 0.003$ in the Fe/W(110).[12]

We now consider the scaling of the loop area with field frequency (Ω) [Eq. (1)]. Figure 4(a) shows the evolution of the hysteresis loops for the 20 μm disk for a fixed amplitude H_0 (=152 Oe) with increasing Ω. At low frequency (<10 Hz) the magnetization M exhibits an almost square loop. With increasing frequency (Ω) the $M-H$ loop develops rounded tips. As the frequency increases further, the $M-H$ loops eventually cannot be saturated with the available field. A similar evolution of loop shapes was observed in the Fe/Au(001) system[10] and Co/Cu(001).[11] The evolution of the hysteresis behavior is more clearly seen in Fig. 4(b), where a log–log plot of the hysteresis loop area is represented for the 400 and 20 μm disks as a function of Ω at a fixed field H_0 of 152 Oe. First, the dynamic coercivity (H_c^*) and the loop area (A) increase monotonically with Ω until the loop area maximum is reached due to the dynamic coercivity (H_c^*) exceeding the available magnetic-field strength. The initial monotonic rise of A is due to the finite time required for the magnetization reversal. Consequently, the magnetization is unable to respond immediately to the rapidly varying field and this effect becomes progressively more pronounced as Ω increases. In the frequency range up to ~100 Hz, the initial rise of A follows a scaling relation of the form of $A \propto \Omega^{\beta}$, where the values for the exponent β for the 400 and 20 μm disks are found to be $\beta_{400} = 0.49 \pm 0.04$ and $\beta_{20} = 0.50 \pm 0.08$, respectively. These values differ from those of $\beta = 0.31 \pm 0.05$ reported for Fe/Au(001),[10] $\beta = 0.66 \pm 0.03$ for Co/Cu(001),[11] and $\beta \approx 0.06$ for Fe/W(110).[12] The determination of universal dynamic exponents in the continuous ultrathin films still remains controversial.[12,13] Since the edges in the patterned structures introduce dipolar fields, our values for the scaling exponents for the disk structures cannot be compared directly with those for the continuous films. Also, theoretical models neglect dipolar fields which, as our results show, are particularly important for finite-size systems.[5,6] Another crucial point is that the exponents β are again identical for both disks within error as is the case for the exponents α (Fig. 3). This is surprising since the available theoretical models assume that the dynamic scaling exponents remain the same only if the magnetization reversal mechanism is identical under a time-varying magnetic field.[5,6,10] However, our measurements indicate that the dynamic scaling exponents are not sensitive to intrinsic parameters such as the magnetic anisotropy and domain structure.

In conclusion, the dynamic hysteresis scaling behavior of micron-size patterned permalloy disks was studied as a function of the disk diameter, amplitude, and frequency of an applied ac magnetic field. The loop area A is found to scale as $A \propto H_0^{\alpha} \Omega^{\beta}$, with $\alpha \approx 0.14$ and $\beta \approx 0.5$. No significant difference between the dynamic scaling exponents determined for the $d = 20$ and 400 μm disks is found, even though the anisotropy behavior and domain state, i.e., multidomain and vortex, differ from each other and an increase in H_c is seen for $d = 20\,\mu$m. We conclude that the dynamic reversal process is independent of the detailed domain structure and that dipolar fields affect the dynamic scaling behavior.

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