Dynamic magnetic hysteresis and anomalous viscosity in exchange bias systems

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(Received 22 September 1999)

A theory for thermally driven time dependent magnetization processes in exchange-coupled magnetic films is presented. Bilinear and biquadratic exchange coupling are used to describe compensated, partially compensated, and uncompensated interfaces between a ferromagnet and an antiferromagnet. Thermal properties of exchange bias are simulated using a Monte Carlo technique. Exchange coupling between a ferromagnetic and an antiferromagnetic film is shown to result in hysteresis without the need for anisotropies or thermal processes in the ferromagnet. Time dependence for the coercive field is calculated for coupled systems and hysteresis is studied as a function of field rate. Competition between demagnetizing effects and intergrain exchange coupling are shown to give rise to anomalous viscosity.

I. INTRODUCTION

The original mechanism for exchange bias proposed by Meikeljohn and Bean[1] provided a qualitative understanding in terms of large anisotropy in the antiferromagnet and a weaker exchange coupling across an ferromagnet/antiferromagnet interface. Subsequent measurements presented a challenge to correctly predict observed magnitudes and coercivities. Additional considerations for the bias were made by Néel[2] who suggested a number of corrections for realistic interfaces and time dependent effects. Several authors have since contributed to the emerging understanding of the effect.[3–7] To date, a complete quantitative understanding of the problem still appears to be lacking, particularly with regards to the coercivity fields exhibiting by biased structures.

In this paper, a theory for exchange bias is presented that provides an explanation of time and temperature-dependent coercivities and predicts features completely in terms of thermally activated magnetic processes in the antiferromagnet. The model is different from previous models for hysteresis in biased systems because no ferromagnetic anisotropy is needed to produce hysteresis and coercivity. The model presented here can be easily adapted to describe a wide range of exchange coupled systems in addition to the exchange bias systems.

The original arguments of Meikeljohn and Bean assumed that an antiferromagnet, after being cooled to below its Néel temperature while exchange coupled to a ferromagnet, would be dominated by large magnetocrystalline anisotropies. As a consequence, if a magnetic field is applied opposite the initial ferromagnetic orientation, reversal of the ferromagnet can not occur until the Zeeman field on the ferromagnet becomes larger than the interlayer exchange field. Because spins in the antiferromagnet are pinned by large anisotropies, a bias of the hysteresis loop away from zero-field results. The amount of bias is determined by the magnitude of the exchange coupling across the interface.

Their model overestimates the magnitude of the bias field by neglecting the possibility to deform the antiferromagnetic order near the interface into a twist or wall. Mauri *et al.*[8] showed that a partial wall in the antiferromagnet could form near the interface through exchange coupling to a ferromagnet. Whereas this does lead to a reduced bias field, the model is not entirely satisfactory in that there still remains the question of how bias can exist in situations where the interface is compensated so that there is no net antiferromagnetic moment present at the interface.

Attempts to deal with this shortcoming have been made by several authors. Estimates for the magnitude of the bias field when domains are formed in the antiferromagnet were made by Malozemoff[9,10] and Koon[11] demonstrated how an interface spin-flop configuration in the antiferromagnet could allow bias at compensated interfaces. In these contexts, stability of the spin-flop mechanism,[12,13] consequences of spin-flop coupling,[14] implications for particulate matter,[12] and imperfections at the interface[15] have been further discussed.

Experimental observations of coercivities,[16,7] temperature,[4] and field rate dependencies[5] are not explained by the above theories. It has been suggested that domain-wall formation and motion in the antiferromagnet may somehow explain both of these phenomena, and work by Fulcomer and Charap[17] explored some issues relating to thermal effects for exchange bias in granular structures. Earlier, Néel[2] presented arguments based on analogy to tilt and creep intended to explain observations for ac, rotational, and oscillatory hysteresis.[16] To date, all theories of hysteresis in exchange-coupled systems have in one way or another required some sort of activation process in the ferromagnetic component. The processes could be governed by intrinsic anisotropies, or anisotropies introduced by the antiferromagnet. A point of this paper is to show that there is no need to assume any such processes or anisotropies in the ferromagnet in order to have hysteresis and viscosity in exchange biased systems. Furthermore, under the proposed mechanism, the rate at which an applied field is changed determines the magnitude of the coercivity.

The main difficulty of constructing a suitable theory is in finding a form for the relevant energies sufficiently simple to analyze. The model proposed here comes to grip with this problem by supposing that partial walls are formed in the antiferromagnet near the interface using bilinear and biquadratic exchange coupling. This provides a representation of

0163-1829/2000/61(18)/12174(7)/$15.00

compensated and partially compensated interfaces by describing essential features introduced by the spin-flop mechanism. The theory is therefore quite distinct from Néel's approach in which he defines an "interface friction."[2]

II. THEORY FOR BIQUADRATIC EXCHANGE BIAS

The theory is constructed by first examining the energy for partial wall formation in the antiferromagnet. The antiferromagnet extends from $x=0$ to $x=\infty$ with the interface in the yz plane. The easy axis of the in-plane uniaxial anisotropy is along the z direction and the in-plane angle of the magnetization from the z direction is θ. To simplify the notation, direction cosines are used with the usual convention α, β, and γ for sublattice magnetization along the x,y, and z directions, respectively. The energy for partial wall formation is found by first searching for the configuration that minimizes the energy:

$$E_{AF}=\int_0^{+\infty}\left\{A\left[\left(\frac{\partial}{\partial x}\alpha\right)^2+\left(\frac{\partial}{\partial x}\beta\right)^2+\left(\frac{\partial}{\partial x}\gamma\right)^2\right]+K\gamma^2-K_o\alpha^2\right\}dx. \tag{1}$$

Equation (1) represents the energy of the antiferromagnetic film where the topmost spin at $x=0$ is rotated an angle $\theta(0)=\psi$ away from the anisotropy axis. The exchange energy constant is A, and the uniaxial anisotropy energy is K. An additional easy-plane anisotropy K_o is also included. If the partial wall is in a Bloch configuration, the resulting energy of the partial wall is

$$E_{wall}=\frac{1}{2}\sigma(1-\cos\psi), \tag{2}$$

where σ is the energy of a complete 180° wall and is given by $4\sqrt{AK}$. As shown in Refs. 8 and 15, Eq. (2) can be used to calculate an exchange bias field for an uncompensated and atomically perfect interface coupled to a ferromagnet by an exchange coupling per area A_{12}. The bias field h_{bias} is proportional to $A_{12}[(2A_{12}/\sigma)^2+1]^{-1/2}$, showing an explicit dependence of the bias on the formation of a partial wall in the antiferromagnet. Results from the model have been compared to results from atomistic numerical simulations[15] and excellent quantitative agreement was found.

In this paper, the above model is extended to describe partially compensated and rough surfaces by including a biquadratic exchange coupling term between the ferromagnet and the antiferromagnet. The bias is determined by finding minimum-energy solutions to the following energy for the ferromagnet/antiferromagnet combination:

$$E=-Ht_FM\cos(\theta_H-\theta_F)+\frac{1}{2}\sigma(1-\cos\psi)-A_{12}\cos(\psi-\theta_F)+B_{12}\cos^2(\psi-\theta_F). \tag{3}$$

Here t_F is the thickness of the ferromagnetic film, θ_F is the angle the magnetization M of the ferromagnet makes with respect to the z direction, θ_H is the angle an in-plane applied field H makes with the z axis, A_{12} is the bilinear exchange across the interface, and B_{12} is a biquadratic exchange across

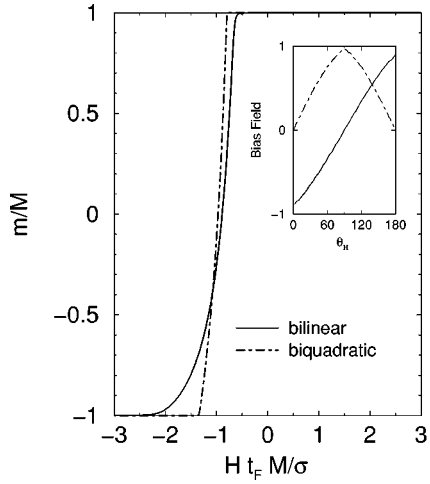

FIG. 1. Model calculations for exchange bias for compensated and uncompensated ferromagnet/antiferromagnet interfaces. The solid line shows hysteresis for a compensated interface using bilinear coupling, and the dashed line shows hysteresis for an uncompensated interface using biquadratic coupling. The inset shows the variation of the bias with angle of the applied field. The calculations are in excellent agreement with atomistic spin dynamic calculations.

the interface. The biquadratic term is used to describe coupling of the ferromagnet to multiple sublattices of the antiferromagnet and was originally suggested by Slonczewski[18] to describe oscillatory exchange coupling across varying thickness films. Use of the term to mimic spin-flop coupling was made by Stiles and McMichael.[12]

Values for the angles that minimize Eq. (3) can be found analytically in special cases, but for the thermal effect calculations to follow, a general numerical scheme is applied. A relaxation approach is used where the magnetization of the ferromagnet is represented by a vector **f** rotated into the direction of the internal magnetic field $\mathbf{h_f}=-\nabla_\mathbf{f}\mathbf{E}$ according to

$$\frac{d\mathbf{f}}{dt}=-\lambda\mathbf{f}\times\mathbf{f}\times\mathbf{h_f}. \tag{4}$$

The parameter λ controls the relaxation rate. Similarly, the magnitude of the partial wall in the antiferromagnet is determined by the orientation of the outermost antiferromagnetic spins. Representing the orientation of these spins by the vector **a**, this vector is likewise rotated into the direction of an internal field $\mathbf{h_a}$. This field is defined by $\mathbf{h_a}=-\nabla_\mathbf{a}\mathbf{E}$ and the rotation is accomplished by a torque equation similar in form to Eq. (4). The rotations of the vectors **f** and **a** are constrained to be in plane by assuming a sufficiently large out-of-plane anisotropy due to film demagnetizing effects in the ferromagnet and K_o in the antiferromagnet.

Example results are shown in Fig. 1 where the magnetization of the ferromagnet is plotted as function of field. Units for energies are reduced in terms of σ, and field units are given as the ratio of Zeeman to wall energy, i.e., Ht_FM/σ. The dotted curve is for the bias with bilinear coupling only (using $A_{12}=2\sigma$ and $B_{12}=0$) and the solid curve is for bias with biquadratic coupling only (using $A_{12}=0$ and $B_{12}=2\sigma$). In terms of real energies, these reduced values correspond to around 1 erg/cm^2 for the interface exchange, 10^7

erg/cm^2 for the uniaxial anisotropy K, with 10^{-8} erg/cm for the exchange A in the antiferromagnet. The domain-wall width in the antiferromagnet is then on the order of 10^{-8} cm, and the wall energy on the order of 0.6 erg/cm^2.

There are slight differences in the shapes of the curves, with the bilinear coupling showing a very different approach towards saturation in the negative field direction from that found with biquadratic coupling. The bias is directional and depends on the angle of the applied field θ_H. The angular dependence for the two types of coupling are shown in the inset. The maximum bias for bilinear coupling is with the field applied parallel to the K anisotropy axis. The maximum bias for the biquadratic coupling occurs for the field aligned 90° from the K axis. Comparison of the results from this model to numerical simulations for arrays of atomistic spins[15] were made. The general features of shape, magnitude, and field angle dependence of the bias are correctly represented for uncompensated interfaces using $B_{12}=0$, and compensated interfaces using $A_{12}=0$. With both bilinear and biquadratic terms present, the results of minimizing Eq. (3) approximately reproduce the features calculated using numerical simulations for imperfect interfaces.[15]

It should be noted that this model is only an approximate representation of the spin-flop coupling mechanism and does not completely reproduce all aspects found from atomistic models. In particular, the dependence of the bias when spin-flop coupling is present shows a complicated dependence on interlayer exchange coupling that is not given by the simple biquadratic term.[15] The reason is that the spin configuration found in atomistic calculations is strongly dependent on magnetic order within a few atomic layers of the interface and this orientation is sensitive to the interface exchange coupling in a way not possible to exhibit with a simple biquadratic term. In any case, the corrections are minor, and effect only the magnitudes of the exchange coupling and not the overall physical behavior.

The stability of the bias and requirements for its existence can be determined from Eq. (3) by including the energy cost of out-of-plane fluctuations of the antiferromagnet. It has been conjectured,[12] and shown in numerical simulations,[13,19] that the spin-flop mechanism is unstable to out of plane fluctuations of the antiferromagnet which tend to unpin the partial wall and reverse the surface flopped spins. The energy incurred by this rotation is approximated by supposing that the entire antiferromagnet wall, with width $\Delta=\sqrt{A/K}$, is unpinned from the interface by an energy proportional to the easy-plane anisotropy. This is estimated by including a barrier term $\sigma_B=\Delta K_o \sin^2\phi$ into Eq. (3) and replacing $\cos(\psi-\theta_F)$ by $\cos\theta_F \cos\psi+\sin\theta_F \sin\psi \sin\phi$. The angle ϕ specifies an out-of-plane orientation of the wall and is measured from the normal to the interface plane. The stability of the wall is then determined by calculating $\partial^2E/\partial\phi^2$ at the equilibrium determined by the conditions $\partial E/\partial\phi=0$ and $\partial E/\partial\theta=0$. If the bilinear coupling is zero, one can show that stability leads to the requirement

$$\Delta K_o > B_{12}. \tag{5}$$

Finally, for $\theta_H=0$, the bias field h_{bias} can be calculated explicitly for $A_{12}=0$ with the result that

$$h_{bias}=\frac{\sigma}{2t_F M}\sqrt{1-\left(\frac{\sigma}{4B_{12}}\right)^2}. \tag{6}$$

Note that bias cannot exist due to biquadratic coupling if B_{12} is small compared to σ. This is in agreement with numerical calculations that exactly describe spin-flop coupling.[15]

III. THERMAL PROCESSES IN THE ANTIFERROMAGNET

The model described above is now applied to the problem of thermally activated magnetization processes in an exchange-coupled system of magnets. As will be shown, hysteresis in the coupled system follows directly as a consequence of thermal activation and annihilation of partial walls in the antiferromagnet.

An estimate for the magnitude of the barrier that must be overcome in order to create or destroy a partial wall in the antiferromagnet can be made as follows. If the exchange coupling is strong, the minimum energy for unpinning is supposed to occur as the antiferromagnet spins rotate out of the film plane, passing through $\phi=\pi/2$. The magnitude of the energy ϵ needed to overcome the barrier is given by Eq. (3) evaluated at $\phi=\pi/2$ less the energy of the initial configuration. With this prescription, ϵ is given by

$$\epsilon=a\left(\Delta K_o+\frac{1}{2}\sigma(1+\cos\psi)\right). \tag{7}$$

Here a is the area of the partial wall determined by the cross section of the antiferromagnet particle in contact with the ferromagnet. This plays the role of ''activation area'' analogous to activation volume in bulk ferromagnets. When the ferromagnet is rotated by an external field away from its lowest energy configuration, a twist is forced into the antiferromagnet as described above. Thermal activation over the barrier ϵ can allow the partial twist in the antiferromagnet to reconfigure into a lower energy configuration. In some cases the partial twist can disappear by thermal activation. If this occurs for enough particles, the bias field changes and can even switch sign. A consequence is that exchange bias can exhibit a variety of behaviors depending on temperature and the rate at which the reversal field is applied. The behaviors can range between a biased magnetization curve with zero hysteresis to a nearly square unshifted strongly hysteretic behavior. As will be seen, these considerations apply for compensated and uncompensated interfaces.

Thermal activation of this sort can be studied as a function of time by following a suggestion by Binder,[20] and applied by Lyberatos to studies of magnetic viscosity.[21] The strategy is to allow a number of reversals to occur in a time interval Δt according to the distribution

$$n(t)=\frac{N}{\tau}\exp\left(-\frac{N\Delta t}{\tau}\exp\left(-\frac{\epsilon}{k_BT}\right)\right). \tag{8}$$

Here τ is the relaxation time (inverse attempt frequency) of the magnetization excluding precession effects. The distribution is simulated numerically using a Monte Carlo method. A collection of N_c antiferromagnetic grains is studied, with each grain coupled via bilinear or biquadratic exchange to ferromagnetic grains. During a time interval, each antiferromagnetic grain is allowed to reverse according to the above distribution in a sequence of Monte Carlo steps. Reversal is described by shifting the zero of the wall energy by 180°, i.e., by modifying the wall energy of the reversed particle [Eq. (2)] to read

$$E_{wall}=\frac{1}{2}\sigma[1-\cos(\psi+\pi)]. \tag{9}$$

Note that an important assumption here is the independence of antiferromagnet wall reversal on the magnitude of the applied field. This is a reasonable approximation for temperatures well below the antiferromagnetic ordering temperature, and is also a feature unique to exchange-coupled systems involving antiferromagnets. It is an approximation by neglecting the small moment associated with the partial twist in the antiferromagnet.

Because a collection of particles is studied, the simulation can also be applied to granular materials if these are thought of as weakly interacting systems of particles. In particular, for the purposes of illustrating the effects of correlations between grains composed of coupled ferromagnetic and antiferromagnetic components, it is useful to examine the effects of weak exchange coupling between the ferromagnetic components of the grains. To explore this, the effects of the coupling is assumed to be a correlation between grains leading to ferromagnetic ordering, and is approximated by including an energy of the form

$$E_{ex}=-J\sum_{\langle i,j\rangle}\mathbf{f_i}\cdot\mathbf{f_j}. \tag{10}$$

For simplicity, the particles are arranged in a two dimensional array where i and j specify the particle. The sum is over nearest-neighbor pairs, indicated by $\langle i,j\rangle$, and J is the magnitude of the ferromagnet exchange coupling. Periodic boundary conditions are assumed. Whereas only ferromagnetic exchange between grains is described by Eq. (10), it will be shown that long-range dipolar interactions between the ferromagnetic components can be important for understanding the viscosity. This will be discussed later.

At each Monte Carlo step during the numerical simulation, a minimum-energy configuration is found by allowing the ferromagnet's θ_F and the antiferromagnet's ψ to relax to equilibrium values as described above. An average over the entire time interval is made in order to determine the magnitude and orientation of the ferromagnet's magnetization. At the end of each time step, the field is adjusted to a new value, and the process is repeated, using the previous time step magnetization configuration as a starting point. The entire calculation is then repeated several times and an average taken. For the examples shown here, the number of particles N_c is 100 and the number of averages 30.

The time is in reduced units $t\upsilon/\tau$ where υ is the ratio of simulation tries to particle number. Note that the important quantities determining the time scale are the relative values of the barrier height and temperature. These are chosen to give a 0.02 acceptance rate for a barrier $\Delta K_o a=\sigma a$ during each time interval and in this way define the unit of time.

Results of the simulations described above show how the magnitude of the hysteresis depends on the field rate. If the rate is very large, then the curve of Fig. 1 results. If the field rate is less, it is possible to observe hysteresis. Examples are shown in Fig. 2 for a collection of $N_c=100$ particles, with 30 averages, with the same parameters used to produce Fig. 1. The system is coupled biquadratically with the above parameters. Several rates for the applied field are used and given in reduced units as $R=Ht_FM/\sigma\cdot$timestep. The system is coupled biquadratically.

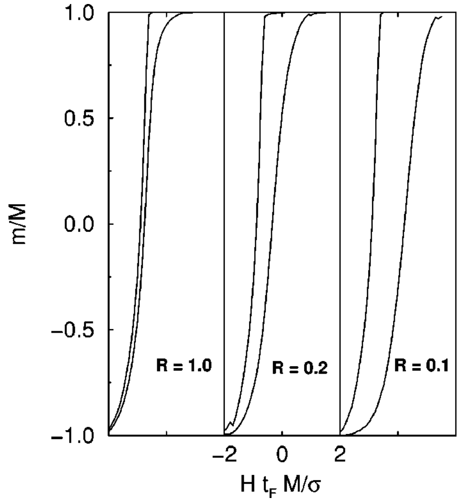

FIG. 2. Hysteresis develops when thermal fluctuations are taken into account and coercivities depend on the rate R at which the field is changed. Hysteresis for three different rates are shown in the panels. The system is bilinear coupled, and the time and temperature are chosen to give a 0.1 acceptance rate for the simulation. The reverse direction coercive field moves toward positive values as the rate is decreased, causing the loop to widen.

The results are for a single hysteresis loop produced by first cooling the system by remaining at a large field with an initially aligned configuration of antiferromagnet grains. After sufficient time, an equilibrium in the reversed and unreversed grains is reached. After this point, the loop is made by varying the field with a uniform rate R between maximum and minimum fields of 2.5 (in reduced units). The rate is given in units of reduced field per time step.

If the rate is very large, there is no hysteresis loop. At slower rates, the reverse coercive field changes and moves towards positive fields. As the rate is lowered, the amount by which the coercive field changes is greater. Note that in this example, only the reverse field changes. This is because of the initial cooling at a static field so that the first loop always begins from the same equilibrium number of reversed and unreversed antiferromagnets.

It is seen immediately that the coercivity is a sensitive function of time. The coercivity measured when the applied field is taken in the reverse direction, from positive to negative, can differ from the coercivity measured when the field is taken in the forward direction, from negative to positive. This difference appears only if the rate of change of the field is slow enough to allow time for reversals to occur in the antiferromagnet.

In general, the forward and reverse coercive fields vary during cycling because the system does not have time to reach equilibrium at each extreme of the loop. This was observed several years ago by Schlenker[16] and can be understood as follows. The barrier to reversal, Eq. (7), is reduced

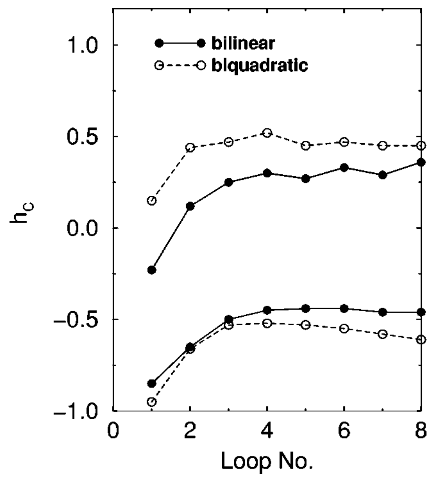

FIG. 3. Reduction of coercive field with repeated loop measurements. The coercive field changes each time the system is cycled through a hysteresis loop. The amount of change depends on the rate of cycling and temperature, and appears for both types of coupling. Over enough cycles, limiting values for the coercive fields are reached.

only when a twist forms (making ψ nonzero). Consequently, starting at the positive field side of the loop, the number of reversals per time is small, and remains small, for decreasing fields until reversal begins. The start of reversal determines the first coercive field, and it is at this point that thermal activation of the antiferromagnet accelerates as the ferromagnet aligns with the field in the negative direction. The reversals continue as long as the ferromagnet is aligned with the field. This increases the number of reversed antiferromagnets which results in a shift of the next coercive field towards less negative values. When the ferromagnet finally realigns in the positive direction, the coercive field appears at a much reduced value compared to before. It can even be of opposite sign.

The dependence of field rate follows from this. A slow rate of change of the field means that the the antiferromagnet reversals can occur over a longer time period, leading to large changes in the coercive fields. This happens for both the forward and reverse directions, strongly reducing the magnitude of the bias. If the field rate is very low, one essentially ''field'' cools the system at each end of the hysteresis loop. When the field rate is very large, few antiferromagnet reversals occur during the loop, and a large bias appears with only one value for the coercive field.

Because of this dependence on time at the extremes of the loop, repeated loops taken in succession do not necessarily result in repeated values for the coercive fields. This is illustrated in Fig. 3 where the coercive fields determined from a sequence of hysteresis curves are shown using the same parameters as for the calculations shown in Fig. 1. The horizontal axis is the hysteresis loop number, and the curves show the forward and reverse coercive fields for a sequence of loops. The field rate is constant during each portion of a loop with magnitude of 0.2 in reduced units. The solid lines show coercive fields for the bilinear coupled system, and the dashed lines show coercive fields for the biquadratic coupled system using the parameters from before. The tendency is to reduce the magnitude of the bias, and the forward and reverse coercivities decrease with repeating cycling. The coercivity decreases quickly at first, and eventually reaches limiting values. The rate of decrease, and value of the limit, depend upon temperature and the field rate. Note that it is possible to arrive at a limiting value while still retaining a shift, as seen in this case for the biquadratic coupled system. The results for biquadratic coupling in this example resemble recent results by O'Grady, *et al.*,[5] with a rapid decrease of the forward coercive field compared to the reverse coercive field, and a limit behavior for both as the cycling is continued.

It is also interesting to note that the antiferromagnet reversal dynamics determine the direction the bias takes relative to the antiferromagnet anisotropy axis during cooling. For bilinear coupling in particular, it is possible to create a bias direction by field cooling in any direction. The bias direction is determined by the relative fractions of reversed and unreversed antiferromagnets. The only requirement is to keep the field aligned in a particular direction long enough for the antiferromagnet system to relax into the orientation determined by the ferromagnet.

Viscosity depends on irreversible processes, and can result in a variety of phenomena. One of these is anomalous viscosity in which the viscosity measured as $S = dM/d\ln t$ changes sign. Anomalous viscosity can be observed in the exchange bias system as follows. First, the system is cooled in a large field. After cooling, the field is reversed and ramped to a negative value less than the saturation field. Then the applied field is reduced to zero and again held constant. The anomaly occurs at the end if the magnetization first tends towards its field cooled value before reversing towards a lower equilibrium value. This behavior has been observed experimentally in Ni/NiO structures.[22]

Anomalous viscosity was found to occur in the exchange bias system only for certain values of ferromagnetic coupling J between ferromagnetic grains, and only if magnetostatic demagnetizing fields were present. These are included in the theory by supposing that each ferromagnetic particle has total moment $V\mathbf{M}$, where V is the particle volume. The magnetostatic field at a given particle is then computed by summing over the fields produced by the other particles in the structure in order to find the total demagnetizing field $\mathbf{h_d}$ acting on the grain. This demagnetizing field is given by

$$\mathbf{h_d} = V\sum_k \left[\frac{\mathbf{M}_k}{r^3} - 3\frac{\mathbf{M}_k\cdot\mathbf{r}}{r^5}\mathbf{r}\right]. \tag{11}$$

Here, the subscript k denotes the particle, the sum is over all particles in the sample and $\mathbf{r}$ is a vector between the kth grain and the grain at which the field $\mathbf{h_d}$ acts. The field $\mathbf{h_d}$ is added to the field $\mathbf{h_f}$ acting on the ferromagnet grain. Finite boundary conditions are used instead of periodic boundary conditions for calculations that include $\mathbf{h_d}$.

Results for a biquadratic exchange-coupled system are shown in Fig. 4 where the magnetization is plotted against field during the generation of a minor loop as described above. The low-field end of the loop is shown in the inset. The time dependence for the same calculation is shown in Fig. 5 where the magnetization at the end of the loop is shown as a function of time with zero applied field. The time scale is logarithmic.

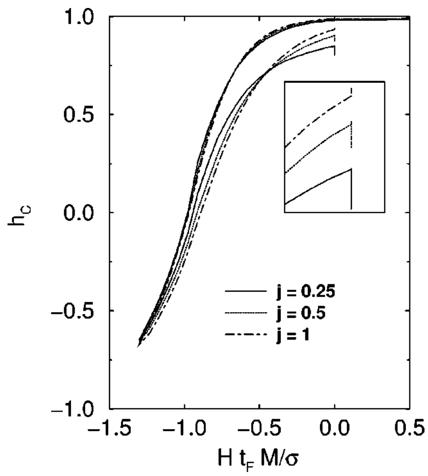

FIG. 4. Anomalous viscosity for a biquadratic coupled system taken through a minor loop between $Ht_FM/\sigma = -1.3$ and $Ht_FM/\sigma = 0$. A small anamolous viscosity is observed at the end for some values of the reduced ferromagnetic coupling, $j = J/\sigma$, between grains. The viscosity is driven by a competition between long-range dipolar interactions and the short-range ferromagnetic interaction.

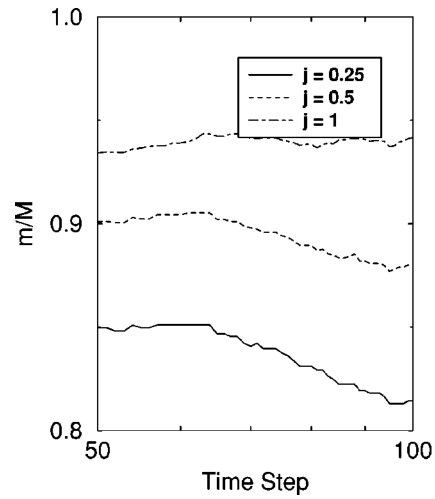

FIG. 5. The time dependence of the data at $Ht_FM/\sigma = 0$ for the curves shown in Fig. 4. The time axis is given in terms of numbers of discretization steps.

The viscosity S does not change sign for zero or large ferromagnetic exchange coupling J between particles. The reason for the dependence on J is that if the exchange coupling is small, ferromagnets coupled to reversed antiferromagnets can reduce Zeeman and interlayer exchange energy substantially by rotating into the field direction. If J is large, rotation of the ferromagnet on a particle with a reversed antiferromagnet is not favorable unless the neighboring particles also have reversed antiferromagnets. If the exchange coupling J is large enough, the initial response of the ferromagnet is to tend toward the initial saturated value. As more ferromagnets align, the magnitude of the demagnetizing field increases and opposes further alignment of the ferromagnets. If the intergrain ferromagnetic exchange is not too large, the process can reverse and an equilibrium configuration forms with a somewhat reduced magnetization in the field direction. Because of the sensitive dependence on exchange coupling and magnetostatic fields, existence of the anomalous viscosity is a measure of the magnitude of interparticle interactions and grain size.

IV. SUMMARY

A theory for time dependence of exchange-coupled magnetic systems has been presented. Bilinear and biquadratic coupling energies are used to describe exchange biased ferromagnet/antiferromagnet combinations, and the bias is created by the formation of partial walls in the antiferromagnet. The model is useful for exchange coupling across compensated, partially compensated, and uncompensated interfaces between ferromagnets and antiferromagnets, and results are in general agreement with atomistic numerical simulations.

A Monte Carlo technique is used to simulate time dependent hysteresis effects, and it is shown how thermal processes in the antiferromagnet alone are sufficient to produce coercivity observed through the ferromagnet. This differs from previous theories for hysteresis in exchange-coupled systems which involve either intrinsic or induced anisotropies in the ferromagnet itself. The present theory explains recent observations of rate dependent coercivity fields, with the result that forward and reverse coercive fields depend strongly on the rate of change of the magnetization field. Time dependent shifts are calculated for forward and reverse fields, and rate dependence is found for biquadratic and bilinear coupling. A prediction for anomalous viscosity is made. A related effect is that application of a large field in any direction long enough for equilibrium to be reached creates a direction for the bias.

Finally, some comments are made on the how anisotropies in the ferromagnet affect the bias. When anisotropies are included in the ferromagnet, the model reproduces features observed in experimental studies of bias made as a function of applied field orientation θ_F. Experiments reported by Tang *et al.*, on Fe/MnPd bilayers,[6] show an angular dependence of the coercive fields that can be fit using a functional form for an energy that contains all the terms in Eq. (3) plus twofold and fourfold anisotropies appropriate to Fe(001) thin films.

The thermal properties are determined by activation of reversal processes with an energy barrier determined in part by the amount of energy contained within partial domain walls. This kind of process is not unique to exchange bias systems, and the theory described here can be adapted to describe time dependent thermal effects in other systems.

ACKNOWLEDGMENTS

The author thanks K. O'Grady, R. Camley, B. Hillebrands, T. Mewes, S. S. Parkin, R. Street, H. Sun, and R. Woodward for stimulating and useful discussions. Special thanks are given to Professor H. Danan for pointing out Ref. 16. This work was supported by an ARC Large Grant. The author also thanks the CNRS for support during the final stages of this work.

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