Micromagnetic and Preisach analysis of the First Order Reversal Curves (FORC) diagram

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The First Order Reversal Curve (FORC) diagrams of interacting single-domain ferromagnetic particle systems have been found experimentally to contain negative regions. In this paper, we use micromagnetic and phenomenological (Preisach-type) models to help explain the occurrence of these negative regions. In Preisach-type modeling, the position of the negative region is correlated with the sign of the mean-field interactions. In micromagnetic modeling, the position of the negative region is correlated with the spatial arrangement of the particles in the model. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1557656]

INTRODUCTION

Recently, the First Order Reversal Curves (FORC) (Ref. 1) diagrams were proposed as an experimental method for the characterization of interparticle interactions in particulate ferromagnetic systems. FORC diagrams are more convenient than other similar experimental methods because they do not require that the magnetization be measured in a remanent state and because they do not require an ac demagnetized state, as is the case in the well-known ΔM experimental procedure. In previous studies with FORC diagrams, both positive and negative regions have been observed on the experimental diagrams. To better understand the source of these negative regions, we have simulated particulate magnetic media with both micromagnetic (a bidimensional system of single-domain particles with magnetostatic interactions with the magnetic moment dynamics described by the Landau–Lifshitz–Gilbert equation) and phenomenological Preisach models. We propose an explanation for why the negative region occurs and what parameters are influencing it.

THE FORC DIAGRAM

A first order reversal curve starts from the descending branch of the Major Hysteresis Loop (MHL) at a reversal field H_r, as illustrated in Fig. 1. The FORC evaluated as a function of the applied field H, where $H>H_r$ is denoted by $m^-_{\mathrm{FORC}}(H_r,H)$. The FORC distribution is defined as the mixed second derivative of the set of first order reversal curves,

$$\rho(H_r,H)=-\frac{1}{2}\frac{\partial^2 m^-_{\mathrm{FORC}}(H_r,H)}{\partial H_r \partial H}. \qquad (1)$$

There is a strong similarity between the definition of the FORC diagram and the experimental method for the determination of the Preisach distribution for a system obeying to the deletion and congruency properties, as presented by Mayergoyz.[2] The FORC diagram and the Preisach distribution will be identical for a system correctly described by the Classical Preisach Model (CPM). But with FORC diagrams, we apply this nonparametric identification procedure directly to the experimental data of any system, regardless of whether it is correctly described by the CPM. As presented in previous papers, the FORC diagram can have strange patterns when measured for various magnetic[1,3] samples. To help us understand the causes of these patterns, we have performed FORC diagram analysis of both micromagnetic and Preisach-type models, as presented in the following sections.

MICROMAGNETIC MODEL

We have simulated the hysteresis behavior of a system of uniaxial single-domain ferromagnetic particles with magnetostatic inter-particle interactions. The particles are arranged in a 2D lattice like the one presented in the Fig. 2, and have

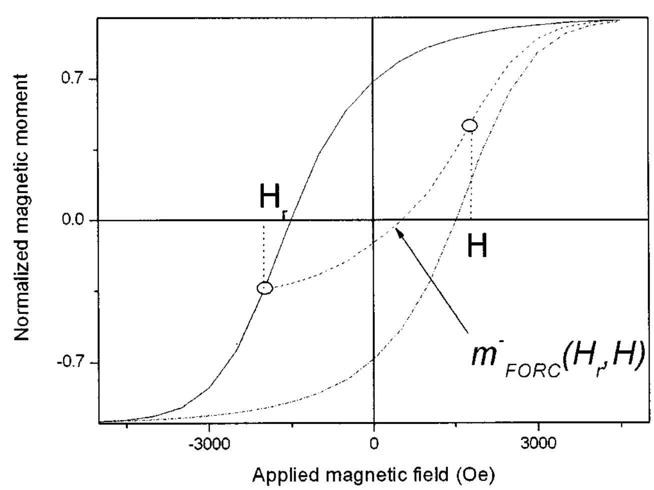


FIG. 1. MHL and FORC curve starting from the descending branch of the MHL.

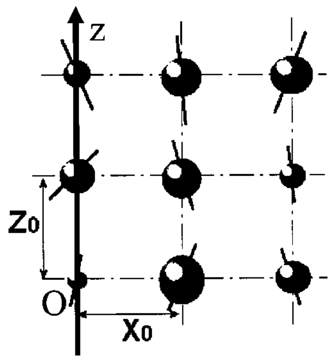
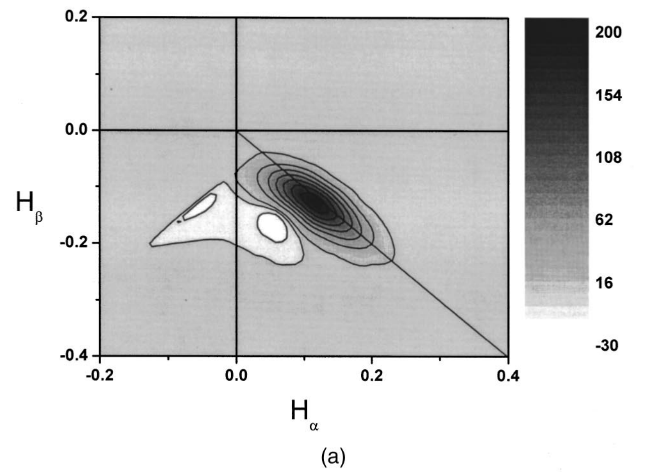


FIG. 2. Particulate system used in the micromagnetic simulation. For each particle the orientation of the easy axis is shown with solid line.

a distribution of easy axes orientations and volumes. Two types of 2D geometries were used (see notation on Fig. 2). In geometry A we let $z_0 > x_0$ (typical for systems of oriented acicular particles) and in geometry P we let $z_0 < x_0$ (typical for systems of platelets particles, like barium ferrite). In our simulations, the external field is applied on the Oz direction. The evolution of the magnetization was calculated with the well-known full 3D Landau–Lifshitz–Gilbert[4,5] equation. Continuity conditions were considered, and in each simulation a complete analysis of the interparticle magnetostatic interactions was performed. These interactions are distributed and both the average value and the variance are dependent on the magnetic state of the system. If the interaction field distribution average becomes positive when the total magnetic moment of the system is positive and becomes negative when the moment is negative, the system is referred to as a system with a positive mean interaction field. If the average is positive when the moment is negative and negative when the moment is positive, the system is referred to as a system with a negative mean interaction field. In our analysis we have found that the P-type geometry is associated with positive mean field interactions, while geometry A is associated with negative mean field interactions. In Fig. 3(a) we present a simulated FORC diagram generated with the micromagnetic code for a "P"-type sample and in Fig. 3(b) we present a FORC diagram for a "A"-type sample. While the "P"-type system has a FORC diagram with the maximum value above the $-45°$ line defined by $H_\beta = -H_\alpha$, the same maximum is shifted below this $-45°$ line for the "A"-type systems. Both FORC diagrams have negative value regions but in different places. To better understand these diagrams we next use a Preisach approach.

PREISACH SIMULATION OF THE FORC DIAGRAM

With a Generalized Moving Preisach model[6] one obtains FORC diagrams like those presented in Figs. 4(a) and 4(b) (for positive and negative moving parameter, respectively), that are in excellent agreement with the micromagnetic calculations presented in the previous section. As shown by Della Torre and Vajda,[7] the systems with linear mean field interactions can be analyzed in a straightforward way in the *operative field plane* in which on the field axis one uses instead of the applied field, H_{appl}, the operative field, H_{op},



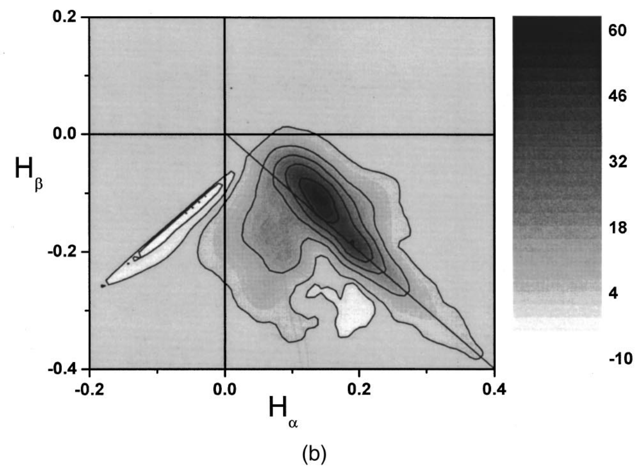


FIG. 3. (a) FORC diagram for micromagnetic calculation and geometry A, i.e., $z_0 > x_0$, where the applied field is along the z axis. The mean interaction field, in this case, is positive. (b) FORC diagram for micromagnetic calculation and geometry A, i.e., $z_0 < x_0$, where the applied field is along the z axis. The mean interaction field, in this case, is negative.

given by $H_{\mathrm{op}} = H_{\mathrm{appl}} + \alpha m$, where α is the moving constant, and m is the value of the magnetic moment normalized to the saturation magnetic moment of the sample. The experimental magnetization loops, can be transferred into the operative field plane by performing a simple transformation with respect to the $m=0$, $H_{\mathrm{appl}}=0$ point clockwise for positive moving constant and counterclockwise for negative moving constant. The mixed double derivative of the FORCs, (1), have a simple geometric[2] interpretation. Since the angle between the tangent to a FORC and the field axis is given by

$$\theta(H_r,H) = \arctan\left[\frac{\partial m^{-}_{\mathrm{FORC}}(H_r,H)}{\partial H}\right], \tag{2}$$

(1) can be written as

$$\rho(H_r,H) = -\frac{1}{2}\frac{\partial[\tan\theta(H_r,H)]}{\partial H_r}. \tag{3}$$

The FORC diagram is positive when $\tan[\theta(H_r,H)]$ is a monotonically decreasing function of H_r for a fixed value of H. This can be observed easier on a plot of the curves characterized by the same value of the susceptibility on the FORC curves described by the equations $\theta(H_r,H) = \text{constant}$ (see

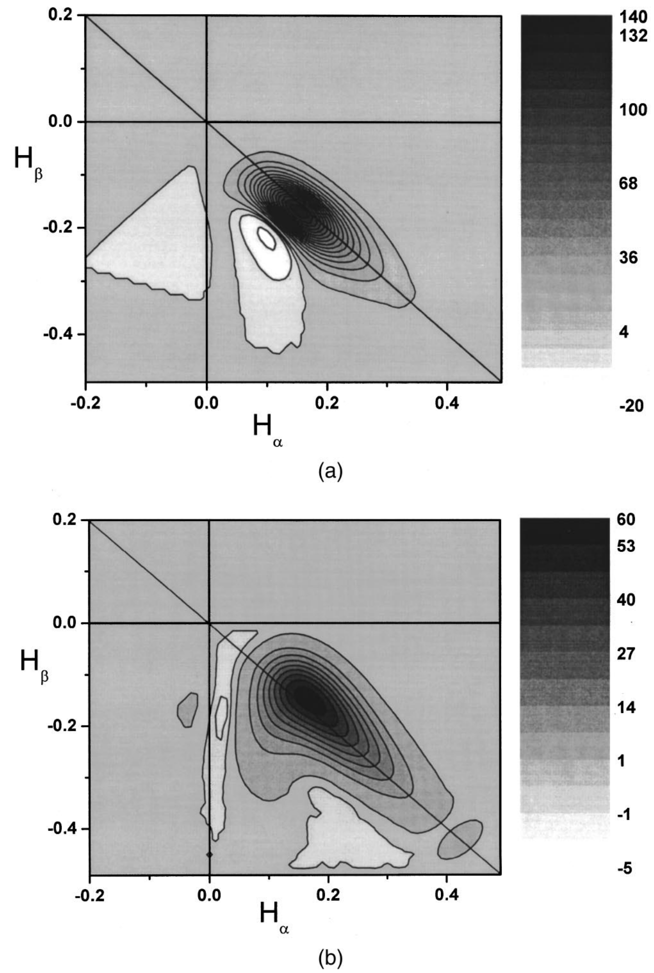


FIG. 4. (a) FORC diagrams calculated with the Preisach model for positive moving parameter. (b) FORC diagrams calculated with the Preisach model for negative moving parameter.

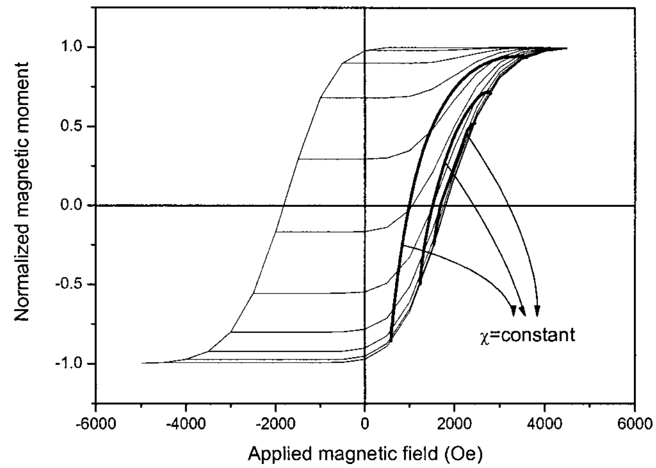


FIG. 5. Curves of equal susceptibility (χ) in the (H,m) plane.

Fig. 5). To have a positive FORC diagram the lines parallel to the m axis in the (H,m) plane (experimental plane) should not intersect twice any equal susceptibility curve. The mixed derivatives for the FORC diagram are calculated along lines parallel to the m axis in the experimental plane. These lines, in the operative field plane, have the slope $1/\alpha$ and are referred to as the transformation lines. If the transformation lines intersect twice the equal susceptibility curves in the operative field plane, that will generate negative regions on the FORC diagram. In Fig. 5 one can also observe that the negative region on the FORC diagram for positive mean field interactions is obtained at H fields less than the field corresponding to the FORC diagram maximum (H_0) and for H_r in the vicinity of $-H_0$. The case of negative mean field interactions is not so obvious. The negative region is in this case given by the FORCs starting on the descending branch of MHL near the negative saturation and for H fields near the positive saturation.

CONCLUSIONS

Our micromagnetic calculations show that systems with different geometrical structures will have negative regions in different locations on a FORC diagram. When the negative region occurs at fields higher than the field corresponding to the FORC diagram maximum, one can conclude that the system has a geometry similar to an oriented acicular particulate system, where the mean field interactions will have a demagnetizing effect. When the negative region is obtained for lower fields, this implies that the system geometry is like an ensemble of platelet particles, and that the mean interaction field has a magnetizing effect.

ACKNOWLEDGMENT

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