Major loop reconstruction from switching of individual particles

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Major hysteresis loops of groups of isolated 60 μm square garnet particles of a regular two-dimensional array, have been measured magnetooptically. Individual loops for each particle were measured, and the statistics of the distribution of coercivities and interaction fields was determined. It is shown that from the measured coercivity distribution and calculated magnetostatic interaction fields the major hysteresis loop can be reconstructed. The switching sequence, and the major loop of an assembly of 5×5 particles were calculated numerically for two cases: first, when calculating the magnetostatic interaction, the 25 particles were assumed to be isolated; second, the major loop of the same 25 particles, embedded into a 9×9 square, was reconstructed taking into account the interactions among all 81 particles. The numerically simulated major hysteresis loops agree very well with the measured loops, demonstrating the reliability of numerical modeling. [S0021-8979(97)39208-1]

I. INTRODUCTION

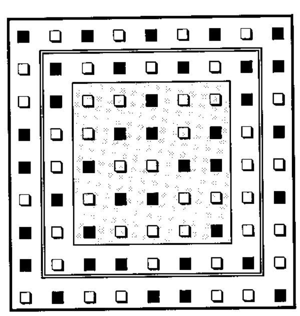
Frequently, information about microstructural characteristics is needed for optimizing materials technology. Structural properties are reflected in coercivity of individual particles, and the material's homogeneity is related to the standard deviation of coercivity. These properties are studied on an artificially structured sample of a regular two-dimensional array of separated, uniaxial, small garnet particles, which were shown to correspond to the assumptions of the classical Preisach model of hysteresis.[1,2] Each particle has a rectangular hysteresis loop. The requirements of wiping-out and congruency properties are fulfilled as there is no reversible magnetization contribution.

This unique system provides us with the opportunity to learn the properties of each individual particle, obtain statistical distributions, and measure macroscopic characteristics. We examine the question of the reliability of the conclusions reached about the microstructure, shape, and size distribution of particles in a particulate material, based on major loop measurements and numerical calculation of magnetostatic interactions. The coercivity of these particles has a Gaussian distribution, and the statistics of the interaction fields follow a Lorentzian distribution.[1–4] The particles have a rectangular shape and the magnetostatic interaction fields can be calculated numerically.[5] Using the measured distribution, the major loop of above assemblies can be reconstructed from the numerically calculated magnetostatic fields, either by using the measured individual switching fields, or the Gaussian distribution parameters. It is shown that major loops can be predicted from numerical, statistical switching models. The numerically simulated major hysteresis loop agrees very well with the measured loop, demonstrating the reliability of numerical modeling.

II. EXPERIMENTS

Magnetization measurements in a magneto-optical setup have been performed on individual particles and square groups of garnet particles (pixels) which are part of a regular two-dimensional array of thousands of pixels within a 5×5 mm^2 sample. The size of each pixel is 60×60×3 μm^3. They are separated by 12-μm-wide nonmagnetic grooves. These particles are etched into a single crystalline epitaxial magnetic garnet film, grown on a transparent nonmagnetic $Gd_3Ga_5O_{12}$ substrate permitting direct visual observation via the magneto-optical Faraday effect with simultaneous electrooptical recording the state, and the hysteresis loop of any pixel or group of pixels (picture elements), using masks, transmitting the light to the detector from only the selected pixel. The pixels are single domain particles, with a very high uniaxial anisotropy field of 2.2 kG of the film, as compared to $4\pi M_s=160$ G.

Because of the high uniaxial anisotropy, the pixels have only two stable magnetic states along the film normal: ''up'' and ''down'', corresponding to ''bright'' and ''dark'' contrast in the micrograph of the switching state of the film. Figure 1(a) illustrates the system. Each pixel has a rectangular hysteresis loop. The major loop and the up and down switching fields (H^+ and H^-) have been measured for 81 (9×9) individual pixels. The coercivity of a pixel is $H_c=(H^+-H^-)/2$. The average H_c for the 81 particles is 223 Oe, the standard deviation $\sigma_c=104$ Oe. Major hysteresis



(a)

79	36	48	29	37	66	33	16	57
69	23	9	78	76	19	7	54	5
43	4	74	64	59	31	62	46	18
70	56	80	52	41	15	73	67	39
75	61	42	71	1	35	60	50	6
24	38	65	45	13	20	72	28	22
14	55	30	3	26	10	40	63	12
58	49	8	51	32	53	77	81	27
34	44	25	47	11	2	21	68	17

(b)

FIG. 1. (a) Geometry of the group of 9×9 pixels; (b) Simulated switching sequence of the 9×9 group of pixels. Pixel (i,j) is located in row i, column j.

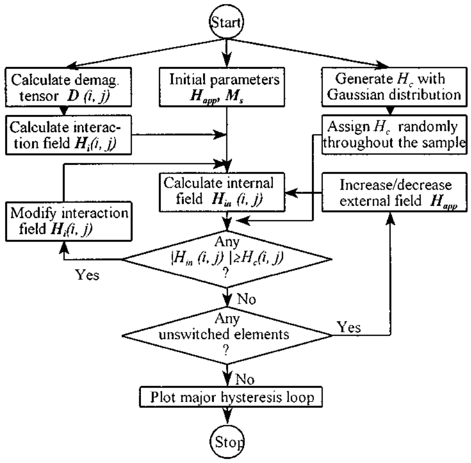


FIG. 2. Flow chart of the numerical model for major hysteresis loop reconstruction.

loops of squares of pixels, embedded into a larger group of particles, have also been measured.

III. SIMULATIONS

Figure 1(a) illustrates the system. As it was shown in Refs. 3 and 4, this system is a good model for studying the switching characteristics of Stoner–Wohlfarth-like particles[5] and Preisach models[6] of magnetic hysteresis. Our measurements and simulations are based on six different size pixel groups. In Fig. 1(a) three of them are shown, containing 5×5, 7×7, and 9×9 pixels.

The procedure to reconstruct the major hysteresis loops is shown in the flow chart of Fig. 2. The external field $H_{\rm app}$ is applied normal to the sample plane (z axis). The magnetization is along the film normal. The pixels interact magnetostatically.[7,8] The effective field acting upon a pixel depends on the state of the neighbors. Assuming the external magnetic field is in the $+z$ direction, each neighbor with a magnetization along $+z$ will have an effective demagnetizing effect on the neighbors having $+M$, i.e., reducing the internal field $H_{\rm in}$, and a magnetizing effect on neighbors with $-M$.

Due to the nonellipsoidal shape, the internal field is not uniform, even when $H_{\rm app} \geqslant 4\pi M_s$. The reason is that the demagnetizing field, acting on each pixel from all other pixels, is not uniform.[9] The interaction tensor elements' $D(|i-i_0|,|j-j_0|)$ at each pixel (i_0,j_0) from any other pixel (i,j) was calculated using the finite difference method (FDM), either by calculating the surface integrals or by the dipole approximation,[8] then the effective interaction field at any pixel, located at (i_0,j_0), from all other pixels can be obtained

$$H_i(i_0,j_0)=4\pi\, M_s \sum_{i,j} \Lambda \quad D(|i-i_0|,|j-j_0|),$$

where $\Lambda=\pm 1$, depending on the orientation of M_s.[10] The internal field acting on each individual pixel can be calculated by

$$\begin{aligned} H_{\rm in}(i_0,j_0) &= H_{\rm app} - H_i(i_0,j_0) \\ &= H_{\rm app} - 4\pi M_s \sum_{i,j} \Lambda D(|i-i_0|,|j-j_0|). \end{aligned} \quad (1)$$

Starting from negative (or positive) saturation, the program changes $H_{\rm app}$ until the condition

$$|H_{\rm in}(i_0,j_0)| \geqslant H_c(i_0,j_0) \quad (2)$$

is satisfied for a particular pixel, where $H_c(i_0,j_0)$ is the coercivity of this pixel, then this pixel will switch up or down. $H_i(i_0,j_0)$ and $H_c(i_0,j_0)$ fully determine if the pixel will change its state at the certain external field $H_{\rm app}$.

Once there is a pixel whose state has been changed, the distribution of the interaction field changes. From Eq. (1) it follows that the distribution of the internal field also, changes the new internal field $H_{\rm in}^{\prime(i_0,j_0)}$ acting on each individual pixel can be calculated by

$$H'_{\rm in}(i_0,j_0)=H_{\rm in}(i_0,j_0)+8\pi M_s D(|i_0-i_s+1|,|j_0-j_s+1|), \quad (3)$$

where (i_s,j_s) is the location of the pixel which just switched its state. Using the formula, the simulation time can be drastically reduced, especially for the three-dimensional (3-D) case.

There are two ways to obtain the coercivity distribution $H_c(i_0,j_0)$. Based on the measurement of switching fields of individual pixels,[1–3] it is known that the coercivity of this system has a Gaussian distribution, with known mean value and standard deviation. The coercivities can be generated based on these two values and these values are assigned to each individual pixel randomly. Another way is to use the measured coercivity of each pixel.

Changing $H_{\rm app}$ between negative and positive saturation, the magnetization curve, i.e., the major loop M vs $H_{\rm app}$ is reconstructed from the sequence of the individual switching events.

IV. RESULTS AND DISCUSSIONS

The measured major hysteresis loops for different groups of pixels are shown in Fig. 3(a). The results of simulation, corresponding to these measurements, are shown in Fig. 3(b). The correspondence between the two sets of data is very good. The simulation is based on measured pixel coercivities. Each pixel was assigned its measured H_c. If the coercivities are assigned randomly, the loops do not change much, but the sequence of switching is different for a pixel group. Figure 1(b) shows the switching sequence for a 9×9 pixel group using the measured H_c.

These 9×9 pixels are part of thousands of pixels in the film. So, they are not isolated. Their switching is affected by the pixels beyond the measured 9×9 pixels. In order to examine the difference between the embedded case, where the interaction and the state of the neighbors are taken into account, and the isolated case when the effect from any outside pixels is ignored, an assembly of 5×5 pixels [shaded in Fig. 1(a)], isolated, or embedded into a 9×9 group, was measured and modeled. Figure 4 shows the simulated major hysteresis loops for both cases. The interaction with all pixels in the

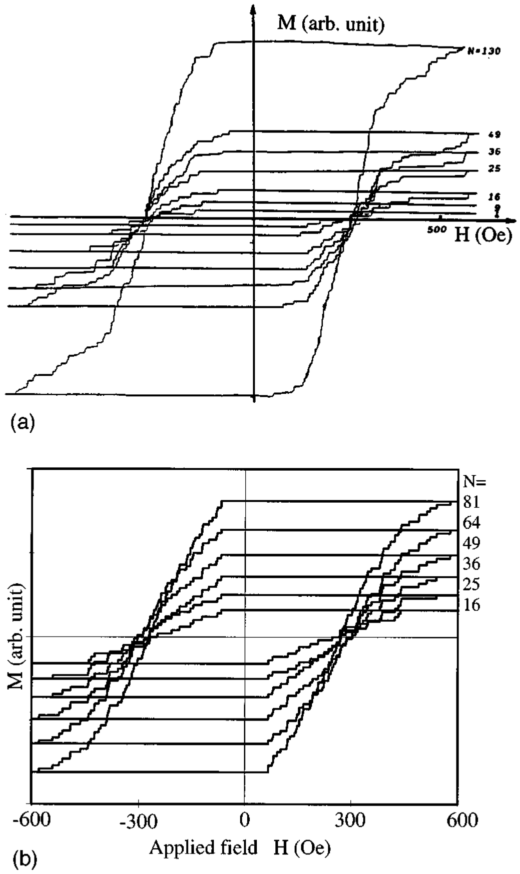


FIG. 3. Major hysteresis loops for different groups of pixels: (a) measured, (b) simulated.

9×9 group are taken into account when calculating the switching of 5×5 pixels. The isolated loop is somewhat more steep than the embedded, showing the effect of the boundary conditions. According to Ref. 9, the interaction fields from outside the 9×9 pixels contribute only 3% to the fields from the pixels inside of the 9×9 group.

The model and the simulation are very reliable and efficient to reconstruct the major hysteresis loop based on the calculated interaction fields and measured major loop coercivity and its standard deviation. Figure 5 shows the calculated switching sequence for the same 5×5 group, embedded into a group of 9×9, and isolated. Figure 5(b) is exactly the same sequence what was actually measured.

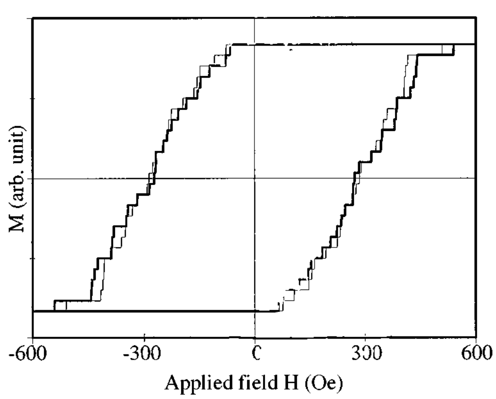


FIG. 4. Major hysteresis loops for 5×5 pixels: isolated (thin line); embedded in a 9×9 group (thick line).

(a)

24	19	16	9	18
25	15	12	5	23
13	21	1	10	17
20	14	4	6	22
8	2	7	3	11

(b)

22	20	17	8	18
25	15	11	5	23
14	24	1	10	16
19	12	3	6	21
9	2	7	4	13

FIG. 5. Switching sequence of a group of 5×5 pixels: (a) isolated group; (b) embedded into a 9×9 group.

More strong evidence to verify our model and simulation is in comparing the average measured value of the coercivity for the 5×5 pixels: $H_{avg}=234$ Oe which agrees well with the simulation for the isolated 5×5 group, $H_{isol}=233$ Oe. As it is expected, the embedded loop simulation gives a result $H_{emb}=217$ Oe, very close to the measured major loop $H_c=213$ Oe.

V. CONCLUSIONS

The major hysteresis loops of groups of particles and the switching fields of each individual particle have been measured magneto-optically. A numerical model has been built to reconstruct the major loop for these assemblies. The simulation results agree very well with the measurements. This demonstrates the efficiency and reliability of numerical modeling.

Thermal fluctuations, leading to fluctuating values of individual switching fields, are not included in the present analysis. This is the reason that the calculated switching sequence is always the same for the same group of pixels. However, repeated measurements of major loops consistently show the same switching sequence, indicating that for the given system the dominant factor, governing the shape of the major loop, is the distribution of the coercivities of the individual particles. This coercivity, in turn, is determined by the microstructure and the defects of the particles.

ACKNOWLEDGMENTS

Stimulating discussions with E. Della Torre and L. H. Bennett are appreciated.

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