First-Order-Reversal-Curve Analysis of Nano-composite Permanent Magnets

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ABSTRACT

The magnetic properties of permanent magnet materials are usually characterized by measuring a hysteresis loop using a vibrating sample magnetometer (VSM). Nano-composite permanent magnets consist of a dispersion of nano-scale magnetic particles that can contain more than one magnetic phase, and interactions between particles can negatively impact the magnetic performance of the magnet. It is not possible to unravel the complex magnetic signatures of multiphase materials or to obtain information of interactions or coercivity distributions from the hysteresis loop alone. First-order-reversal-curves (FORC) provide a means for distinguishing between magnetic phases and for determining the distribution of interaction fields. In this paper we will discuss the FORC measurement and analysis technique, and present results for multiphase nano-composite permanent magnets.

Keywords: nano-composite permanent magnets, first-order-reversal-curves, FORC

1 INTRODUCTION

Rare-earth and ferrite permanent magnet materials are indispensable elements in many electronic devices such as electrical motors, hybrid vehicles, portable communications devices, speakers, sensors, etc. The magnets have major influence on the size, efficiency, stability, and cost of these devices and systems.

Owing to the decreased availability and increasing cost of rare-earth elements, significant research is underway to develop strong permanent magnet materials that do not rely as heavily on rare-earth constituents. These can include nano-composite exchange spring magnets comprised of a hard high coercivity phase, exchange coupled to a soft high saturation magnetization phase, which increases the energy density and decreases the cost of the magnet because less hard phase material is needed; multi-phase composite nanostructures such as soft shell/hard core magnetic nanowires; and hybrid magnets, etc.

Additionally, magnetically hard ferrite nano- or micron-scale powders are widely used owing to their low-cost production and good performance in many electronic devices and magnetic storage media. When the stoichiometry is not precise or the fabrication process is not adequate, however, the ferritic phase is accompanied by other phases that promote magnetic interactions that results in a decrease of the magnetic performance of the magnet.

The magnetic characterization of such materials is usually made by measuring a hysteresis loop using a VSM. It is very difficult, however, to unravel the complex magnetic signatures of multiphase materials and obtain information of interactions or coercivity distributions from the hysteresis loop alone. FORC provide a means for determining the distribution of interaction fields between magnetic particles, and for distinguishing between magnetic phases in composite materials that contain more than one magnetic phase.

2 MAGNETIZATION MEASUREMENTS AND FIRST-ORDER-REVERSAL-CURVES (FORC)

2.1 The most common measurement that is performed to characterize a materials' magnetic properties is measurement of the major hysteresis or M(H) loop. The parameters that are usually extracted from the M(H) loop are illustrated in Figure 1 and include: the saturation magnetization M_{sat} (the magnetization at maximum applied field), the remanence M_{rem} (the magnetization at zero applied field after applying a saturating field), and the coercivity H_c (the field required to demagnetize the material). For permanent magnet materials, the maximum energy product BH_{max}, which is determined from the second quadrant demagnetization curve, is also commonly of interest. Note that the measured coercivity H_c is the average coercivity (or average distribution of switching fields) of the entire ensemble of magnetic particles that constitute a magnetic material.

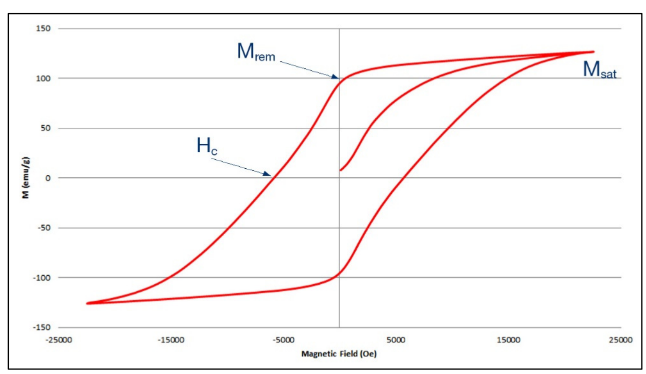

Figure 1: Hysteresis M(H) loop for NdFeB nanoparticles

More complex magnetization curves covering states with field and magnetization values located inside the major hysteresis loop, such as first-order-reversal-curves (FORC)[1], can give information that is not possible to obtain from the hysteresis loop alone. These curves include the distribution of switching and interaction fields and differentiation of multiple phases in composite or hybrid materials containing more than one phase. A FORC is measured by saturating a sample in a field H_{sat}, decreasing the field to a reversal field H_a, then sweeping the field back to H_{sat} in a series of regular field steps H_b. This process is repeated for many values of H_a, yielding a series of FORCs. This is illustrated in Figure 2. The measured magnetization at each step as a function of H_a and H_b gives $M(H_a, H_b)$, which is then plotted as a function of H_a and H_b in field space. The FORC distribution $\rho(H_a, H_b)$ is the mixed second derivative, i.e., $\rho(H_a, H_b) = -\partial^2 M(H_a, H_b)/ \partial H_a \partial H_b$.

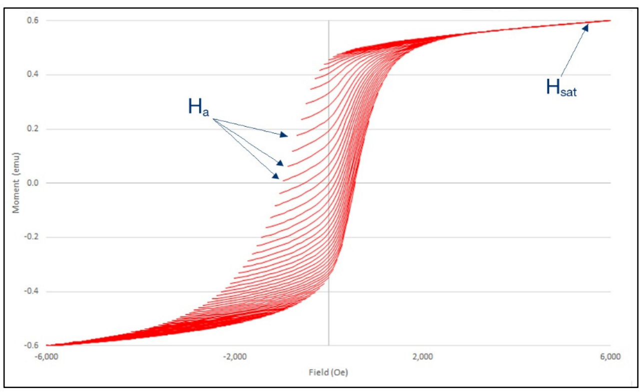

Figure 2: Measured first-order-reversal-curves for a ferrite permanent magnet

The FORC diagram is a 2-D or 3-D contour plot of $\rho(H_a, H_b)$ with the axis rotated by changing coordinates from (H_a, H_b) to $H_c = (H_b - H_a)/2$ and $H_u = (H_b + H_a)/2$, as illustrated in Figure 3, where H_u represents the distribution of interaction fields, and H_c represents the distribution of switching fields.

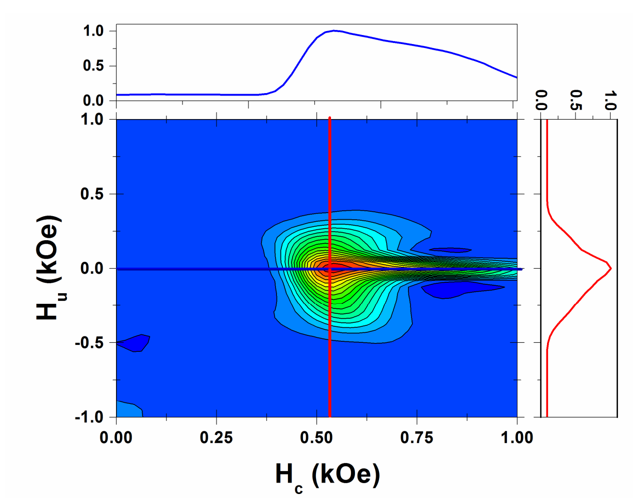

Figure 3: A 2-D FORC diagram for a periodic array of Ni nanowires showing the distribution of switching (H_c) and interaction (H_u) fields[2]

3 FORC RESULTS FOR MULTI-PHASE NANO-COMPOSITE FERRITE MAGNETS

To demonstrate the utility of FORC analysis for differentiating multiple phase materials, multi-phase composites were synthetically produced by mixing together single-phase magnets including: Sr-ferrite and Ba-ferrite nanoparticles, and yttrium-iron-garnet (YIG) and co-doped YIG nanoparticles. All magnetic measurements were performed at ambient temperature using a Lake Shore Cryotronics MicroMag™ vibrating sample magnetometer (VSM). There are a number of open source FORC analysis software packages such as FORCinel[3], although in this paper custom analysis software was used to calculate the FORC distributions.

Figure 4 and Figure 5 show the measured hysteresis M(H) loop and FORCs for a sample consisting of a mixture of Sr-ferrite and Ba-ferrite nanoparticles. The coercivities for each sample as determined from their individual M(H) loops were 1 kOe and 3 kOe, respectively. The coercivity for the mixed sample is 2.3 kOe and there is no clear evidence of multi-phase behavior from the M(H) loop results shown in Figure 4.

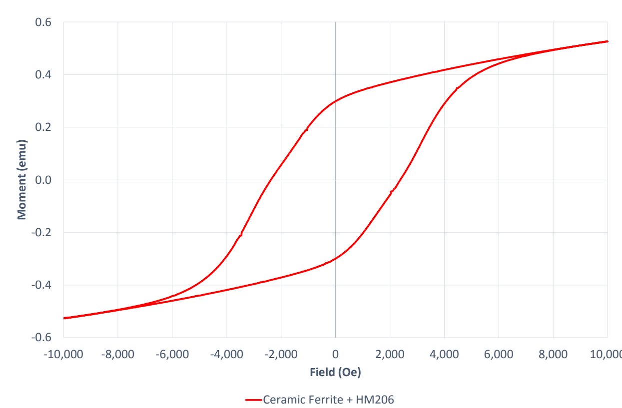

Figure 4: Hysteresis M(H) loop for a mixture of Sr-ferrite and Ba-ferrite nanoparticles

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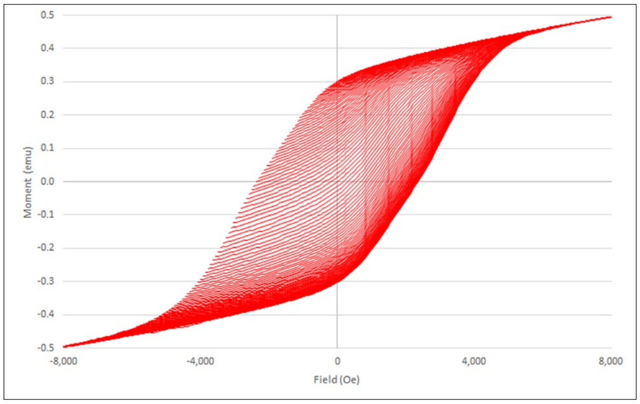

Figure 5: FORCs for a mixture of Sr-ferrite and Ba-ferrite nanoparticles

Figure 6 shows the 2-D FORC diagram for the mixture of Sr-ferrite and Ba-ferrite nanoparticles. There are two peaks in the distribution centered at 1 kOe and 3 kOe, corresponding to the Sr-ferrite and Ba-ferrite, respectively.

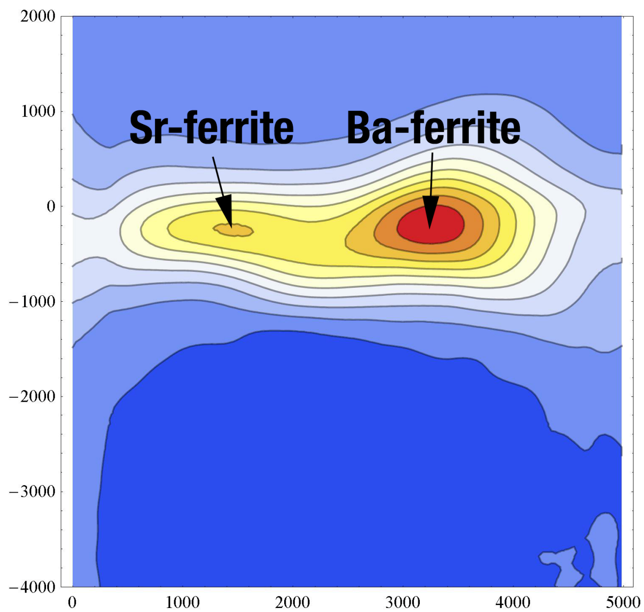

Figure 6: 2-D FORC diagram showing the distribution of switching (H_c) and interaction (H_u) fields for a mixture of Sr-ferrite and Ba-ferrite nanoparticles, showing the phases of each individual material clearly differentiated

Figure 7 shows the M(H) loop for a mixture consisting of a yttrium-iron-garnet (YIG) and co-doped YIG nanoparticles with individual coercivities (as determined from the individual M(H) loops) of 71 Oe and 950 Oe, respectively. The M(H) loop is devoid of any indication of multi-phase behavior.

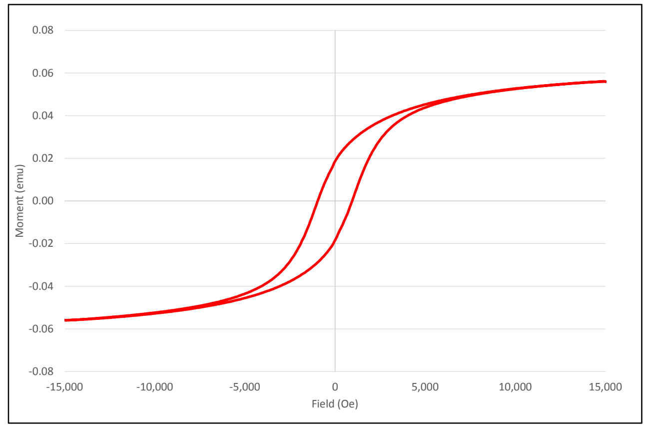

Figure 7: Measured M(H) loops for a mixture of YIG and co-doped YIG nanoparticles

Figure 8 and Figure 9 show the measured FORCs and 2-D FORC diagram, respectively, for the mixture of YIG and co-doped YIG nanoparticles. There are two peaks in the distribution centered at 71 Oe and 950 Oe, corresponding to the YIG and co-doped YIG nanoparticles, respectively.

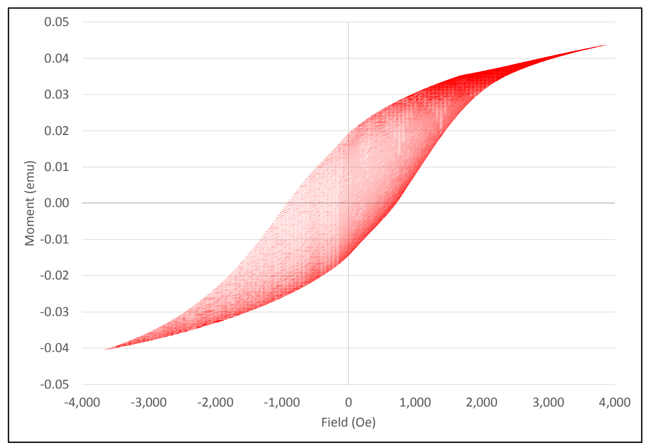

Figure 8: Measured FORCs for a mixture of YIG and co-doped YIG nanoparticles

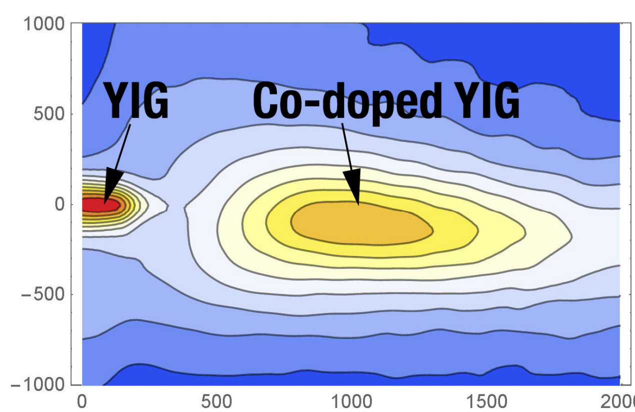

Figure 9: 2-D FORC diagram showing the distribution of switching (H_c) and interaction (H_u) fields for a mixture of YIG and co-doped YIG nanoparticles

4 CONCLUSIONS

FORC analysis is indispensable for characterizing interactions and coercivity distributions in a wide array of magnetic materials including: nanomagnets[2], permanent magnets[4], exchange-coupled magnetic multilayers[5], and geomagnetic and geological samples[6]. In this paper, we have shown that FORC also provides a means for distinguishing between magnetic phases in composite materials that contain more than one magnetic phase.

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