First-Order-Reversal-Curve (FORC) Studies of Nanomagnetic Materials

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ABSTRACT

The magnetic characterization of nanoscale materials is usually made by measuring a hysteresis loop. However, it is not possible to obtain information of interactions or coercivity distributions from the hysteresis loop alone. Studies of magnetic interactions and magnetization mechanisms at the nanoscale level are of interest not only from a fundamental perspective, but also from a technological perspective because interactions can significantly affect magnetic properties, which in turn impacts their usefulness for technological applications. First-order-reversal-curves (FORCs) are an elegant, nondestructive tool for studying the magnetic properties of materials composed of fine (micron- or nanoscale) magnetic particles. We will discuss the FORC measurement and analysis protocol, and present results for various nanoscale magnetic materials.

Keywords: first-order-reversal-curves, forc, nanoscale magnetic materials

1 MAGNETIZATION MEASUREMENTS AND FIRST-ORDER-REVERSAL-CURVES (FORCS)

The most common measurement used to characterize a material's magnetic properties is measurement of the hysteresis or M(H) loop. The most common parameters extracted from the hysteresis loop that are used to characterize the magnetic properties of magnetic materials include: the saturation magnetization M_s (the magnetization at maximum applied field), the remanence M_r (the magnetization at zero applied field after applying a saturating field), and the coercivity H_c (the field required to demagnetize the sample).

More complex magnetization curves covering states with field and magnetization values located inside the major hysteresis loop, such as first-order-reversal-curves (FORCs) can give additional information that can be used for characterization of magnetic interactions [1]. FORC has been extensively used by earth and planetary scientists studying the magnetic properties of natural samples because FORC can distinguish between single-domain (SD), multi-domain (MD), and pseudo single-domain (PSD) behavior, and because it can distinguish between different magnetic mineral species [2,3]. It has also been used to differentiate between phases in multiphase magnetic materials because it is very difficult to unravel the complex magnetic signatures of such materials from a hysteresis loop measurement alone [4,5,6].

A FORC is measured by saturating a sample in a field H_{sat}, decreasing the field to a reversal field H_a, then measuring moment versus field H_b as the field is swept back to H_{sat}. This process is repeated for many values of H_a, yielding a series of FORCs as shown in Figure 1. 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., $\rho(H_a, H_b) = -(1/2)\partial^2 M(H_a, H_b)/\partial H_a \partial H_b$. The FORC diagram is a 2D or 3D contour plot of $\rho(H_a, H_b)$. It is common to change the coordinates from (H_a, H_b) to $H_c = (H_b - H_a)/2$ and $H_u = (H_b + H_a)/2$. H_u represents the distribution of interaction or reversal fields, and H_c represents the distribution of switching or coercive fields. There are a number of open source FORC analysis software packages such as FORCinel [7] and VARIFORC [8]. In this work a Lake Shore Cryotronics vibrating sample magnetometer (VSM) was used to measure the FORCs, and FORCinel was used to calculate the FORC distributions and plot the FORC diagrams. A typical 2D FORC diagram is illustrated in Figure 2.

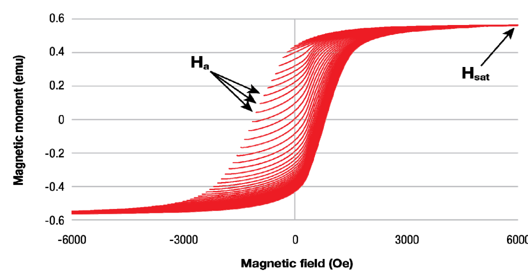

Figure 1: Measured First-Order-Reversal-Curves for a ferrite permanent magnet.

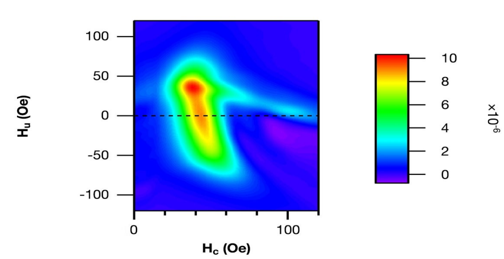

Figure 2: A typical 2D FORC diagram.

2 TYPICAL MAGNETIC MEASUREMENT RESULTS

In this section we will present FORC measurement and analysis results for: nanocomposite permanent magnets, nickel nanowire arrays, high density patterned media consisting of CoPt nanomagnet arrays, and exchange-biased magnetic multilayer thin films.

2.1 Nanocomposite Permanent Magnets

Rare-earth permanent magnet materials are indispensable elements in many electronic devices such as electrical motors, hybrid vehicles, and portable communications devices. The magnets have major influence on the size, efficiency, stability, and cost of these devices and systems [9]. Over the last couple of decades there has been interest in the development of nanostructured magnets, and exchange-coupled nanocomposite alloys with co-existing soft and hard phases because of the coercivity enhancement that is obtained at the single-domain size (nanometer scale).

To demonstrate the utility of FORC analysis for differentiating phases in exchange-coupled nanocomposites, FORC data were acquired on nanometer-sized barium hexaferrite $BaFe_{12}O_{19}$.

Figures 3 and 4 show the measured hysteresis M(H) loop and FORCs, respectively. Figure 5 shows the resultant 2D FORC diagram. There is a subtle 'kink' in the M(H) loop (Figure 3) at low fields suggesting the presence of a low and high coercivity phase. The FORC diagram (Figure 5) shows two peaks corresponding to the low and high coercivity components, and the region between the two peaks is related to the coupling between the two phases [10].

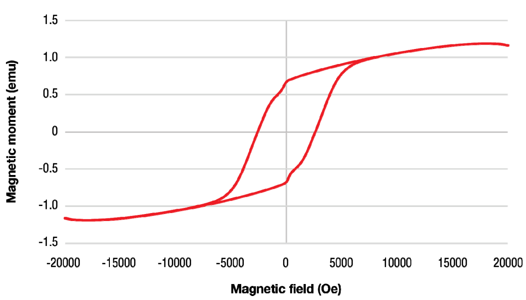

Figure 3: Hysteresis M(H) loop for $BaFe_{12}O_{19}$ nanoparticles.

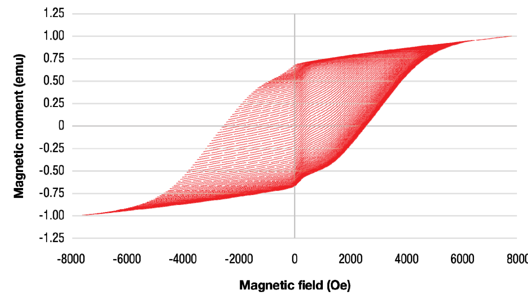

Figure 4: FORCs for $BaFe_{12}O_{19}$ nanoparticles.

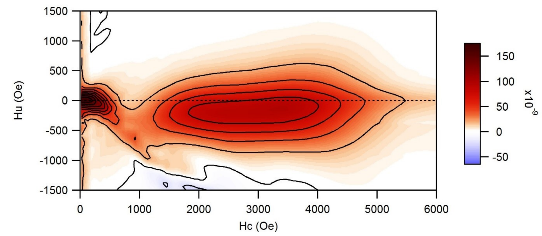

Figure 5: 2D FORC diagram showing the distribution of switching (H_c) and interaction (H_u) fields for $BaFe_{12}O_{19}$ nanoparticles, showing the low and high coercivity phases clearly differentiated.

2.2 Nanomagnet Arrays

Magnetic nanowires, nanodots, and nanoparticles are an important class of nanostructured magnetic materials. At least one of the dimensions of these structures is in the nanometer (nm) range and thus, new phenomena arise in these materials due to size confinement. These structures are ideal candidates for important technological applications in spintronics, high density recording media, microwave electronics, permanent magnets, and for medical diagnostics and targeted drug delivery applications. In addition to technological applications, these materials represent an experimental playground for fundamental studies of magnetic interactions and magnetization mechanisms at the nanoscale level. When investigating the magnetic interactions in these materials, one of the most interesting configurations is a periodic array of magnetic nanowires, because both the size of the wires and their arrangement with respect to one another can be controlled. Inter-wire coupling is one of the most important effects in nanowire arrays because it significantly affects magnetization switching, and microwave and magneto-transport properties. Experimentally, FORCs are used to investigate the effect and strength of these interactions.

Figure 6 shows a series of FORCs measured for a periodic array of Ni nanowires with a mean diameter of 70 nm and an inter-wire distance of 250 nm [11]. Figure 7 shows the FORC diagram and shows the distribution of both local interaction H_u and coercive H_c fields resulting from coupling between adjacent nanowires.

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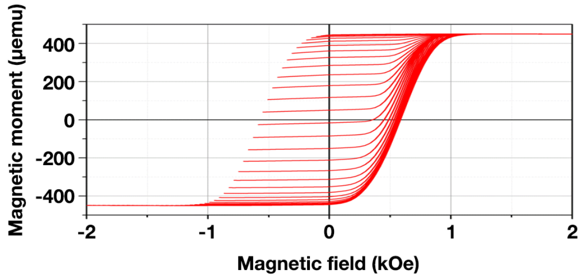

Figure 6: FORCs for an array of nickel nanowires.

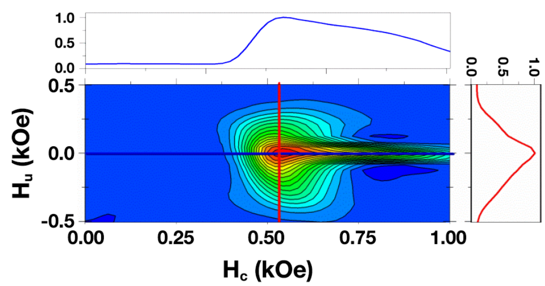

Figure 7: Distribution of interaction and coercivity fields as determined from FORC analysis.

Figure 8 shows a series of FORCs for an array of sub-100 nm CoPt nanomagnets in a high density patterned magnetic recording media, and Figure 9 shows the resultant FORC diagram. Note that the peak in the FORC distribution is shifted towards negative interaction fields (H_u, vertical axis), and that the distribution has a 'boomerang' shape. These features are typically associated with exchange interactions occuring between magnetic particles [12].

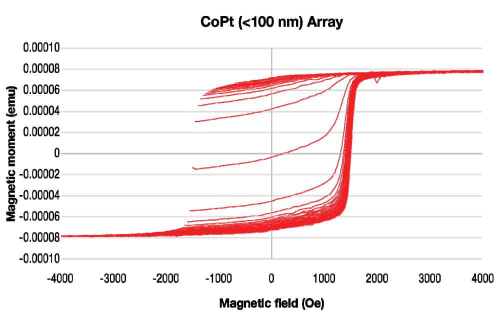

Figure 8: FORCs for an array of sub-100 nm CoPt nanomagnets.

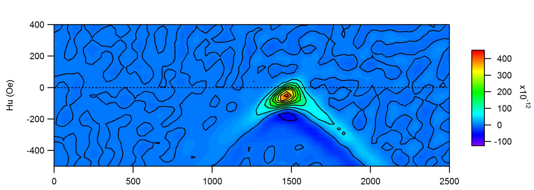

Figure 9: FORC diagram for an array of sub-100 nm CoPt nanomagnets.

2.3 Exchange Bias Magnetic Multilayer Films

Exchange bias magnetic multilayer films are technologically important materials for applications such as spin-valve read heads for hard disk drives, and gigahertz-range microwave devices. In these materials at least one anti-ferromagnetic (AFM) layer is intercalated between ferromagnetic (FM) layers. In addition to their technological applications, they are also useful for fundamental studies of magnetic interactions and magnetization reversal processes in magnetic nanostructures because both the number (n) of AFM/FM interfaces, and the thickness of the FM and AFM layers can be controlled.

Figure 10 shows the M(H) loop with the applied field oriented in-plane, and parallel to the easy axis for a multilayer film [13] of composition [FeNi (60 nm)/IrMn (20 nm)]n where FeNi represents Ni (80%) Fe (20%), and the number of layers n = 5.

When the magnetic field is applied parallel to the exchange bias field the loop is shifted towards the left (negative field values), and the exchange bias and coercivity fields are: H_{ex} = -30 Oe and H_c = 4 Oe. The extra steps in the curve between positive and negative saturation magnetization are related to microstructural defects/roughness of the AFM/FM interfaces. FORC analysis can give a more detailed account of the effect of in-homogeneities on the magnetization reversal of the AFM/FM interface.

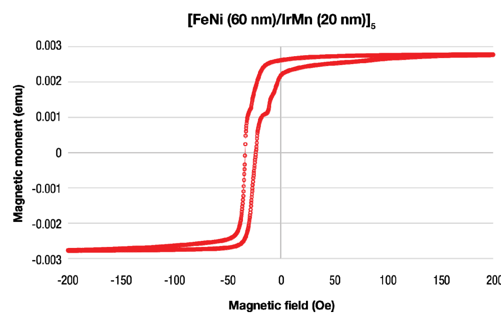

Figure 10: Hysteresis loop for [FeNi (60 nm)/IrMn (20 nm)]$_5$ for the applied field parallel to the easy axis.

Figure 11 shows a series of FORCs for the field oriented parallel to the exchange bias field, and Figure 12 shows the corresponding FORC diagram [14]. In the diagram there is a main FORC distribution that is centered around H_c (4 Oe), however note that the distribution of switching fields extends over several Oe. The peak of the distribution in the H_u direction corresponds to the exchange bias field H_{ex} (-30 Oe). The spread of the distribution in the H_u direction is related to interactions between the AFM and FM layers. The satellite distribution centered at H_u = -20 Oe and H_c = 7 Oe is related to structural in-homogeneities at the

AFM/FM interface and are more pronounced the higher the number of layer repetitions, or equivalently the higher the number of AFM/FM interface in-homogeneities. The FORC measurement and analysis protocol provide additional information that cannot be obtained from the standard hysteresis loop measurement alone.

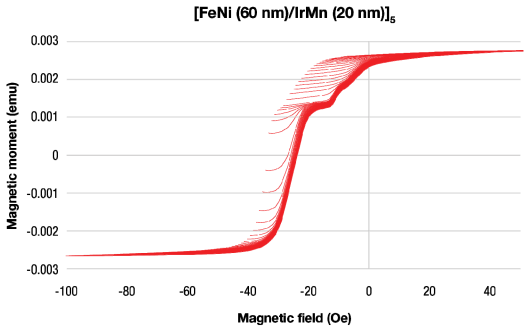

Figure 11: FORCs for [FeNi (60 nm)/IrMn (20 nm)]$_5$ for the applied field parallel to the easy axis.

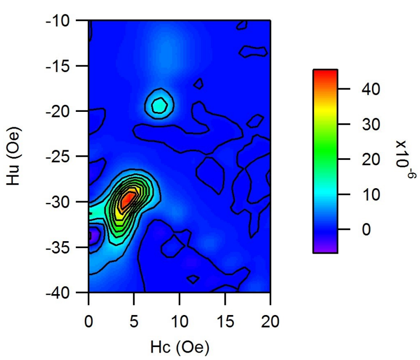

Figure 12: FORC diagram for [FeNi (60 nm)/IrMn (20 nm)]$_5$ for the applied field parallel to the easy axis.

3 CONCLUSION

FORC analysis is indispensable for characterizing interactions and coercivity distributions in a wide array of magnetic materials, including: natural magnets, magnetic recording media [15,16], nanowire arrays, exchange coupled permanent magnets [10], and exchanged biased magnetic multilayers. In this paper we have discussed the FORC measurement technique and subsequent analysis that leads to the FORC diagram, and presented measurement results for several nanoscale magnetic materials.

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