APPLICATION NOTE

First-Order-Reversal-Curve (FORC) Measurements of Magnetic Materials

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Abstract

The magnetic characterization of 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 and thus, first-order-reversal-curves (FORC) provide insight into the relative proportions of reversible and irreversible components of the magnetization of a material. Some examples of materials to which FORC measurements are applicable include:

- Geomagnetic and geological materials for which FORC enables the determination of the composition and grain size distribution of magnetic minerals within a sample[1].
- Exchange-coupled nanocomposite permanent magnet materials for which FORC enables investigation of the magnetostatic and exchange interactions between the magnetically hard and soft phases[2].
- Exchange-biased spin-valves for which FORC enables studies of the switching distribution and exchange bias in materials where the switching of the free layer magnetization is strongly influenced by the magnetic state of the fixed layer[3].
- Arrays of magnetic nanowires, nanodots or nanoparticles for which FORC enables investigation of irreversible magnetic interactions or processes in the array due to coupling between adjacent wires, dots or particles[4].

In this paper we will discuss the FORC measurement technique and subsequent analysis which leads to the FORC diagram, and present measurement results for a sample consisting of an array of Ni nanowires.

[a] *Lake Shore Cryotronics*

Lake Shore CRYOTRONICS

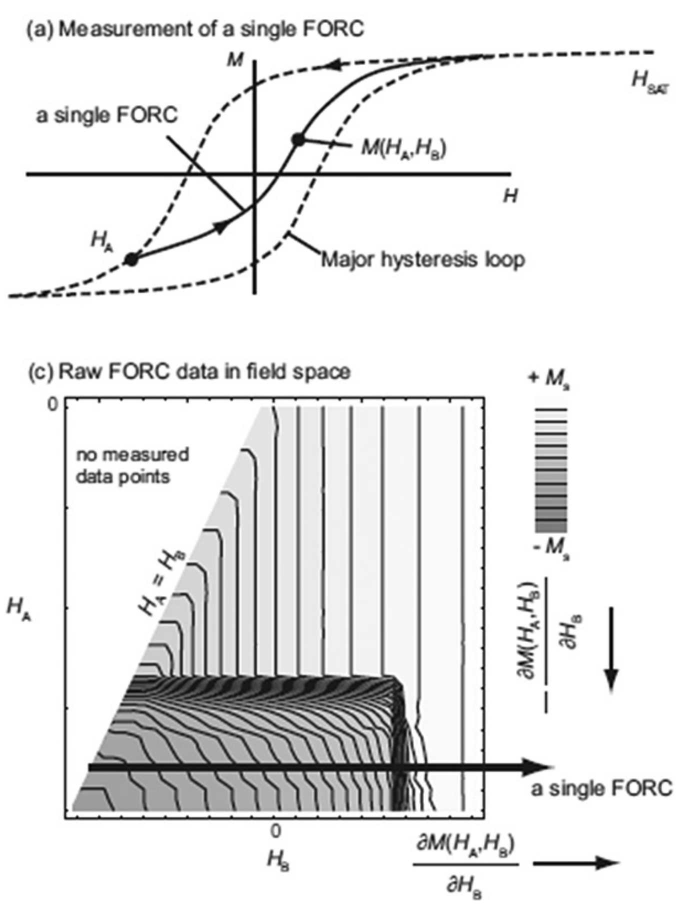

Figure 1[1]

FORC Curves and FORC Diagrams

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 as illustrated in Figure 1a. This process is repeated for many values of H_a yielding a series of FORCs, and the measured magnetization at each step as a function of H_a and H_b gives $M(H_a, H_b)$ as shown in Figure 1b. As shown in Figure 1c, $M(H_a, H_b)$ is then plotted as a function of H_a and H_b in field space. The FORC distribution $\rho(H_a, H_b)$ is defined as the mixed second derivative of the surface illustrated in Figure 1c:

Eq. 1) $\rho(H_a, H_b) = -\partial^2 M(H_a, H_b)/ \partial H_a \partial H_b$

A FORC diagram is a contour plot of $\rho(H_a, H_b)$ as shown in Figure 1d with the axis rotated by changing coordinates from (H_a, H_b) to $H_c = (H_b - H_a)/2$ and $H_u = (H_b + H_a)/2$ where H_u corresponds to the distribution of interaction fields, and H_c the distribution of switching fields.

FORCs can be measured by using any type of magnetometer that measures the DC or static magnetic properties of a material. The most common techniques are vibrating sample magnetometry (VSM), SQUID magnetometry and alternating gradient magnetometry (AGM). There are two technical considerations for FORC measurements: 1) because the second derivative in equation 1 significantly amplifies measurement noise, the sensitivity of the measurement technique is important for magnetically weak samples, as is any smoothing that may be applied to the raw data, and 2) a typical sequence of FORCs may contain thousands of data points which can be unwieldy and cumbersome if the measurement is inherently slow; therefore, measurement speed is very important.

The Lake Shore PMC MicroMag™ VSM and AGM systems are arguably the standard for FORC measurements, owing to their sensitivity and measurement speed.

Typical Magnetic Measurement Results

In this section we will present AGM FORC curve measurement results for an array of magnetic nanowires.

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 2: FORC measurements are made using systems such as the PMC MicroMag™ VSM (top) and AGM (bottom)

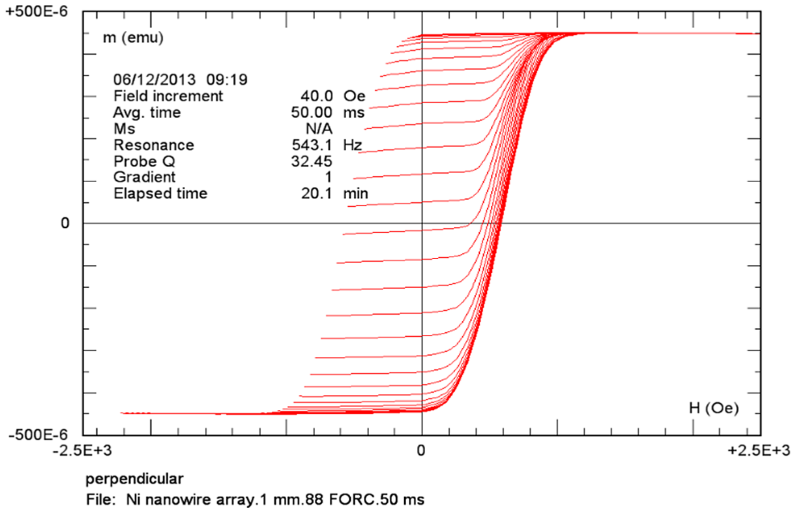

Figure 3: First-order-reversal-curves (FORC) for an array of Ni magnetic nanowires (sample courtesy of L. S. Spinu[5].)

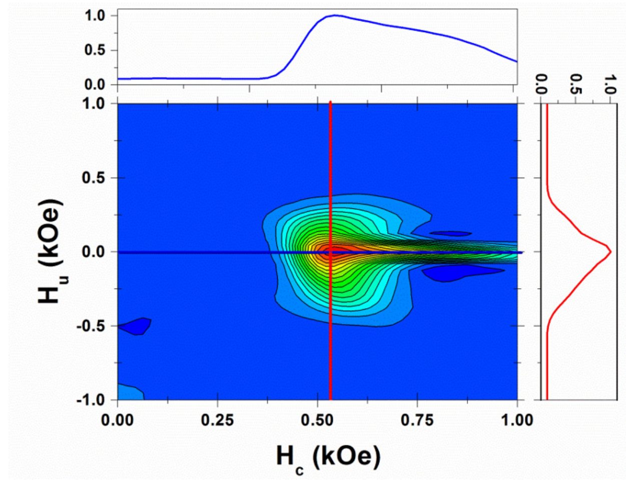

Figure 4: Distribution of interaction fields as determined from FORC analysis

Figure 3 shows a series of first-order-reversal-curves (FORC) measured using an AGM for a periodic array of Ni nanowires with a mean diameter of 70 nm and an inter-pore distance of 250 nm[5]. The nanowire samples were fabricated by electro-deposition using anodic aluminum oxide membrane as a template. As an example of AGM measurement speed, the FORC curves consist of 4,640 points, and the data was recorded in only 20 minutes. Analysis of these FORC curves yields the local interaction H_u and coercive H_c field distributions shown in Figure 4. This measurement protocol and analysis provide additional information regarding irreversible magnetic interactions or processes in this array of nanoscale wires, which cannot be obtained from the standard hysteresis loop measurement.

Conclusion

FORCs are indispensable in characterizing interactions and coercivity distributions that reveal insight into the relative proportions of reversible and irreversible components of the magnetization in many technologically important magnetic materials. In this paper we have discussed the FORC measurement technique and subsequent analysis which leads to the FORC diagram, and presented measurement results for a sample consisting of an array of Ni nanowires.

References

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