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Probing the interdependence between irreversible magnetization reversal processes by first-order reversal curves

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A procedure to probe the interdependence between irreversible magnetic processes is presented. It consists of measuring the first-order reversal curves (FORCs) without saturating the system. Depending on the variation of the reversal fields during the curves' acquirement (increasing or decreasing), it fixes the hardest or softest hysterons into their negative saturation level throughout the measurement. Differences between these FORC diagrams and the classical one, as well as variation of the end magnetization as a function of the reversal field, indicate and characterize the requirement that some irreversible processes arise from others. The procedure is described to investigate magnetic systems, but can be directly used to study any hysteretic system. © *2011 American Institute of Physics*. [doi:10.1063/1.3538940]

Over the last ten years, experimental use of the first-order reversal curve (FORC) method has expanded considerably. Using a simple magnetometer, this magnetostatic characterization technique presents the advantage to discriminate the various hysteretic phenomena occurring during magnetization reversal. This is in contrast to the major hysteresis curve, which gives only the average value of the magnetization for a given applied field. The strengths of the FORC method have been used successfully to characterize various types of structures where the magnetization reversal is not uniform throughout the sample.[1–5] The mathematical principle of the method is based on the classical Preisach model, where hysteretic operators are represented as square irreversible hysteresis curves.[6] The FORC distribution represents the statistical distribution of these mathematical hysterons, which are each characterized by a coercivity H_c and a bias field H_u.[7]

The principal difficulty during the experimental use of the FORC method resides in the correct identification of the physical meaning of the mathematical hysterons. This step can be complicated by the presence of a magnetization-dependent interaction field, which will modify the FORC distribution. Therefore, its analysis can be achieved with the help of simulations with adequate models, like the physical analysis model.[8] For the elaboration of a representative model involving multiple populations of irreversible entities, it is critical to know if the behaviors of the populations are dependent (or not dependent) on each other. This information is also crucial when investigating the magnetization reversal of a system, for example, to discriminate between cases in which two different types of entities reverse independently and the case in which a unique process occurs in two steps, both leading to identical FORC distributions. This article discusses a procedure based on the FORC method that shows the interdependence between irreversible populations. Moreover, it provides the dependence direction, i.e., which population requires another in order to arise itself, and for which applied field this dependence appears. The examples presented to illustrate the procedure involve magnetic hysteresis, but it remains valid for any type of hysteresis that can be decomposed into mathematical hysterons.

The FORC method consists of the measurement of various first-order reversal curves, which are minor curves, each initiating from a different reversal point (H_r) and ending at a saturation point (H_{sat}) (see the insets of Fig. 1). An effective way to determine the proportion of hysterons having given H_c and H_u parameters is by measuring the magnetization (M) difference between $H_r = -H_c - H_u$, where several different hysterons have reversed, and a given $H = H_c - H_u$, where only the investigated hysterons reverse back. The FORC distribution ρ results from the extrapolation of this idea by deriving M with respect to H and H_r (Ref. 7):

$$\rho(H,H_r) = -\frac{1}{2}\frac{\partial^2 M(H,H_r)}{\partial H \partial H_r} \quad (H \geq H_r). \qquad (1)$$

The FORC diagram is its graphical representation as a contour plot ranging from blue ($\rho = 0$) to red (ρ maximum), where the two sets of axes are commonly shown (see Fig. 1).

Independent hysterons, and thus populations of hysterons, exhibit identical behavior regardless of the state of the rest of the system, i.e., the other hysterons. Thus, maintaining a portion of the hysterons in a certain state does not affect the behavior of the others or the FORC distribution. However, it affects the FORC distribution of a system where hysterons are required for the switching of others. Therefore, differences between the FORC distributions of the whole system and with fixed hysterons reveal the existence of a link between hysterons. This relationship can be characterized by varying the parameters of the fixed hysterons. Hence, the proposed procedure consists of following the same steps as for the classical (saturated) FORC method, but where each minor curve ends intentionally at $H_{\text{end}} < H_{\text{sat.}}$, in order to keep the hysterons with $H > H_{\text{end}}$ in the negative state through the whole measurement, i.e., to probe only the behavior of a certain

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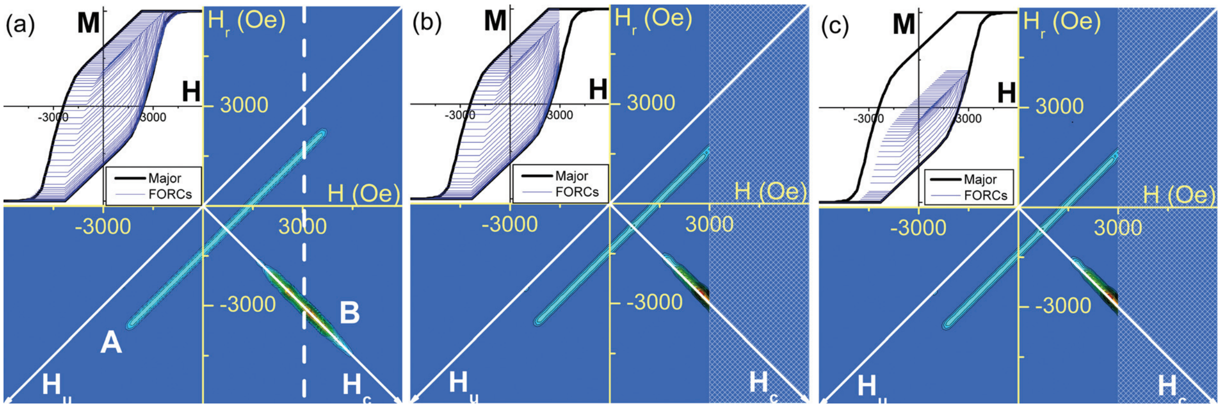

FIG. 1. (Color online) Simulated FORC diagrams and FORCs (inset) of a two-population system of symmetric hysterons ($H_u = 0$ Oe). A: mean interaction field $H_{\mathrm{int}} = -3000M$ ($H_c = 700$ Oe), B: normal distribution of coercivity (mean = 3000 Oe, standard deviation = 750 Oe). (a) Saturated, (b) decreasing unsaturated, and (c) increasing unsaturated. All diagrams are presented with the same scale. The dashed vertical line on the saturated one (a) indicates the $H_{\mathrm{end}} = 3000$ Oe value used for the unsaturated ones [(b) and (c)], where the area not measured is covered by a translucent rectangle.

fraction of hysterons. Both unsaturated FORCs with increasing and decreasing values of H_r are measured this way and their respective FORC diagrams are compared altogether with the classical FORC. The unsaturated decreasing FORC distribution corresponds to the system behavior when the hysterons that reverse first for decreasing field (large H_r, i.e., low H_c and/or H_u) remain fixed into the negative state. A difference from the saturated FORC distribution signifies that the switching up of those hysterons is prerequisite to other irreversible processes arising. Further, the unsaturated increasing FORC distribution is affected if the switching up of those that reverse last for decreasing field (large H, i.e., high H_c and/or low H_u) is prohibited, indicating their requirement for other processes. For saturated FORCs, the H_r variation does not matter because the system reaches the saturation between each FORC, hence erasing the magnetic history. The unsaturated FORCs should not be confused with second-order reversal curves (SORCs),[9] where the system undergoes a complete saturation between the measurement of each curve. Also, any FORC is acquired while H is varied toward the saturation, whereas it is going away from the saturation field in the case of SORC.

For systems constituted of independent hysterons, one should expect identical increasing and decreasing FORC diagrams, which simply correspond to the classical FORC distribution without the $H > H_{\mathrm{end}}$ part that was not measured. They are independent of the measurement direction and of the fraction probed, determined by H_{end}. This hypothesis was proved by simulating a system, using the algorithm presented in Ref. 8, of 1000 symmetric hysterons equally divided into two different populations in a way that covers the FORC diagram area: a harder one exhibiting a large coercivity distribution and a softer one submitted to an interaction field proportional to M. As expected, the increasing and decreasing unsaturated FORC diagrams are absolutely identical and correspond to the saturated one (Fig. 1). This result was proved to remain valid for systems with more than two populations, which can contain reversible hysterons, as well as nonuniform interaction field.

Results differ when some hysterons are linked together. To investigate this case, we chose an experimental system of Co nanowire array (diameter = 35 nm, length = 2250 nm, details about fabrication are related in Ref. 10), applying the field parallel to the nanowires' axes. Due to the large shape anisotropy, each nanowire can be associated, in first approximation, to an irreversible hysteron, while the high packing ratio creates a large dipolar interaction field. However, the saturated FORC

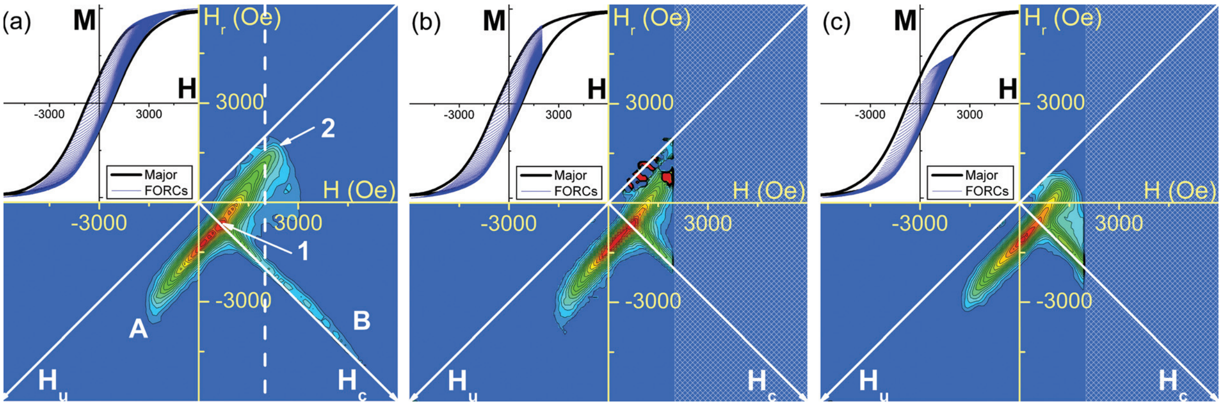

FIG. 2. (Color online) Experimental FORC diagrams and FORCs (inset) of a Co nanowire array, with the applied field parallel to the nanowire's axis. (a) Saturated, (b) decreasing unsaturated, and (c) increasing unsaturated. All diagrams are presented with the same scale. The dashed vertical line on the saturated one (a) indicates the $H_{\mathrm{end}} = 2000$ Oe value used for the unsaturated ones [(b) and (c)], where the area not measured is covered by a translucent rectangle. Positions of points 1 (H_c axis) and 2 ($-H_u$ axis) are shown in (a).

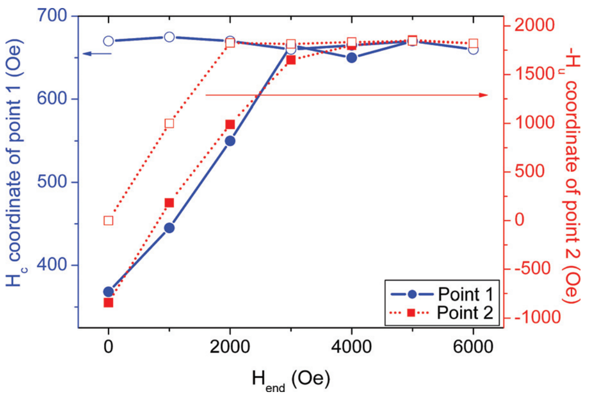

FIG. 3. (Color online) Evolution of the distribution A in function of H_{end} for decreasing (open symbols) and increasing (closed symbols) unsaturated FORC diagrams of Co nanowire array.

diagram exhibits two distributions: in addition to the one elongated along the H_u axis (A), which corresponds to the expected behavior of magnetic nanowires, a second one lying on the H_c axis (B) is visible in Fig. 2(a). This additional distribution, typical of small diameter nanowire array FORC diagrams, was observed for different compositions without being attributed to a particular physical explanation.[3–5]

The decreasing unsaturated FORC diagram [Fig. 2(b)] remains the same as the saturated one, a tendency observed for every value of H_{end}. Figure 3 shows the position in function of H_{end} of two distinctive points of the distribution A: the H_c coordinate of the maximum (point 1) and the H_u coordinate of the right extremity (point 2), as shown in Fig. 2(a). Both values stay constant, except when H_{end} is low enough to cut the distribution right extremity (Fig. 3, open symbols). Therefore, the hardest nanowires continue to reverse under the same applied field even if the softest ones remain with their magnetization pointing down.

On the other hand, the increasing unsaturated FORC diagram [Fig. 2(c)] exhibits two main differences for the distribution A: It is shifted toward lower H_c values and its elongation along the H_u axis terminates before reaching H_{end}. Both positions follow the same behavior, quickly increasing more or less proportionally to H_{end} until 3000 Oe (Fig. 3, closed symbols). The distribution remains almost identical afterwards. This kind of behavior suggests that the distribution B is the consequence of the end of a unique irreversible magnetization reversal process, while its initiation gives rise to the distribution A. In the case that the low value of H_{end} prohibits the process to saturate positively, it will remain or return in its negative saturation state. It is corroborated by the fact that the magnetization at H_{end}, M_{end}, does not remain constant, as for the independent system previously simulated (Fig. 4). As H_r increases, M_{end} first decreases until a certain field denoted $H_r(M_{\text{end}}\ \text{min})$, before increasing and saturating to a higher value than at the beginning. Several reasons can explain such variations of M_{end}, all of them consequences of the nonsaturation of the FORCs: rotation of the magnetization away from the applied field direction, creation/annihilation of domain walls, change in the interaction field, etc. The physical interpretation of this behavior in the case of the Co nanowire array is beyond the scope of this study, but some interesting facts can be observed. With the exception of the case in which the distribution B is completely absent ($H_r = 0$ Oe), $H_r(M_{\text{end}}\ \text{min})$ appears to be proportional to H_{end} (inset of Fig. 4), while the saturating value of M_{end} decreases with increasing H_{end}, with an abrupt jump at $H_{\text{end}} = 5000$ Oe. This last feature might suggest that the requisite for the reversing up of some hysterons begins to be important for fields lower than 5000 Oe. Finally, the M_{end} variation in function of H_r seems to be a more sensitive tool to probe the interdependence between irreversible processes.

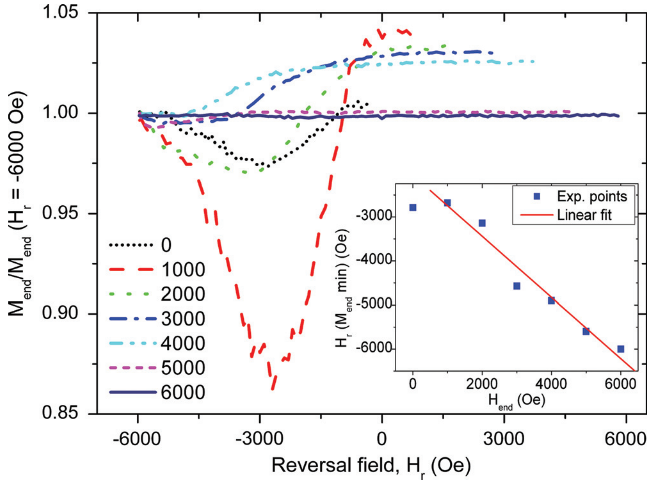

FIG. 4. (Color online) Magnetization at H_{end} in function of the reversal field, for different values of H_{end}. Inset: H_r coordinate of the minimum value of M_{end}.

Knowledge of the presence of interdependence between irreversible processes can be of crucial importance when investigating the magnetic behavior of nanostructured systems, but few experimental tools allow probing this feature. Measuring unsaturated FORCs, both with increasing and decreasing reversal fields, proved to be an effective and adequate procedure to study this phenomenon. In addition to discriminating the presence of dependent hysterons, it yields to a quantitative characterization of this relationship. This procedure remains valid for any hysteretic phenomena that can be decomposed into mathematical hysterons.

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