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Tracking the individual magnetic wires' switchings in ferromagnetic nanowire arrays using the first-order reversal curves (FORC) diagram method

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ABSTRACT

The complex hysteretic properties observed in structured ferromagnetic materials can be revealed with remarkable details in magnetization processes like the first-order reversal curves (FORC) – a characterization technique extensively used in recent years. The really fundamental problem in the analysis of experimental FORC diagrams is related to the possibility to link the hysteretic properties of real physical entities in a unique way with regions from the FORC distributions. Actually, what many scientists are often doing is to use a Preisach-type interpretation of FORC data without a proof for the accuracy of this procedure. In this paper we analyze in detail the relation between the switching events of physical entities given by the Preisach function and the FORC distribution in magnetic nanowire arrays with the aim to show the limits of the conventional interpretation of FORC data. For this type of sample we show how the real switching events are contributing to the experimental diagram. We present in a systematic manner the way in which the switchings of the physical wires are observed multiple times (both as positive or negative contributions). The multiplicity of switching occurrences is not the same for all the wires in the sample, being dependent on the wire intrinsic coercivity and its position in the array. In this manner one can track the switchings contributions of real magnetic wires on the FORC diagram.

1. Introduction

In 1935 Ferenc Preisach [1] had the brilliant idea to build an elegant model for magnetic hysteresis based on a bi-dimensional distribution of coercive and interaction fields of the fundamental elements of hysteresis – the hysterons, named *Preisach distribution*. Classical Preisach Model (CPM) establishes a hypothetical bi-univocal correspondence between physical entities (ferromagnetic particles) and the Preisach distribution of hysterons. Many researchers, especially in the field of magnetic recording media, developed in the 1960's methods intended to provide Preisach distributions for real samples [2–5], but each time significant problems were evidenced. Virtually all the experimentally obtained distributions were asymmetrical with respect to the interaction field axis, and the results were dependent on the experimental procedure used [2–5] (essentially on the sequence of fields used in the experiment). The solution found at that time to give a physical meaning to these experimentally determined Preisach distributions was related to the idea of *statistical stability* [5]. However there is an inconvenient in this assumption: within this framework, one actually abandons the direct link between the hysteresis of physical entities and the Preisach hysterons. The aim of the identification techniques for the Preisach model was reduced to the evaluation of statistical distributions of coercivities and interactions but the attempt to accurately simulate with the CPM higher order magnetization curves was not really successful. Modified versions of the CPM were developed to improve the prediction capability of the model (for example, Moving Preisach Model [6,7]). An important milestone in the development of robust identification techniques for the CPM is the theoretical study of Mayergoyz [8,9] in which he mention that along with the interpretation of the CPM given in Ref. [8] "Krasnosel'skii separated Preisach's model from its physical meaning and represented it in a pure mathematical form". The necessary and sufficient conditions to describe correctly a hysteretic system with the CPM were identified as the wiping-out and congruency properties. For an ideal CPM system, a new identification method of the Preisach distribution based on the measurement of the first-order reversal curves (FORC) was also presented in this article [8]. However, as virtually all physical hysteretic systems do not obey both the wiping-out and congruency properties, this technique has not been in fact used in laboratories. The actual practical use of the FORC identification technique was triggered by the paper

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published by Pike and collaborators [10] in which the authors have introduced the idea that the FORC method is purely experimental and that it should be used for any hysteretic system just to provide its *fingerprint*. In this understanding FORC technique is decoupled from the Preisach model ("A FORC distribution, by contrast, is not based on any assumptions. It is not part of a theoretical model" [10]). Nonetheless, in the practical use of this method this aspect is not thoroughly remembered (see also Refs. 11,12).

The main aim of this paper is to present a systematic study of the relation between the individual switchings in a simple magnetic system (parallel magnetic wires organized in almost perfect 2D array) and the FORC diagram. We focus our attention on how far is the coercivity and interaction distribution, provided by the FORC data, from the classical Preisach image.

2. FORC diagram of the nanowire array

The arrays of ferromagnetic nanowires in axial applied field are the best candidates to be described within the general framework of the Preisach-type models. In a given magnetic state, the magnetic moment of each wire is in one of two equilibrium states ("up" or "down"), and the wire has an intrinsic coercive field depending on the geometrical characteristics, structural defects and impurities [13]. When the distances between wires are very large, their magnetic moments are not interacting and associated Preisach hysterons are symmetrical. In this specific case any magnetization process is governed only by the individual coercivities of the wires and the system can be described with the CPM using a singular distribution along the coercive field axis. When the inter-wire distance is decreasing, the magnetostatic interactions between wires are gradually increasing.

In the stable equilibrium state of any given cylindrical nanowire, only uncompensated magnetic charges on the cylinder bases are contributing to the interaction field in the other wires from the array [12,14]. In this case, the switching events are influenced not only by the intrinsic coercivities but also by these interaction fields. To simulate the nanowire arrays behavior, we use a toy-model (Ising-Preisach zero Kelvin model) described in details in Ref. [12]. Typically, in simulations one considers a rectangular network of $N=1600$ Nickel cylindrical wires with the same length, $L=6$ μm, and radius, $R=40$ nm, perfectly ordered in a 2D square grid with the distance between neighboring wires $a=250$ nm. The intrinsic coercive field distribution is considered a Gaussian distribution with the average value $H_{c0}=150$ Oe and the standard deviation $H_{c\sigma}=20$ Oe. The coercivity of the wires generated with this distribution was randomly allocated to the wires in the sample. In each state a nanowire is subjected to an effective field obtained by adding to the applied field, H, the interaction field created in the center of the nanowire by all the other wires from the array:

$$H_{eff}=H+\sum_{k=1}^{N-1}(-1)^{s_k}\frac{\pi R^2 L M_s}{\left(x_k^2+L^2/4\right)^{3/2}}, \tag{1}$$

with $M_s=485$ emu/cm^3 the saturation magnetization for Nickel, x_k the interwire distance, and $s_k=0$ if the k-th wire is in "down" position and $s_k=1$ if the k-th wire is in "up" position. Magnetization curves are computed following a simple switching events algorithm. The magnetic moment of a wire is "up" until the effective field becomes lower than $-H_c$ (switching "up–down" occurs). If the magnetic moment of a wire is "down" and the effective field becomes higher than $+H_c$, a switching "down–up" occurs. In simulations we have used field steps small enough to have at most one switched nanowire in a field step. After each switching event the interaction fields are updated.

In the case of FORCs measurement starting from the descending branch of the major hysteresis loop, the applied field is initially decreased from positive saturation to a reversal field, H_r. The actual FORC measurement starts in this field and continues as the applied field is increased until the positive saturated state is obtained again. The magnetic moment measured on this curve, $m_{FORC}(H_r,H)$, is dependent on both the reversal and the applied fields. Using a set of FORCs, covering the entire surface bounded by the major hysteresis loop, the FORC distribution is defined as the mixed second order derivative [8]:

$$\rho_{FORC}(H_r,H)=-\frac{1}{2}\frac{\partial^2 m_{FORC}(H_r,H)}{\partial H\cdot\partial H_r}. \tag{2}$$

As both in experiments and simulations the field steps are finite, FORC distribution is approximated with

$$\rho_{FORC}(H_r,H)=-\frac{1}{2}\frac{\Delta}{\Delta H_r}\left[\frac{\Delta m_{FORC}(H_r,H)}{\Delta H}\right]=-\frac{1}{2}\frac{\Delta\chi_{FORC}(H_r,H)}{\Delta H_r}, \tag{3}$$

where ΔH and ΔH_r are the field steps used in the experiments or simulations and $\chi_{FORC}(H_r,H)=(\Delta m_{FORC}(H_r,H)/\Delta H)$ is the magnetic susceptibility measured along one FORC. This expression clearly indicates that the value of the FORC distribution is actually defined for each small squared area from the Preisach plane, $\Delta H\cdot\Delta H_r$. The value associated to the mentioned area is the variation of the FORC susceptibility on two successive FORCs having starting points separated by ΔH_r. This representation of the distribution is in fact a FORC histogram whose values may be expressed by integers if one considers that all the wires have the same magnetic moment. The FORC histogram is computed as the difference between the number of wires that switch "down–up" on the inferior FORC and the number of wires that switch "down–up" on the superior FORC. However many researchers using the FORC technique prefer a continuous representation – the FORC diagram – which is the contour plot of the FORC distribution defined by (2). In this study we are using the FORC histogram in order to be able to perform quantitative evaluations which are affected, sometimes dramatically, when the data are numerically treated. For example, in the technique presented by Pike and coworkers [10,15] a fitting algorithm is suggested in order to provide data smoothing which is necessary especially when experimental data with significant random errors are used [15,16].

The typical shape of the ferromagnetic nanowire array FORC diagram is a two branch structure (a "T" shape), as it is usually observed in experiments [17–28] and in the diagram calculated for simulated data presented in Fig. 1 [29]. The branch denoted AB appears as an extended distribution along the interaction field axis with lower dispersion along the coercive field axis. The other branch denoted CD in Fig. 1(b) is less prominent than the first one and can be interpreted, at first appearance, as a distribution of Preisach hysterons with negligible interaction fields but with a large dispersion of the coercive fields. The region CD is an important specific feature for nanowire arrays observed in most of the published experimental FORC diagrams, [17–28] being linked to the reversal field memory effect [12,23,30–32.] Analogous ridges along the interaction field axis are observed in FORC diagrams obtained for networks of magnetic nanoelements [33,34] and for granular thin films [35,36]. A Preisach type analysis have been used in Ref. [12] to provide the physical explanation for both branches of the nanowire array FORC diagram.

3. FORC histogram of the nanowire array

In order to provide a complete quantitative understanding of the FORC histogram we propose a detailed analysis of the