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Modeling of irreversible switching and viscosity phenomena in perpendicular thin films

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ABSTRACT

We have developed a simple numerical model for simulating domains as well as remanence and viscosity curves in the slow dynamics regime, for thin films characterized by perpendicular magnetization and irregular domain configurations due to strong disorder. The physical system is represented as constituted of identical switching units, described by proper switching field distributions and energy barrier laws for pinning and nucleation processes. The model also includes an effective field which accounts for magnetic forces proportional to magnetization, on average. Simulations of DCD curves show that when the reversal of magnetization is governed by pinning, the coercive field depends on the physical size of the film area on which the external field is applied. In the case of viscosity phenomena described by a linear energy barrier law associated with a single predominant reversal process (pinning or nucleation), universal viscosity curves can be generated by properly transforming the DCD curve of the system. We also demonstrate that a reduction of the maximum viscosity coefficient can coexist with a reduction of the energy barrier heights.

1. Introduction

In this paper, we present a numerical model aimed at simulating irreversible processes in the slow dynamics regime, for magnetic systems characterized by irregular domain configurations, as typically observed in thin film that combine strong perpendicular anisotropy and strong disorder [1]. Fractal geometries of magnetic domains are frequently observed in these systems [2]. The corresponding magnetization reversal process is determined by the nucleation of a few nucleation centers followed by the growth of magnetic domains. Moreover, the domain wall motion is mainly governed by the presence of pinning centers with a random distribution of energy barriers [2,3].

2. Numerical model

The simulated magnetic system is represented as a periodic hexagonal grid of hysteretic switching units. The units have magnetization perpendicular to the film plane and are characterized by proper switching field distributions (SFDs) and energy barrier laws for nucleation and pinning processes. The assumed SFDs allow us to generate the switching events either directly, in the case of simulated remanence curves, or indirectly, through the Arrhenius law, in the case of viscosity curves. The SFDs are expressed in terms of internal field, sum of external and effective fields. The effective field accounts for magnetic forces proportional to the magnetization, on average ($H_{\mathrm{eff}} = 4\pi d_{\mathrm{eff}} M$). For small film thicknesses, the effective field factor d_{eff} tends to zero, because of the reduced efficiency of dipolar interactions [3,4]. In the model, the presently switchable units are inserted in a queue organized as a binary search tree ordered by the switching field or the switching time values.

3. Remanence curves

To exemplify the application of the model to the simulation of DC demagnetization (DCD) and isothermal remanence (IRM) curves, we have assumed Gaussian SFDs for both pinning and nucleation. Moreover, we have supposed that the nucleation SFD is defined at fields sufficiently larger with respect to the pinning one, so that the direct contribution of nucleation to the magnetization reversal is negligible (*pure pinning* process). This approach can be considered as a significant extension of the large scale model proposed in Ref. [2]. Specifically, we have imposed a mean value of 4 kOe (10 kOe) and a standard deviation of 0.5 kOe (1.5 kOe) for the pinning (nucleation) SFD. In the performed simulations, the considered values of the internal field are sufficiently far from zero so that one can neglect the probability of back-switching of the reversed units to their original state. The

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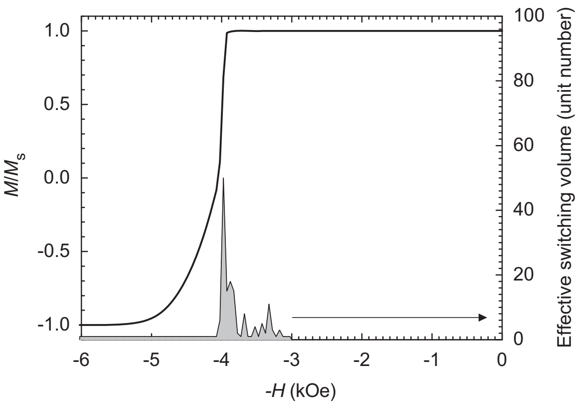

Fig. 1. Simulated DCD curve (left scale) and effective switching volume (right scale) for a pure pinning process with $d_{eff}=0$.

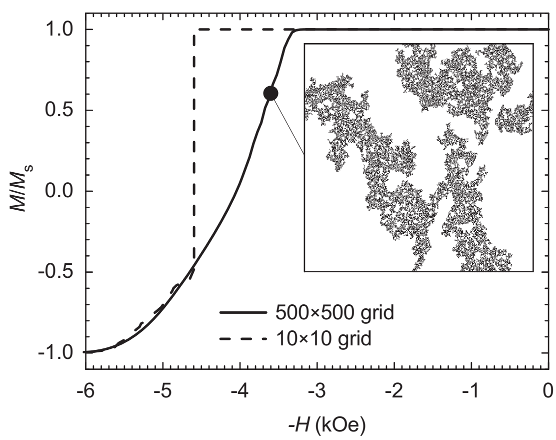

Fig. 2. Simulated DCD curves for a pure pinning process with non negligible effective field. Inset: simulated domain configuration ($H=3.6$ kOe).

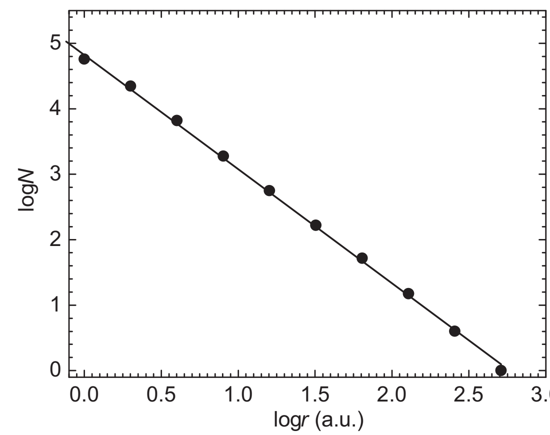

Fig. 3. Box counting analysis of the domain configuration reported in the inset of Fig. 2: r is the counted box size and N the number of boxes containing reversed units.

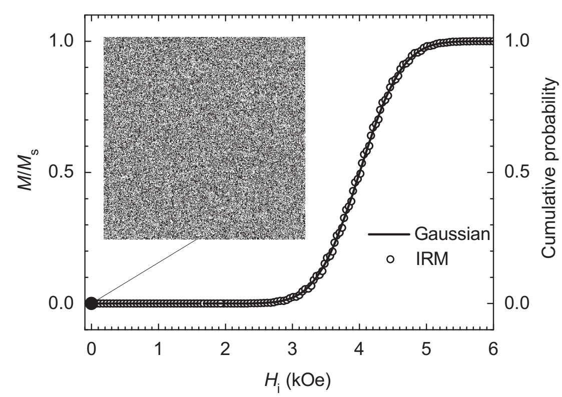

Fig. 4. Simulated IRM curve (left scale) compared with the corresponding pinning SFD (right scale). Inset: simulated domain configuration in the demagnetized state.

DCD curve, simulated on a 500×500 grid for a system with $d_{eff}=0$, is reported in Fig. 1 (thick solid line) as a function of the external reverse field H. The curve shows a typical abrupt magnetization reversal at a field $H\cong4$ kOe which is markedly lower than the mean nucleation switching field (10 kOe). This behavior is typical of a pure pinning process, because the switching of a unit can originate the avalanche switching of adjacent units with lower pinning switching fields. Accordingly, the mean effective switching volume (thin solid line with filled area in Fig. 1) varies in a non-random way, increasing for fields below coercivity and then reducing to the volume of a switching unit above coercivity. Therefore, the DCD curve, normalized such as it assumes values between 0 and 1 and expressed in terms of internal field, tends to reproduce the pinning SFD for fields greater than coercivity. In the limiting case of a single nucleated unit, the phenomenology of the pure pinning reversal process fit with the percolation theory [2]. The inclusion of an even small effective field ($d_{eff}=0.05$, $M_s=1000\,\text{emu/cm}^3$) appreciably reduces the slope of the DCD curve (solid line in Fig. 2). In general, the effective field factor for a pure pinning process can be evaluated starting from the slope of the curve in the range of fields below coercivity. The inset of Fig. 2 displays the simulated domain configuration at an external reverse field $H=3.6$ kOe. The corresponding mean fractal dimension extracted from box counting analysis [5] (see Fig. 3), turns out to be $1.74<2$ (1.79 on a 2000×2000 simulation grid), thus confirming the fractal nature of the domain structure. However, when increasing the counted box size r on large grids, the fractal dimension approaches 2 due to the homogeneity induced by the nucleation events at large scales (116 nucleation events during the simulation with the 2000×2000 grid).

In the case of pinning type magnetization reversal, the coercive field increases when reducing the size of the film area on which the external field is applied. The pinning process requires indeed to be triggered by nucleation events to take place, and so it is the nucleation SFD, together with the area size, which essentially determines the coercive field value. To illustrate this point, we report in Fig. 2 (dashed line), the DCD curve obtained on a 10×10 grid without periodic boundary conditions. Due to the reduced area, the probability that triggering nucleation events occur at low fields is reduced, as clearly evidenced by the increased coercive field.

Differently from the DCD curve, the simulated IRM curve results to be directly related to the SFDs [6]. To generate IRM curves, a demagnetization procedure has to be performed at the beginning of the simulations. At each step of this procedure, we have to apply a field greater than the coercive field of the saturated sub-system constituted by the presently non-reversed units. In this way, the effective switching volume is coincident with the volume of a switching unit. The IRM curve of Fig. 4 has been obtained for the pure pinning process with non negligible effective field, after having performed an initial demagnetization procedure with field steps of 100 Oe. The IRM curve expressed as a function of the internal field results to be coincident with the corresponding Gaussian SFD of the pinning process. The simulated domain configuration of the demagnetized state is also reported