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Modeling of hysteresis in magnetic multidomains

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ABSTRACT

In this paper, the analysis of multi-domain nanostructures is made by means of numerical approaches. The Landau–Lifshitz–Gilbert LLG equation is used to compute the magnetic hysteresis loops for different alternate scalar polarizations. The data computed are then used to identify the parameters of a phenomenological model, based on the extension of the Preisach model in 2-D. The identification in this case is the evaluation of the size and the position of the hysterons in the H-plane. Each hysteron is associated to a domain of the nanostructure and the assembly of hysterons reproduces with satisfactory accuracy the hysteretic behavior of the nanostructure computed by the LLG equation with an extremely reduced computational time. Some possible relationships between the magnetization nanostructure and the parameters of the hysteron are suggested. These relationship should be used for a "blind" prediction of the magnetization state of much larger magnetic structures, whose computation using the LLG equation is not possible in practice due to the enormous computational time, supposing that magnetic structures with the same aspect ratio exhibit a similar distribution of magnetic domains. The theory is applied here to an example of Permalloy nanostructure.

1. Introduction

The complete modeling of magnetic hysteresis at macroscopic scale is a difficult task being the material behavior influenced by different factors such as the grain size, the structural stress, the presence of enclosures, etc. [1–4] One idea should be the use of a physical-based model derived for sub-micrometer materials, but its use for macroscopic materials (geometrical dimensions of several millimeters at least) is actually limited by the description scale to use (the exchange length is of the order of 5–8 nm) which gives rise to numerical problems with matrix of more than 200 billions of elements (see Ref.[4] for a complete review). Differently, the use of phenomenological models [5–8] is able to reproduce the macroscopic magnetic hysteresis. To this aim the main challenging is the identification of the approximation functions to use in the model. A promising approach to treat the magnetic vector hysteresis is an extension of the Classical Scalar Preisach Model from the 1-d case to the 3-d one [9]. The model is based on the definition of a vector hysteron characterized by a material-dependent Preisach distribution in the H-space. In a previous paper [10], we have reproduced the static magnetic behavior of some ferromagnetic materials (simple physical and geometrical structures) at nanomagnetic scale. We have used the results of the micromagnetic simulation either to identify the parameters of the 3-d Preisach-type vector model, and to identify some possible relationships between physical properties of the material and the properties of the vector model. The key point of our previous study was the absence of magnetic domains (uniform magnetization).

In this paper, we present the results achieved extending our investigation to different structures, where magnetic domains during the switching process of the magnetization are observed. In particular, we discuss about the identification of the model and the possible useful extension of the approach to magnetic structures at larger scale.

2. The multidomain nanostructure analyzed

The material we have investigated is Permalloy (Py) alloy with about 20% iron and 80% nickel content in weight. As known, the crystalline structure of this material has no magnetocrystalline anisotropy. Of course, the total amount of anisotropy present is given by the geometrical properties of the sample analyzed, in relation to the magnetostatic energy distribution. We studied a sample of the above material with rectangular cross section having dimensions of 1200 nm × 400 nm and a thickness of 4 nm. These dimensions have been selected in order to have on one hand the

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possibility to perform numerical calculations by means of the micromagnetic model (described in the next section), and on the other hand to have a multi-domain sample.

3. The micromagnetic analysis

The analysis at micromagnetic scale has been performed by the numerical modeling of the LLG Eq. (1)

$$\frac{d\boldsymbol{m}}{d\tau} = -(\boldsymbol{m}\boldsymbol{h}_{eff}) + \alpha_G \boldsymbol{m}\frac{d\boldsymbol{m}}{d\tau} \quad (1)$$

being $\boldsymbol{m}$ and $\boldsymbol{h}_{eff}$ the magnetization and the effective field of the ferromagnet respectively, α_G is the Gilbert damping. The effective field takes into account the magnetostatic field component $\boldsymbol{h}_M$, the exchange field $\boldsymbol{h}_{exch}$ and external field $\boldsymbol{h}_{ext}$, while the magneto-crystalline anisotropy field is neglected being in Py the uniaxial magneto-crystalline anisotropy constant very low.

$$\boldsymbol{h}_{eff} = \boldsymbol{h}_{exch} + \boldsymbol{h}_{ext} + \boldsymbol{h}_M \quad (2)$$

The material exchange constant is $A = 1.3 \times 10^{-11}$ J/m, the magnetization at saturation state is $M_S = 1.08$, $T = 0.01$ and is the dimensionless integration time step in unit of γM_S (γ is the gyromagnetic ratio). The mesh is based on a time domain finite difference scheme with a discretization cell used of $5 \times 5 \times 4$ nm^3. The size used in our discretization is lower than the exchange length of the material ($l_{exc} = 5.3$ nm) and higher than the typical size for which it is possible to apply the micromagnetic theory (1 nm) [4]. Tests have been performed by using a discretization cell having side of 2 nm, and the numerical results are practically the same. The time domain integration scheme used is a semi-implicit method which uses the Adams–Bashforth algorithm as a predictor, and a second order Adams–Moulton procedure as a corrector [11–15].

4. The phenomenological approach

The phenomenological model is an extension in 2-D of the Classical Scalar Preisach Model [6]. We will call here this model as macromagnetic model. A vector mathematical operator, here called for simplicity hysteron, is described in the $\boldsymbol{h}_{ext}$ plane by a closed critical curve. In this case the material is quasi anisotropic and the critical curve becomes a circle. For external fields inside the critical curve the magnetization is frozen in the direction that it had immediately before to enter inside the critical curve, remaining constant until it exits from the critical curve itself. At this last point, the magnetization instantly rotates so as to align itself along a new direction, perpendicular to the critical curve. Each hysteron is associated to a single magnetic domain of the structure. The absolute value of the magnetization $\boldsymbol{m}_i$ for each hysteron is M_S/Γ, where Γ is the volume of the magnetic domain considered divided by the total volume of the magnetic structure. Each hysteron center is displaced from the origin of the vector $\boldsymbol{h}_I$, called here interaction field. $\boldsymbol{h}_I$ is calculated for each hysteron as the negative value of the sum of the mean value of the exchange field and of the magnetostatic field in the magnetic domain referred to the hysteron. An assembly of hysterons for a simulation of a multidomain nanostructure is represented in Fig. 1. The number of the hysterons is equal to the maximum number of domains created into the magnetic structure. When two or more domains annihilated to create a single domain the domain is represented by the sum of the hysterons related to the original domains.

For one of the hysterons in the figure is indicated the radius of its critical circle, its interaction field and its contributed $\boldsymbol{m}_i$ given to the total magnetization. The interaction field is in general a

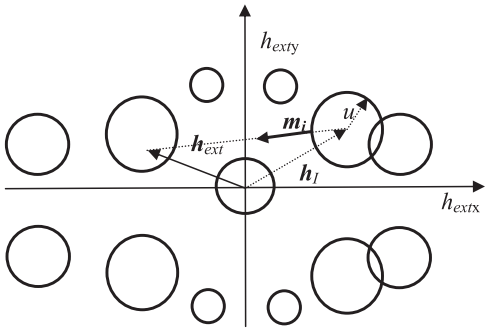

Fig. 1. Illustration of the working principle of the phenomenological model.

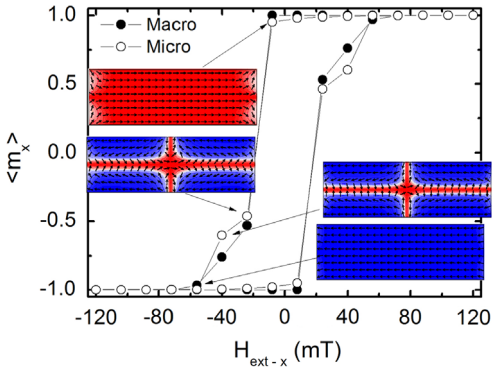

Fig. 2. Computed major loop for a magnetic polarization of the nanostructure along the easy-axis and snapshots of the magnetization during the descending branch. Macro means data computed by the phenomenological approach, micro refers to data computed by the LLG.

function of the magnetization state. The total magnetization is the vector sum of the magnetization due to all the vector hysterons. In our case the magnetization is directed along the radius from the center of the circle to the considered point of the critical curve.

In order to simplify the identification procedure, we assumed that the radius of all the hysterons is constant and equal to the value of the coercive field of the magnetic structure along the easy direction calculated via the micromagnetic numerical simulation.

5. The micromagnetic structure behavior

As discussed below, it is important to check the results of phenomenological vector hysteresis model with magnetization pattern where domains are nucleated. In detail, for each applied field value we launched the numerical simulation for a time interval of 20 ns, and at the end, the resulting magnetic state is saved. We would like to stress the fact that the intermediate states achieved are obtained only because the simulation time is not enough to permit the full switching of the magnetization and the magnetic nanostructure state computed is metastable. For example, for the descending branch the switching occurs at −19.1 kA/m if the simulation time is much longer.

This fact, anyway, did not affect the validity of the comparison, because the phenomenological approach do not differ in the reproduction of a metastable or a stable magnetization state.

In the considered sample the external magnetic field is applied starting from the saturation configuration $\boldsymbol{M}_i$; then the field amplitude changes of a step $\Delta H = 16$ mT, corresponding to about 12 kA/m. For the field applied along the x-direction (the easy-axis of the sample) the resulting major loop is shown in Fig. 2 ($\boldsymbol{M}_i = (M_S,0,0)$). The starting value of $\boldsymbol{h}_{ext}$ is at the posi-