

Experimental determination of the magnetization dependent part of the demagnetizing field in hard magnetic materials

A. N. Dobrynin,^{1,2} T. R. Gao,¹ N. M. Dempsey,¹ and D. Givord^{1,a)}

¹Institut Néel, CNRS-UJF, 25 Rue des Martyrs, 38042 Grenoble, France

²Diamond Light Source, Chilton, Didcot, Oxfordshire OX11 0DE, United Kingdom

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A method for extracting the magnetization dependent part of the demagnetizing field from minor hysteresis loops is described. It applies to hard magnetic materials with irreversible magnetization switching. The method's validity is tested on the simulated magnetization curves of an assembly of hard magnetic grains, as well as on a thin NdFeB film with out of plane magnetization. Effective demagnetization factors are extracted from the analysis. These factors are smaller than the usually applied sample shape dependent demagnetizing factors. © 2010 American Institute of Physics. [doi:10.1063/1.3514554]

The response of a magnetic material, submitted to an applied magnetic field H_{app} , is determined by the internal field within matter $H_{\text{int}}=H_{\text{app}}+H_D$, where H_D is the demagnetizing field.¹ H_D represents the magnetostatic interactions within matter. Most generally, H_D along a given axis is expressed as $H_D=-NM$, where M is the sample magnetization, and N is the demagnetizing factor, along this axis. It is generally assumed that N depends only on the sample geometry. In a number of recent studies dealing with hard magnetic materials, it was found that the application of the demagnetizing field corrections derived from above leads to difficult to understand modifications of the hysteresis cycles and this was attributed to the contribution of volume magnetic charges in such heterogeneous magnetic materials.²⁻⁷

In the present paper, a method is proposed to determine directly the magnetization dependent part of the demagnetizing field in hard magnetic materials. This method exploits minor loop measurements as do other methods proposed to derive the switching field distribution in, e.g., perpendicular recording media.¹⁰⁻¹⁴

In high coercivity hard magnetic materials when magnetization reversal occurs by irreversible discrete switching, the reversible susceptibility contribution to magnetization processes is negligible on both the main loop and the minor loops. Typical associated loops are schematized in Fig. 1. Let h_c be the coercive field (see Ref. 8) of a given grain. The slope of the magnetization variation in Fig. 1(a) is determined by the combined effect of the coercive field distribution $P(h_c)$ and of the demagnetizing effects. Along a given minor loop it is convenient to separate the distribution $P(h_c)$ into two distributions: $P_1(h_c)$, including the lower h_c values, such that the grains' magnetization reverses when the considered minor loop is described, and the distribution $P_2(h_c)$, including higher coercive field values, such that the grains' magnetization remains unchanged along this minor loop [see Fig. 1(b)]. Let us consider specifically the points A^+ and A^- of the minor loop, for which half the P_1 grains have the moment $+m$ ($m=M_sV$, where M_s is the spontaneous magnetization and V is the grain's volume), and the other half of P_1 grains have the moment $-m$ [see Fig. 1(a)]. Consequently, in

states A^+ and A^- , the contribution of the P_1 grains to $H_D^{\text{eff}}(M)$ vanishes. $H_D^{\text{eff}}(M)$ is uniquely determined by the P_2 grains. Since the magnetization of the P_2 grains remains unchanged, $H_D^{\text{eff}}(M)$ has exactly the same value in A^+ and A^- . Let H_{app}^+ and H_{app}^- be the applied fields associated with the points A^+ and A^- , respectively [see Fig. 1(a)]. One derives

$$H_{\text{app}}^+ + H_{\text{app}}^- = -2H_D^{\text{eff}}(M). \quad (1)$$

Relation (1) shows that the magnetization dependent part of the demagnetizing field $H_D^{\text{eff}}(M)$ can be extracted from minor hysteresis loops. Once the thus derived $H_D^{\text{eff}}(M)$ term is added to the applied magnetic field, the intrinsic h_c distribution, independent of intergranular dipolar interactions, is obtained.

The applicability of this approach is restricted to systems where collective effects in magnetization reversal can be neglected. This is more specifically the case of samples in the form of a foil with magnetization perpendicular to the foil's plane.⁹ This was numerically modeled considering an assembly of exchange decoupled hard magnetic grains in the form of cubes, arranged on a two-dimensional x - y lattice, with both the anisotropy axes of the grains and the applied magnetic field H_{app} being oriented along the z axis and the grain being saturated in either the $+m$ or the $-m$ state. In the cal-

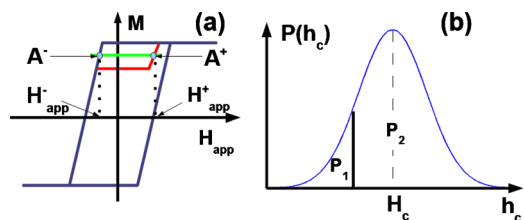


FIG. 1. (Color online) (a) Schematic representation of the main loop and of a minor loop in hard magnetic materials in which magnetization reversal occurs by discrete switching. Points A^+ and A^- are characterized by identical values of the sample magnetization and they divide the minor loop into two equal parts. The associated applied magnetic fields are H_{app}^+ and H_{app}^- . The effective demagnetizing field, H_D^{eff} , is the same in A^+ and A^- , equal to $-(H_{\text{app}}^+ + H_{\text{app}}^-)/2$. (b) Schematic drawing of the coercivity distribution function $P(h_c)$. The left part represents the part, P_1 , of the distribution function, for which the grains' moments reverse during minor loop measurements. The right part represents the part of the distribution function, P_2 , for which the grains' moments remain unchanged during minor loop measurements.

^{a)}Electronic mail: dominique.givord@grenoble.cnrs.fr.

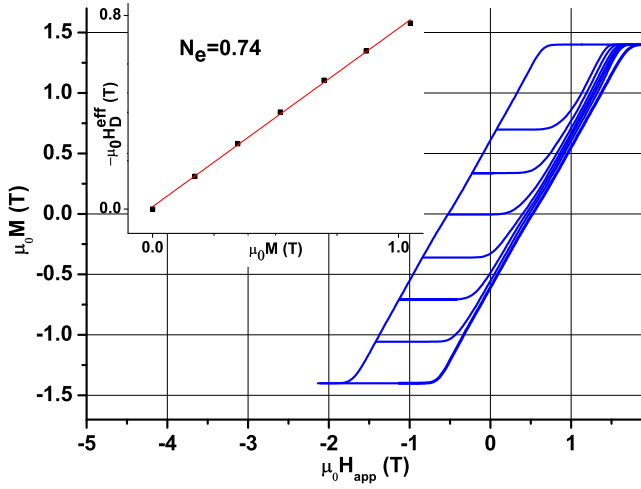


FIG. 2. (Color online) Simulated minor hysteresis loops for a system made of exchange-decoupled dipolar-coupled 200×200 magnetic cubes with perpendicular magnetization. Inset: effective demagnetizing factor, N_e , derived from the hysteresis loops.

ulation $\mu_0 M_s = 1.4$ T was taken and a normal distribution of coercive field values was assumed with a mean value $\mu_0 H_c = \langle \mu_0 h_c \rangle = 1$ T. The main and minor hysteresis loops for a system consisting of 200×200 particles are shown in Fig. 2. $H_D^{\text{eff}}(M)$ was extracted from the simulated minor loops using the above described method. The thus derived $H_D^{\text{eff}}(M)$ dependence is shown in Fig. 2, inset. The M dependence of $H_D^{\text{eff}}(M)$ is linear. It results that $H_D^{\text{eff}}(M)$ may be expressed as $N_e M$, where N_e is the effective demagnetizing factor.

The N_e factor extracted from the calculated hysteresis loops in Fig. 2 is equal to 0.74. As usual, the contribution of $H_D^{\text{eff}}(M)$ should be added to the applied magnetic field. This is done by applying a $1/N_e$ correction to the slope of the calculated magnetization variation. The corrected slope thus obtained is very close to the slope representing the h_c distribution (compare lines 4 and 5 of the last column in Table I). This demonstrates that the M dependent part of the demagnetizing field is well represented by the $-N_e M$ term. The same calculation was applied to similar systems but having different sizes, namely, made of 40×40 , 60×60 , 80×80 , 100×100 , and 120×120 cubic particles. The term N_e extracted from the calculated hysteresis loops varies from 0.74 in the 200×200 system to 0.68 in the 40×40 system. Without examining for the moment the reason for this variation, one notes that $N_e = 0.76$ is obtained by extrapolation to an infinite size system. In all cases, a $1/N_e$ correction was applied to the calculated hysteresis cycle and the slope of the corrected magnetization variation was found to closely re-

produce the slope representing the intrinsic coercive field distribution (see Table I).

For all cases, the term N_e extracted is far from the usual sample shape dependent demagnetizing factor, which varies from $N = 0.98$ in the 200×200 sample to $N = 0.93$ in the 40×40 sample. The difference found between N_e and N can be understood in the light of our recent analysis⁸ in which we demonstrated that the magnetization dependent part of the demagnetizing field may be approximated by $-(N - N_g)M = -N'M$, where M , N , and N_g are the sample's magnetization, the sample's demagnetizing factor, and a grain's demagnetizing factor along this direction, respectively. Rather than being compared to N , N_e should thus be compared to N' the so called Hard Demag factor.^{8,9} Taking $N_g = 1/3$ which applies to cubic shape grains, N' varies from 0.65 in the 200×200 sample to 0.60 in the 40×40 sample, in relatively fair agreement with the N_e values derived from the calculated hysteresis loops (see Table I). The variation in N' from the smallest 40×40 system to the largest 200×200 one, may be directly related to the usual variation in the sample shape demagnetizing factor and it explains the above observed variation in N_e . However, a systematic difference which amounts to 0.09 is found. We attribute this difference to the fact that collective effects are neglected in the evaluation of N' . They tend to generate a contribution to the cavity field which does not depend on the magnetization state, and thus is proportional to M_s rather than to M . In the presence of such collective effects, N_e becomes larger than $N' = N - N_g$, somehow approaching N , as observed in the simulations.

A $5 \mu\text{m}$ thick NdFeB hard magnetic film was prepared by triode sputtering (see Ref. 15 for details). The room temperature hysteresis loops measured on this film are shown in Fig. 3(a). The film is highly textured with the grains c -axis of easy magnetization being almost aligned along the direction perpendicular to the plane. The loop is characterized by a remanent magnetization equal to $\mu_0 M_r = 1.23$ T at 300 K, and a very large coercive field, $\mu_0 H_c = 2.55$ T. The superimposed susceptibility due to reversible magnetization processes is very weak, and the corresponding linear term was subtracted from the $M(H_{\text{app}})$ dependence.

Applying the same method as above, the magnetization dependence of $H_D^{\text{eff}}(M)$ was extracted from the experimental minor hysteresis loops [Fig. 3(b)]. The experimental $H_D^{\text{eff}}(M)$ is proportional to M , as was found in the case of the simulated curves.

The experimental effective demagnetizing factor thus extracted N_e is equal to 0.82. This is significantly smaller than 1, the usually applied demagnetizing field correction for an infinite thin film with out-of-plane magnetization. By con-

TABLE I. Hard Demag factor N' ($N' = N - N_g$ where N is the sample-shape demagnetizing factor and N_g is the grain self-demagnetizing field), N_e (effective demagnetizing factor derived from the simulated hysteresis cycles), slope (dM/dH) of the calculated main loop, slope characterizing the assumed h_c distribution, and slope of the calculated loop after application of the $1/N_e$ corrections. The variations from one system to another in the slope representing the intrinsic h_c distribution and the $1/N_e$ corrected loops are due to statistical errors resulting from the small size of the considered systems.

System size	40×40	60×60	80×80	100×100	120×120	200×200
N'	0.60	0.62	0.63	0.63	0.64	0.65
N_e	0.68	0.70	0.72	0.72	0.73	0.74
Slope of the calculated main loop	1.25	1.21	1.20	1.19	1.18	1.16
Slope representing the h_c distribution	8.05	7.95	8.10	8.23	7.92	8.04
Slope of the $1/N_e$ -corrected calculated loop	8.24	7.98	8.42	8.29	8.14	8.08

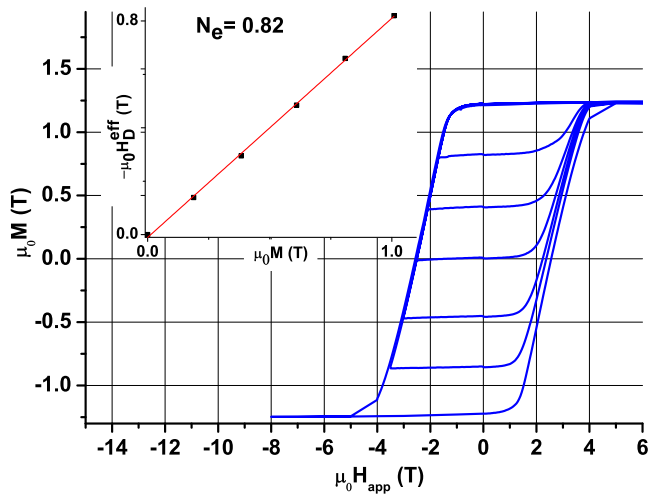


FIG. 3. (Color online) Experimental major and minor hysteresis loop for a 5 μm thick NdFeB film with perpendicular to plane magnetization. Inset: extracted dependence of the effective demagnetizing field on magnetization $H_D^{eff}(M)$.

trast, it is close to the effective demagnetizing factor, $N_e = 0.76$, extrapolated to an infinite flat sample from the calculated hysteresis loops. Scanning electron microscopy observations on these hard magnetic films indicate that the grains are slightly elongated in the direction perpendicular to the film plane. Smaller N_g implies larger N' , which may explain the 7% difference between the experimental N_e and the one derived from calculation in which cubic grains were considered.

In this paper, a simple method for extracting the magnetization dependent part of the demagnetizing field from minor hysteresis loops has been proposed. The validity of the method was demonstrated by analyzing simulated hysteresis loops of an assembly of exchange-decoupled magnetic grains, as well as experimental magnetization curves of a

hard magnetic NdFeB film. The effective demagnetizing field factor, N_e , derived from both calculated hysteresis loops and experimental ones do not coincide with those usually assumed. This may be attributed to the fact that the considered systems are heterogeneous at the scale of the events involved in magnetization reversal. The so-called ‘‘Hard Demag factors’’ introduced in a recent study^{8,9} appear to be in fair agreement with the N_e factor determined here.

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