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THEORETICAL STUDY OF TRANSVERSE SUSCEPTIBILITY IN UNIAXIAL FERROMAGNETS

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The effect of the second anisotropy constant K_1 in the series expansion of the uniaxial magneto-crystalline free energy on the transverse susceptibility is analysed. A generalized 2D Stoner-Wohlfarth model and a micromagnetic 3D model based on the Landau-Lifshitz-Gilbert equation approach are used in this analysis. The effect of K_2 on the transverse susceptibility is discussed for particle distributions.

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1. Introduction

The well-known experimental method of transverse susceptibility (TS) is used for direct measurement of the anisotropy in ferromagnetic systems. This is due to the fact that usually these systems show sharp peaks located at the anisotropy which makes possible a precise detection and the calculation of these important physical parameters 0, 0. This was proven for non-interacting uniaxial single particles systems by Aharoni et al. 0 within the coherent rotation Stoner-Wohlfarth theory. When applied to real systems a number of systematic errors are observed due to the disregard of some complex phenomena which occur in real systems, like inter-particle interactions 0,0 and relaxation 0,0.

In this paper one analyses a problem which should be carefully considered in order to correctly exploit the TS experimental data. The series expansion for the magneto-crystalline anisotropy usually taken into account in the calculus of the TS curve is:

$$W_k = K_1 \sin^2\theta + K_2 \sin^4\theta + ... \tag{1}$$

where θ is the angle between the easy axis and the magnetic moment of the particle; only the first term is introduced in the calculus, as in 0. However, this is accurate only when the angle between the easy axis and the magnetic moment is sufficiently small. In the TS experiment, it was shown that the particles with the easy axis oriented near 90° to the DC field direction are responsible for the peaks located at $\pm H_K$ 0, 0, where H_K is the anisotropy field; the shape of the TS curve is significantly influenced by the particles with the easy axis oriented near 90°. For these particles, when the field is near H_K the angle between their easy axis and the magnetic moment is close to 90º. Therefore neglecting the higher order terms in the TS calculation is a major source of errors. For materials with high values of K_2 this error is more significant (see also 0, 0, 0)

2. TS experiment

In the TS experiment one applies simultaneously to the sample two fields: a DC field, H_{DC}, and a very small amplitude AC field, H_{AC}, perpendicular to the DC field direction. Maintaining the

DC field and the amplitude of the AC field constant, with an appropriate coils system, one detects the variation of the total magnetic moment projection on the AC field direction.

If the easy axis of the single-domain particle orientation in this system is given by the spherical coordinates (θ_K, φ_K) and the orientation of the magnetic moment is given by (θ_M, φ_M), using the same methodology as presented in 0 one obtains after simple but straightforward approach the following expression for the TS:

$$\chi_T = \frac{3}{2}\chi_0 \left[\cos^2 \varphi_K \frac{\cos^2 \theta_M}{h_{DC} \cos\theta_M + \cos 2\theta + k_2 (\cos 2\theta - \cos 4\theta)} - \sin^2 \varphi_K \frac{\sin\theta}{h_{DC} \sin\theta_K} \right] \quad (3)$$

where $h_{DC} = H_{DC} / (2K_1 / M_s)$ is the reduced DC field, $k_2 = K_2 / K_1$, and $\theta = \theta_M - \theta_K$. The TS evaluation is simpler for $k_2 = 0$ due to the fact that the free energy has only two minima which can be selected with the well-known SW astroid critical curve. When $k_2 \neq 0$, the free energy landscape is more complicated. The number of minima is higher and the selection of the stable state in the TS measurement is more complex and the use of the critical curves formalism in this case is a helpful tool 0. However, the 2D critical curve could be misleading for the minima selection and a 3D model should be used.

Due to the difficult use of the 3D Stoner-Wohlfarth critical surfaces approach, developed by Thiaville 0, we preferred to use a micromagnetic model based on the Landau-Lifshitz-Gilbert equation 0.

3. The micromagnetic model. Results of simulations

The dynamic of the magnetisation vector $\vec{M}$ of each particle in the applied field $\vec{H}$ is described by the Landau-Lifshitz-Gilbert (LLG) equation 0.

The TS process was simulated by a sequence of fields, identical with those applied in the experiment, applied to a system of a few thousand particles. In this paper we present the results for a non-interacting system of identical particles. The results obtained in this way are, in fact, identical with those calculated for one particle. The program allows the calculation of the TS response for systems of interacting particles. These results will be published in a further paper. However, one can mention that the comparison between the “one particle” results obtained with the LLG program and calculated with the generalized SW approach described here is a test for the micromagnetic program.

Using both the 2D critical curves and the micromagnetic LLG model, a systematic analysis has been performed for positive and negative K_1 and K_2.

In Fig. 1 one presents the hysteresis loop and the TS curve in a complex case ($K_1 > 0$, $k_2 = -0.45$, $\theta_K = 77°$). With lines are represented the results calculated with the critical curve approach and with points the LLG simulation. One observes the excellent agreement between the two models. The random errors, which can be noticed on the LLG/TS simulation, are due to numerical round off errors. These errors are increasing if the amplitude of the AC field is decreased in the simulation. As the amplitude of the AC field decreases, the modification in the equilibrium state of the magnetic moment in comparison with that calculated when only the DC field is applied becomes smaller and more difficult to calculate with accuracy. So, in the simulations we have used an AC field amplitude which was sufficiently high to avoid the increase of the round off errors in the calculation of the equilibrium state variation due to the AC field. The TS curve shape is changing dramatically with the modification of the value of k_2 for both positive and negative K_1. In certain cases, supplementary peaks in the TS curves appear. Combination of measurements could be used to evaluate the K_1 and k_2 for non interacting systems of identical particles. For an assembly of non-interacting single domain particles the TS response is given by the integral of the transverse susceptibility of each particle over the easy axis distribution. Fig. 2 displays the results obtained for a randomly oriented system for different values of k_2. The well-known TS curve, with anisotropy peaks located at $h = \pm 1$ and switching field peak located at $h = -0.5$ is replaced by a curve with a more complicated shape. The anisotropy peaks are located now at $h(k_2) = \pm(1+2k_2)$ and the switching peak location and height depends on k_2 value.

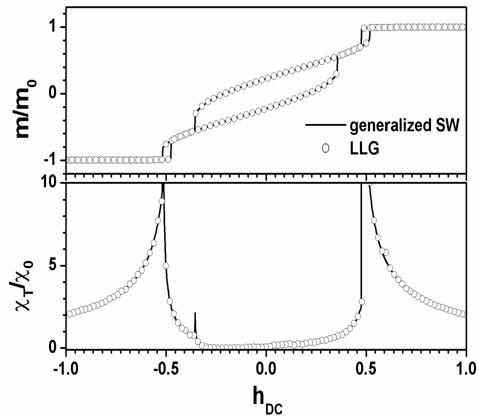

Fig. 1. (left) Hysteresis loop and TS curve for $K_1 > 0$, $k_2 = -0.45$, $\theta_K = 77°$.

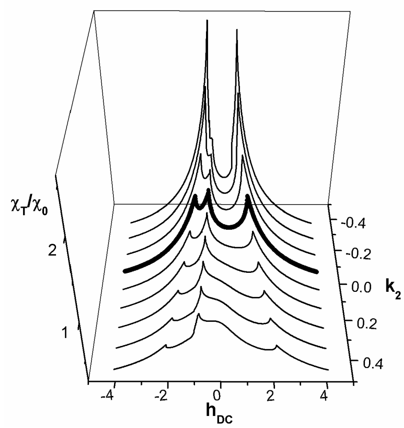

Fig. 2 (right). The mean TS of an assembly of randomly oriented monodomain particles, having an uniaxial anisotropy energy with $K_1 > 0$, and different values for k_2.

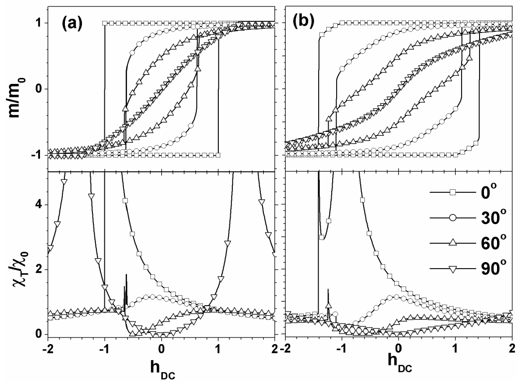

Fig. 3. Calculated hysteresis loops (top panels) and corresponding TS curves (bottom panels) for $K_1 > 0$, $k_2 = 0.2$ (a) and $K_1 > 0$, $k_2 = 1.0$ (b) for different orientations θ_K of the static applied field H_{DC}.

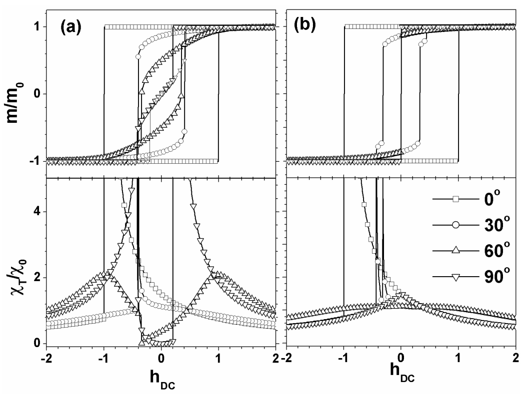

Fig. 4. Calculated hysteresis loops (top panels) and corresponding TS curves (bottom panels) for $K_1 > 0$, $k_2 = -0.4$ (a) and $K_1 > 0$, $k_2 = -1.0$ (b) for different orientations θ_K of the static applied field H_{DC}.

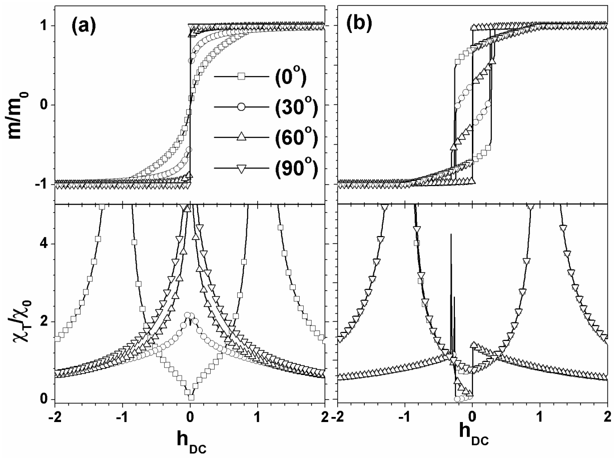

Fig. 5. Calculated hysteresis loops (top panels) and corresponding TS curves (bottom panels) for $K_1 < 0$, $k_2 = 0.4$ (a) and $K_1 < 0$, $k_2 = 1.0$ (b) for different orientations θ_K of the static applied field H_{DC}.

4. Conclusions

In this paper we used a micromagnetic approach based on LLG equation in order to calculate the TS of uniaxial ferromagnets, taking into account the first two order anisotropy constants, K_1 and K_2. Neglecting K_2 could be the origin of significant systematic errors in the anisotropy constants deconvolution from TS experiments (see also Figs. 3-5). In conclusion, this generalized approach of TS makes possible the expansion of the range of applicability of TS experiments as a method for determining the anisotropy in magnetic materials. The micromagnetic program described in this paper will provide an analysis tool for studying the effect of interactions on the TS curves.

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