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Size dependence of the magnetization reversal in a ferromagnetic particle

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ABSTRACT

In this work the finite elements method is used to simulate by micromagnetic modelling the behavior of a spherical ferromagnetic particle with uniaxial magnetocrystalline anisotropy. Full magnetization loops are taken in the easy axis direction at different values of anisotropy constant and particle size. The results indicate reversal mechanisms such as the coherent rotation, the curling mode and the growth of a reverse magnetization domain. The size dependence of critical fields and of other magnetic parameters, such as the nucleation volume of the reverse domain, the domain wall width and the susceptibility, is presented.

1. Introduction

Magnetization reversal in a ferromagnetic particle has been studied extensively but fragmentarily as regards the size of the particle. For small particles coherent rotation governs the reversal process and is described by the Stoner–Wohlfarth model [1]. At intermediate sizes the curling mode normal to the applied field appears. It has been studied analytically [2–4] and numerically for different particle shapes [5–10]. Finally, for large particles the reversal is incoherent through the nucleation and expansion of a reversed magnetic domain. The latter reversal mechanism has been studied approximately [6,8] but mainly qualitatively [11,12] and its effects are described by empirical rules [11–13]. The study of each mechanism separately is due mainly to the competition of the short-range exchange interactions and the long-range dipole interactions. Increasing the particle size, the number of interactions increases disproportionately, making the analytical study hard and leading to simplifications and approximations.

Micromagnetism is a widely used theoretical model, due to its capability of predicting the magnetic behavior of a continuous medium. On the other side, the finite element method (FEM) is a widely used numerical method for the solution of partial differential equations (PDE) in large-scale continuous media. Both have been used in simulations regarding magnetic particles and structures [14–18]. In this work micromagnetism and FEM were used in order to simulate the magnetic behavior of a ferromagnetic particle with uniaxial anisotropy under the influence of an external field and to study the reversal process with respect to the size of the particle.

2. Simulation method

The simulation method used is described in detail in an earlier publication [19]. The main features are the following:

2.1. PDE

The evolution of the magnetization vector $\vec{M}$ is governed by the damped PDE

$$\tau\frac{\partial\vec{M}}{\partial t}=\frac{1}{M_s^2}(\vec{M}\times\vec{H}_{eff})\times\vec{M}$$

where τ is the relaxation time of the system, M_s is the saturation magnetization and $\vec{H}_{eff}$ is a local effective field, described by the equation

$$\vec{H}_{eff}=\ell_{ex}^2\nabla^2\vec{M}+\kappa^2(\hat{u}\cdot\vec{M})\hat{u}+\vec{H}_d+\vec{H}$$

where $\ell_{ex}=\sqrt{2A/\left(\mu_o M_s^2\right)}$ is the exchange length $\kappa=\sqrt{2K_1/\left(\mu_0 M_s^2\right)}$, is the dimensionless hardness parameter and $\hat{u}$ is the direction of the easy axis. $\vec{H}_d$ is the demagnetizing field, calculated from the gradient of the magnetic scalar potential φ, which is derived from the Poisson equation $\nabla^2\varphi=-\nabla\vec{M}$ [20]. The last

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0927-0256/

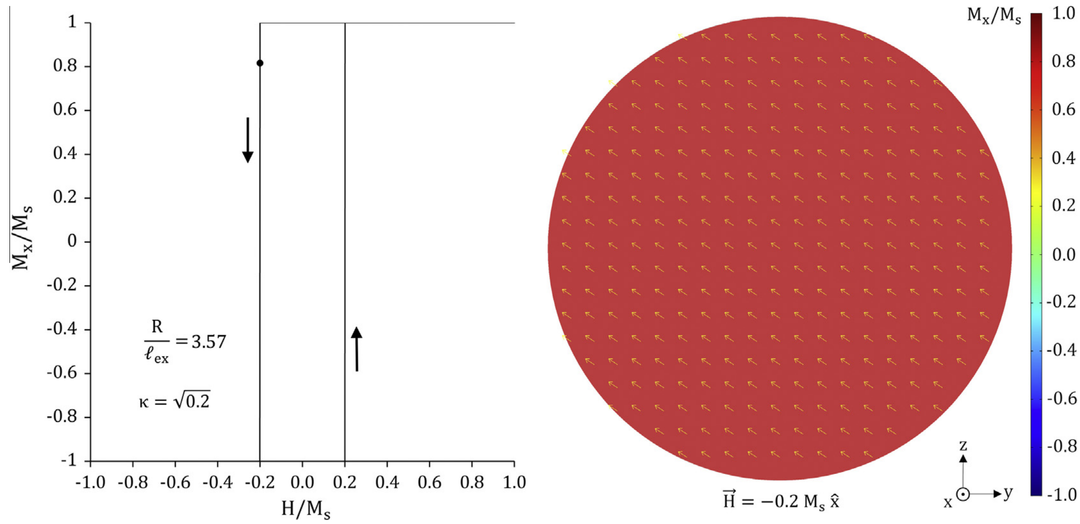

Fig. 1. Magnetization loop for a particle with $R = 3.57\ell_{ex}$ and $\kappa = \sqrt{0.2}$. The reversal mechanism is the coherent rotation of magnetic moments. On the right there is shown the orientation of the magnetic moments on the equatorial plane of the particle that is normal to the applied field, when the hysteresis loop is on the point indicated by the dot (left). The colorscale depicts the magnitude of the parallel to the field component of the magnetization. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

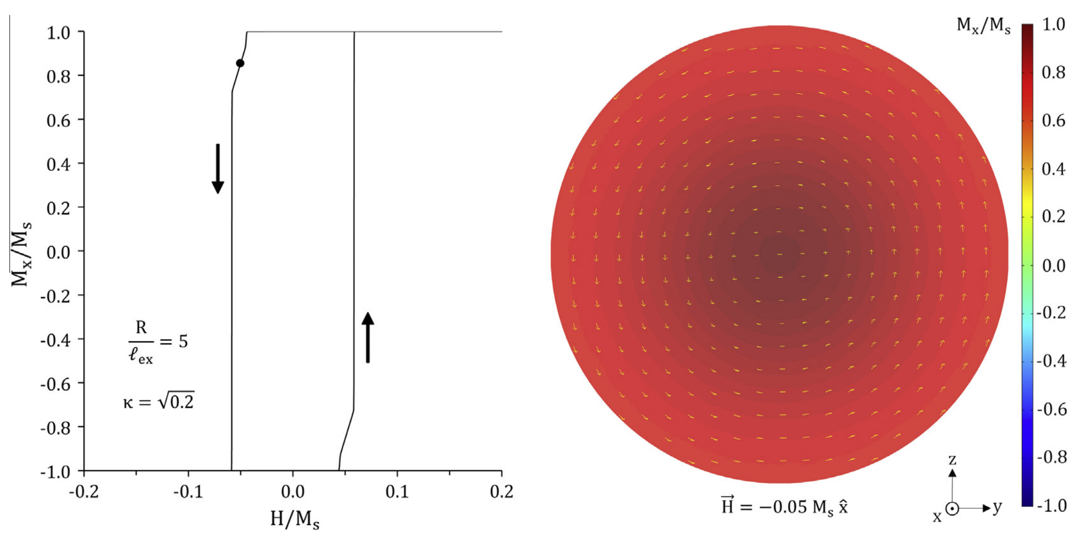

Fig. 2. Magnetization loop for a particle with $R = 5\ell_{ex}$ and $\kappa = \sqrt{0.2}$. The reversal mechanism starts with the curling of magnetic moments. On the right there is shown the orientation of the magnetic moments on the equatorial plane of the particle that is normal to the applied field, when the hysteresis loop is on the point indicated by the dot (left). The colorscale depicts the magnitude of the parallel to the field component of the magnetization. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

term, $\vec{H}$, is the external field, which is varied from M_s to $-M_s$ in a linear manner over 10^6 τ. The governing equations are supplemented with the boundary condition $\partial\vec{M}/\partial\hat{n} = 0$, where $\hat{n}$ represents the unit vector normal to the surface of the particle.

2.2. Meshing

Magnetization is interpolated using 3rd order Lagrange elements in the domain of a magnetic particle. The mesh consists of simplex tetrahedra and the mean mesh size is kept smaller than the width of a Bloch wall ($2\ell_{ex}/\kappa$). For the magnetic potential, 2nd order Lagrange elements have been used, both on the magnetic particle domain and on the surrounding outer domain. The outer domain is subdivided in two subdomains. In the closest to the particle subdomain, the mesh size was gradually increased, starting from that in the interior of the particle while in the second subdomain, mapped infinite elements [21,22] were used.

2.3. Solver

The three PDE for magnetization components and the one for magnetic scalar potential are solved simultaneously through the FEM by directly applying the weak form, which is derived by the Galerkin method. A BDF scheme [23] of variable step size and order is used for the time integration, and the PARDISO solver [24] is used for the linear system of equations.

3. Simulation results

The simulations, in their totality, were applied to spherical particles presenting uniaxial symmetry; the parametric constants were the (reduced) radius of the particle, R/ℓ_{ex}, and the anisotropy constant, that is, the hardness parameter,κ. Let it be noted that, for a given anisotropy constant, the biggest particle volume that could be subjected to simulation was confined by (a) the demand that