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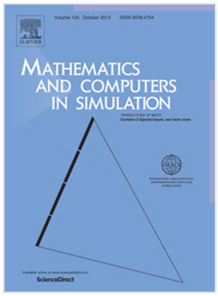

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Computational modeling of magnetic hysteresis with thermal effects

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Abstract

We study computational behavior of a mesoscopic model describing temperature/external magnetic field-driven evolution of magnetization. Due to nonconvex anisotropy energy describing magnetic properties of a body, magnetization can develop fast spatial oscillations creating complicated microstructures. These microstructures are encoded in Young measures, their first moments then identify macroscopic magnetization. Our model assumes that changes of magnetization can contribute to dissipation and, consequently, to variations of the body temperature affecting the length of magnetization vectors. In the ferromagnetic state, minima of the anisotropic energy density depend on temperature and they tend to zero as we approach the so-called Curie temperature. This brings the specimen to a paramagnetic state. Such a thermo-magnetic model is fully discretized and tested on two-dimensional examples. Computational results qualitatively agree with experimental observations. The own MATLAB code used in our simulations is available for download.

Keywords: Dissipative processes, hysteresis, micromagnetics, numerical solution, Young measures
2000 MSC: 35K85, 35Q60, 49S05, 78A30, 78M30, 80A17

1. Introduction

In the isothermal situation, the configuration of a rigid ferromagnetic body occupying a bounded domain $\Omega \subset \mathbb{R}^d$ is usually described by a magnetization $m : \Omega \to \mathbb{R}^d$ which denotes density of magnetic spins and which vanishes if the temperature θ is above the so-called Curie temperature θ_c. Brown [5] developed a theory called "micromagnetics" relying on the assumption that equilibrium states of saturated ferromagnets are minima of an energy functional. This variational theory is also capable of predictions of formation of domain microstructures. We refer e.g. to [15] for a survey on the topic. Starting from a microscopic description of the magnetic energy we will continue to a mesoscopic level which is convenient for analysis of magnetic microstructures.

On microscopic level, the magnetic Gibbs energy consists of several contributions, namely an anisotropy energy $\int_\Omega \psi(m,\theta)\,\mathrm{d}x$, where ψ is the-so called anisotropy energy density describing crystallographic properties of the material, an exchange energy $\frac{1}{2}\int_\Omega \varepsilon|\nabla m(x)|^2\mathrm{d}x$ penalizing spatial changes of the magnetization, the non-local magnetostatic energy $\frac{1}{2}\int_{\mathbb{R}^d}\mu_0|\nabla u_m(x)|^2\mathrm{d}x$, work done by an external magnetic field h which reads $-\int_\Omega h(x)m(x)\,\mathrm{d}x$, and a calorimetric term $\int_\Omega \psi_0\,\mathrm{d}x$. The anisotropic energy density depends on the material properties and defines the so-called easy axes of the material, i.e., lines along which the smallest external field is needed to magnetize fully the specimen. There are three types of anisotropy: uniaxial, triaxial, and cubic. Furthermore, ψ is supposed to be a nonnegative function, even in its first variable, i.e., $\pm m$ are assigned the same anisotropic energy. In the magnetostatic energy, u_m is the magnetostatic potential related to m by the Poisson problem $\mathrm{div}(\mu_0\nabla u_m - \chi_\Omega m) = 0$ arising from Maxwell equations. Here $\chi_\Omega : \mathbb{R}^d \to \{0,1\}$ denotes the characteristic function of Ω and $\mu_0 = 4\pi\times10^{-7}\mathrm{N/A}^2$ is the permeability of vacuum.

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