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Magnetic behavior of Joule-heated magnetic core–shell nanowires with positive magnetostrictive core material

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ABSTRACT

Temperature field is an important parameter to be known and controlled in the magnetization process of the core–shell nanowires. The paper analyzes the temperature dependence of hysteretic process in a core–shell nanowire subjected to a dc Joule heating process. An electrical current that passes through the wire induces a temperature and a thermal stress field in the system. Spatial and temporal evolution of the temperature in system was analyzed using a model based on time-dependent heat conduction equation. The stresses determined by thermal gradients and different expansion characteristics of core and shell materials were computed. The temperature and stress depend on the size parameters of the system, dc Joule current and the initial temperature of the system. The magnetic behavior of the nanowire was analyzed using the Micromag application. The magnetic state of the core is influenced by the temperature field induced by a dc current applied to the system. For core materials with positive magnetostriction coefficient the coercive field increases at the increase of dc current intensity passed through the system.

1. Introduction

The nanowires with core–shell structure present a new challenge topic in the field of advanced magnetic materials [1–4]. Due to their specific magnetic properties which are not present in the bulk materials, these structures are intensively used in applications as: magnetic recording media, nanosensors and magnetodielectrics for microwave devices [5,6].

Study of the thermal stability in the magnetic nanowires during the heating processes presents a special interest for technological applications as heat assisted magnetic recording (HAMR) [6,7]. The magnetic behavior of the core–shell system is strongly influenced by the thermal effects that appear in the presence of a heating source. The induced temperature field presents an interest subject study in experimental and theoretical research of the magnetic materials [5,6]. A good control of the temperature field in the system is important for precise defining of the magnetic behavior of the system. The paper analyzes the temperature field of a magnetic core–shell nanowire passed by a dc current. The temperature evolution of the core–shell system in time was obtained by solving the Fourier heat conduction equation with proper thermal boundary conditions in Comsol Multiphysics.

A 3D spatio-temporal model was developed to predict the evolution of the temperature and stress field for the core–shell system. This allows a direct computation of the temperature values produced by a dc current, in the transitory regime to the thermal equilibrium as well as at the thermal equilibrium, using material and geometric parameters. The stress values were computed using the determined temperature field and solving the thermo-elastic equations with a finite element method (FEM). The temperature and thermal stress depend on dc current densities values. A dc current that pass the wire heat it by Joule effect and the temperature increases from the room temperature to a temperature that correspond to the thermal equilibrium. On radial direction the temperature values decreases from center to the external surface. The spatial temperature gradients profile is source for the thermal stress distribution in the system. Small values of the thermal gradients into core–shell system on axial and radial direction determine the small values of the thermal stresses. The computed values of the stresses have the magnitude order of 100 MPa and are expected to strongly influence the magnetic state of the system. The paper provides a phenomenological study on temperature dependence of a hysteretic process in a core–shell nanowire subjected to a dc Joule heating process.

2. Temperature and thermal stress due to dc Joule heating process

A dc current that passes through the core–shell system determines a temperature and a thermal stress field which can influence

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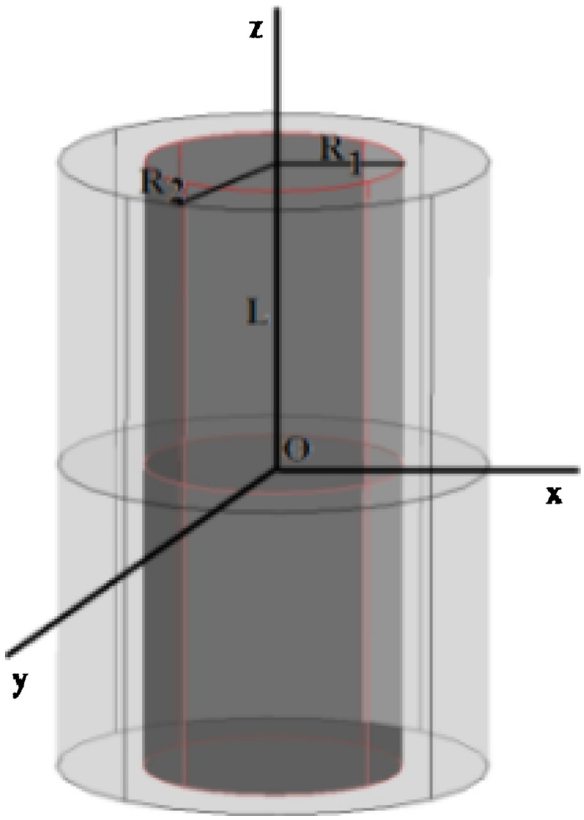

Fig. 1. Geometric configuration of the core–shell system.

the magnetic behavior of system. An important task is to evaluate and control the temperature and stress in the system when a dc current is passed. A theoretical model which predicts the evolution of the temperature and stress field allows the optimization of the parameters involved in the heating process. In our model a core–shell system composed by a magnetic core surrounded by a non-magnetic shell was considered (Fig. 1).

The system core representing the wire has the radius R_1. The system has the length L and external radius R_2. In calculations it was considered the radial coordinate r and axial coordinate z. The radial coordinate r and the axial coordinate z are considered in following calculations. On core–shell interface, the radial coordinate is $r = R_1$. A dc electric current is passed through the core and shell and this act as a heat source. The system starts to be heated from the room temperature T_0 at the moment $t = 0$. The external surfaces of the system were permanently kept at the room temperature.

2.1. Temperature field in the core–shell system

In this section it will be analyzed the temperature field determined by Joule heating effect taking into account the linear temperature dependence of core and shell electrical resistivity.

The temperature distribution in core and shell resulted in the heating process – $T_i(r, z, t) = T_i$ $(i = 1, 2)$ is computed as a solution of the time – dependent heat conduction equation [8]:

$$k_i \Delta T_i + Q_i = \rho_i c_i \frac{\partial T_i}{\partial t}, \tag{1}$$

The index $i = 1$ denominates the core and the index $i = 2$ denominates shell. The thermal characteristics of the system are: k_i – the thermal conductivity; ρ_i – the mass density; c_i – the specific heat, and t is heating time measured from the beginning of heating. The solutions of the Eq. (1) were computed to describe temperature evolution of the core–shell system.

The heat Q_i developed in the unit volume by the Joule effect in the wire has the following form:

$$Q_i = \rho_i j^2 = \rho_i \frac{I^2}{S_i^2}$$

where ρ_i is the resistivity at the temperatures T_i given by the relation:

$$\rho_i = \rho_0^i (1 + \alpha_i (T_i - T_0)),$$

α_i are the temperature coefficients of resistance, S_i – the cross sections of the systems (core and shell), ρ_0^i – the resistivities at room temperature and I – the intensity of the electrical current that pass the system.

The heat developed in the system by Joule effect depends on the value of dc current. In the transitory stage of the system, this thermal source increases the internal energy. In the steady state, the thermal equilibrium between system and the environment is achieved.

The following boundary conditions at core–shell interface were considered:

(1) the heat flux from the magnetic core is received by the shell. This heat flux must be continuous at interface:

$$k_1 \left. \frac{\partial T_1}{\partial r} \right|_{r=R_1} = k_2 \left. \frac{\partial T_2}{\partial r} \right|_{r=R_1} \tag{2}$$

(2) the temperatures of adjacent regions must be equal:

$$T_1(r = R_1, z, t) = T_2(r = R_1, z, t) \tag{3}$$

(3) the temperature on the external surface of the system, is equal to the temperature T_0:

$$T_2(r = R_2, z, t) = T_0 \tag{4}$$

2.2. The thermal stress field

The thermal gradients and the mechanical constraints due to the different elastic properties of materials that are in contact lead to the appearance of some thermal stresses in the core–shell system. In the thermo-elastic formulation, the equations of equilibrium for connected bodies known as the compatibility equations are described in reference [9] and link the stress field distribution with thermal field distribution.

The thermal stress distribution presents in core–shell system during the heating process was computed in Comsol Multiphysics using the temperature distribution inside the core and shell by solving the Eq. (1) with the boundary conditions (2)–(4). The thermal stress components in Cartesian coordinates were obtained as solutions of the equations presented in references [10,11]:

$$\begin{aligned}
&(1+\nu_i)\Delta\sigma_{xx}^i + \alpha_i(T)E_i\left(\frac{1+\nu_i}{1-\nu_i}\Delta T_i + \frac{\partial^2 T_i}{\partial x^2}\right) \\
&= 0,\ (1+\nu_i)\Delta\sigma_{yy}^i + \alpha_i(T)E_i\left(\frac{1+\nu_i}{1-\nu_i}\Delta T_i + \frac{\partial^2 T_i}{\partial y^2}\right) \\
&= 0,\ (1+\nu_i)\Delta\sigma_{zz}^i + \alpha_i(T)E_i\left(\frac{1+\nu_i}{1-\nu_i}\Delta T_i + \frac{\partial^2 T_i}{\partial z^2}\right) \\
&= 0,\ (i = 1, 2)
\end{aligned} \tag{5}$$

where x, y and z are the Cartesian coordinates. The Δ is Laplace operator, α_1 and α_2 are the thermal expansion coefficients of core and shell materials in contact, ν_1 and ν_2 are the Poisson's coefficients for core and shells. The cylindrical stress components in core $(\sigma_{rr}^1, \sigma_{\phi\phi}^1, \sigma_{zz}^1)$ and shell $(\sigma_{rr}^1, \sigma_{\phi\phi}^1, \sigma_{zz}^1)$ were obtained by a