Journal of Magnetism and Magnetic Materials 419 (2016) 282–291

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

# Ordering in rolled-up single-walled ferromagnetic nanomembranes

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ARTICLE INFO

*Article history:*
Received 24 January 2016
Received in revised form
2 May 2016
Accepted 11 June 2016
Available online 14 June 2016

*Keywords:*
Ferromagnetic nanotube
Ferromagnetic microtube
Stress-driven anisotropy
Magnetic domain structure
Analytical micromagnetism
Micromagnetic simulations

ABSTRACT

Magnetization of soft-ferromagnetic nano- and microtubes of nanometer-thin walls (a single-widening rolled-up nanomembranes) is theoretically studied using analytical and numerical approaches including different stress-induced anisotropies. Within the analytical study, we consider magnetostatic effects qualitatively, with an effective anisotropy, while they are fully treated in the micromagnetic simulations (limited to the tubes of submicrometer diameters however). Basic types of the periodic ordering have been established and their presence in nanotubes of polycrystalline Permalloy and cobalt has been verified within the simulations. The domain structure is basically determined by a material-deposition-induced helical stress or a cooling-induced axial stress via the volume magnetostriction while it is influenced by the distribution of magnetic charges as well. Also, it is dependent on the initial state of the magnetization process.



## 1. Introduction

Ordering in a small ferromagnetic tube with very thin wall compared to its radius is difficult to anticipate since that structure shares features of the thin film and magnetic wire relevant to the magnetostatics (a radial anisotropy of the hard-axis type and easy long axis of the tube) with a strong stress-driven anisotropy dependent on fabrication conditions. Because of complexity of the anisotropy, there are many metastable states of the magnetization, thus, the ordering is sensitive to initial conditions and external factors. On the other hand, the tube is a very important geometry among magnetic nano- and micro-systems since tubular coverings enable modifications of magneto-transport; GMI effect, and magneto-optical properties of wires and fibers to be utilized for sensing applications [1–3]. Also, magnetic microtube can serve as a sensing pipe for magnetic nanofluids [4].

Techniques of manufacturing single-crystalline and polycrystalline micro- and nanotubes of magnetic materials include electrochemical and chemical routes [2,5–7]. Highly efficient production methods are developed for magnetic microtubes of a thin wall. They are produced with sputtering in the form of microwire or microfiber coverings or rolled-up membranes of nanometer thicknesses [8,9]. Note that an outer shell of the amorphous glass-coated magnetic microwire can be considered as a tube as well, albeit it strongly interacts with the inner core of the wire, (the glass-coated magnetic microwire is a single-phase system with a core-shell type magnetic ordering [10]), and its wall is quite thick relative to the wire radius [11,12]. However, upon glass removal, the outer shell becomes very thin while the thickness of a domain wall (DW) that separates it from the inner core increases [13,14]. This is accompanied by a reorganization of the domain structure and influences the GMI characteristics [15]. With regard to functionalized wires and fibers, there is a need for modeling the dynamics of the thin-wall tube magnetization. The first step to do in order to formulate an effective model is to understand dominant mechanisms responsible for ordering in the nano- and microtubes without external influences.

In microtubes of very small wall-thickness to radius ratio, the longitudinal easy-axis anisotropy of the magnetostatic origin is weaker than in tubes of a thick wall or in wires. Thus, influenced by the stress-driven anisotropy, the domain magnetization can strongly deviate from the long-axis direction even in very elongated systems. Moreover, the magnetostatically-induced hard-axis anisotropy (the hard axis is normal to the tube surface) is strong, which facilitates in-the-wall ordering (excluding singularities; vortex and antivortex cores) independent of the stress direction and sign of the volume magnetostriction. Despite the shape anisotropy is not well defined in the system with an inhomogeneous magnetization, any efficient analytical approach to establishing equilibrium states of the tube requires introducing such an effective anisotropy into the model. Full micromagnetic simulations are necessary to verify the validity of such a simplification to the nanotubes while they are not any efficient alternative to the analytical evaluations of the microtube characteristics at present. It is because, simulating microtubes requires too large computational resources.

The purpose of the present study is to identify basic

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http://dx.doi.org/10.1016/j.jmmm.2016.06.030
0304-8853/

equilibrium states of thin-wall microtubes and nanotubes including longitudinal, transverse, and helical anisotropies. We compare static analytical and numerical solutions to the Landau–Lifshitz–Gilbert equation for nanotubes, modeling the magnetostatics effect with an effective anisotropy or performing full micromagnetic calculations, respectively. The evaluations are focused on the polycrystalline tubes of perhaps the most popular magnetic materials; Co and Py tubes. When exclude the crystalline anisotropy effect, important differences in ordering of these two materials follow from different saturation magnetizations. The influence of other factors (origin of the internal stress, initial state of the magnetization) on the formation of the magnetic texture is discussed as well.

In Section 2, a model of the thin-wall nano- and microtube is formulated, its analytical solutions are pointed out. Section 3 is devoted to presenting results of micromagnetic simulations of the process of tube ordering. Conclusions are collected in Section 4.

## 2. Model

In our analytical approach to study the magnetization of a polycrystalline or amorphous tube, the LLG equation in 3D is included in the form

$$
\begin{aligned}
-\frac{\partial \mathbf{m}}{\partial t} &= \frac{J}{M_s}\mathbf{m}\times\Delta\mathbf{m} + \frac{\beta_1}{M_s}(\mathbf{m}\cdot\hat{i})\mathbf{m}\times\hat{i} \\
&-\frac{\beta_2}{M_s}\frac{[\mathbf{m}\cdot(0,y,z)]\mathbf{m}\times(0,y,z)}{y^2+z^2} \\
&+\frac{\beta_3}{M_s}\frac{[\mathbf{m}\cdot(0,-z,y)]\mathbf{m}\times(0,-z,y)}{y^2+z^2} \\
&+\frac{\beta_4}{M_s}(\mathbf{m}\cdot\mathbf{a})\mathbf{m}\times\mathbf{a} - \frac{\alpha}{M_s}\mathbf{m}\times\frac{\partial\mathbf{m}}{\partial t}
\end{aligned}
\tag{1}
$$

Here, $\hat{i} \equiv (1, 0, 0)$, (the wire is directed along the $x$ axis), $M_s = |\mathbf{m}|$ represents the saturation magnetization, $J$ denotes an exchange constant, ($J \equiv 2\gamma A_{ex}/M_s$; $A_{ex}$ is called the exchange stiffness while $\gamma$ a gyromagnetic factor), $\beta_1$, $\beta_2$, and $\beta_3$ determine the strength of effective axial, radial, and circumferential anisotropies, respectively. An additional anisotropy in the tube wall is included with the $\beta_4$ constant. In the relevant term of the torque, $\mathbf{a}$ is a combination of $\hat{i}$ and $(0, -z, y)/\sqrt{y^2+z^2}$ vectors and $|\mathbf{a}| = 1$.

In order to establish main contributions to the anisotropy constants, utilizing analogies to the tubes, we adapt elements of the theory of elasticity of the amorphous and polycrystalline glass-coated microwires which is well developed [10]. According to this theory, the internal stress can be created at two production stages; the solidification of the magnetic material and its cooling that is a much slower process. The solidification of the magnetic microwire develops in the radial direction. In the surface layer of the microwire that can be considered as a tube, it produces equal to each other axial and circumferential components of the stress while the relevant radial stress is negligibly small. This kind of stress follows from a homogeneous shrinking of the inside surface of the tube compared to the outside surface and we call it a “solidification stress”, (in the body of the “rapidly-solidified” wire, the relevant stress is created layer by layer). In the presence of that stress, in the tubes made of amorphous or polycrystalline materials, the magnetostriction that is of the volume type only (isotropic) is expected to equally contribute to the $\beta_1$ and $\beta_3$ constants of the anisotropy.

However, the tube manufacturing is a different process from the wire production in general. Typically, the magnetic tubes are formed via rolling-up planar magnetic (created with sputtering or evaporation) layers or via direct sputtering on a surface of cylindrical wires. Those methods of the material deposition are accompanied by another “solidification stress” and a resulting easy direction in the magnetic layer that is parallel or perpendicular to the sputtering (evaporation) plane usually. While the rapid-solidification stress is not expected to be strong in a very thin film, the directed sputtering can result in the creation of a significant anisotropy relevant to $\beta_4$ constant [16,17]. Note that such an anisotropy can be weakened or completely removed via annealing. That “helical” anisotropy in a magnetic tube has been modeled previously in [18].

Another type of the stress can dominate in multi-layered tubes. Since the thermal expansion is isotropic within the cross-section of the double-layer tube, for a sufficiently long tube, a difference in the thermal expansion coefficients of the magnetic and non-magnetic layers results in equal to each other radial and circumferential stresses as well as in a much higher axial stress which are induced during the slow cooling process. Therefore, in the amorphous or polycrystalline tubes, the “cooling stress” contributions to the constants of the radial and circumferential anisotropies are equal.

Denoting the magnetostatic, solidification, and cooling contributions to the anisotropy constants with the relevant indices; $\beta_i = \beta_i^{(ms)} + \beta_i^{(solid)} + \beta_i^{(cool)}$, $(i = 1, 2, 3)$, we establish $\beta_2^{(cool)} = -\beta_3^{(cool)}$, $\beta_2^{(solid)} \approx 0$, $\beta_1^{(solid)} = \beta_3^{(solid)}$, $\beta_2^{(ms)} > 0$, $\beta_1^{(ms)} \geq \beta_3^{(ms)} \approx 0$. In particular, it follows from above formulae that the effective cooling-induced anisotropy is uniaxial with the anisotropy axis oriented along the tube. In the limit of infinitely thin tube, the axial contribution to the shape anisotropy becomes negligible; $\beta_2^{(ms)} \gg \beta_1^{(ms)} \approx 0$.

Searching for the static solutions to (1) and performing the micromagnetic simulations of tubes, we restrict our considerations to the regimes of solidification-dominated stress and cooling-dominated stress. Also, we focus on thin-wall tubes taking $\beta_1^{(ms)} = \beta_3^{(ms)} = 0$ in analytical evaluations. Thus, we consider a quasi-2D system with a periodic boundary condition relevant to the tube geometry. It is basically in-the-plane magnetized due to the magnetostatics.

### 2.1. Tubes with cooling-dominated stress

According to the above analysis of the anisotropy constants, the cooling-dominated stress produces an axial anisotropy mainly. Therefore, having in mind the aim of obtaining the periodic along the tube axis solutions, first, we seek for single-DW solutions assuming the domains to be magnetized longitudinally to the wire. Thus, the boundary condition $\lim_{|x|\to\infty}\mathbf{m} = \pm(M_s, 0, 0)$ is satisfied. Using a systematic approach of the soliton theory, we look for the equations of motion in the multi-linear form. Following [19], we apply the transform

$$
m_+ = \frac{2M_s}{f^*/g + g^*/f}, \quad m_x = M_s\frac{f^*/g - g^*/f}{f^*/g + g^*/f},
\tag{2}
$$

where $m_\pm \equiv m_y \pm i m_z$, and we find tri-linear equations of motion for the complex functions $g(x, y, z, t)$, $f(x, y, z, t)$ (secondary dynamical variables)

$$
\begin{aligned}
&-f\,\mathrm{i}D_t f^*\cdot g = f\left[\alpha D_t + J\left(D_x^2 + D_y^2 + D_z^2\right)\right]f^*\cdot g \\
&\quad + Jg^*\left(D_x^2 + D_y^2 + D_z^2\right)g\cdot g \\
&\quad - \frac{2\beta_1 + \beta_2 - \beta_3}{2}|f|^2 g - \frac{\beta_2 + \beta_3}{2}\frac{(y + \mathrm{i}z)^2}{y^2 + z^2}f^{*2}g^*, \\
&\quad - g^*\mathrm{i}D_t f^*\cdot g = g^*\left[\alpha D_t - J\left(D_x^2 + D_y^2 + D_z^2\right)\right]f^*\cdot g \\
&\quad - Jf\left(D_x^2 + D_y^2 + D_z^2\right)f^*\cdot f^* \\
&\quad + \frac{2\beta_1 + \beta_2 - \beta_3}{2}|g|^2 f^* + \frac{\beta_2 + \beta_3}{2}\frac{(y - \mathrm{i}z)^2}{y^2 + z^2}g^2 f.
\end{aligned}
\tag{3}
$$