Journal of Magnetism and Magnetic Materials 440 (2017) 217–220

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

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

Self-organization of the magnetization in ferromagnetic nanowires

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ARTICLE INFO

Keywords:
Domain wall
Nanowire
Magnetic inhomogeneities
Stochastic domains

ABSTRACT

In this work we demonstrate the occurrence of the characteristic spatial scale in the distribution of magnetization unrelated to the domain wall or crystallite size with using computer simulation of magnetization in a polycrystalline ferromagnetic nanowire. This is the stochastic domain size. We show that this length is included in the spectral density of the pinning force of domain wall on inhomogeneities of the crystallographic anisotropy. The constant and distribution of easy axes directions of the effective anisotropy of stochastic domain, are analytically calculated.

1. Introduction

Recently, there has been a keen interest in studying relatively new magnetic objects - ferromagnetic nanowires - with self-organization elements in the structure. In particular, the authors of [1,2] demonstrated the simplest case of magnetization self-organization in a nanowire bunch under the action of demagnetizing fields. The result observed was quite expected: neighboring nanowires appeared oppositely magnetized. The phenomenon of self-organization of the structures was observed in many systems containing the factor responsible for ordering: in the electric systems [3], the system of magnetic dipoles [4], superconductors [5], and thin ferromagnetic films [6–8]. In addition, it is interesting to consider the magnetization self-organization processes in 1D systems (nanowires and nanoribbons) [9,10]. In particular, Rougemaille et al. [9] studied the formation of an ordered domain structure in wires with a diameter of a few atomic layers depending on the fabrication technique used.

In this work, we investigate the unusual self-organization type, specifically, the occurrence of the stochastic magnetization superstructure in a polycrystalline 1D ferromagnet. We consider a polycrystalline wire as a one-dimensional chain of crystallites with a linear size somewhat smaller than the domain wall (DW) thickness $\delta_0 = \sqrt{A/K}$, (A and K are the exchange and anisotropy constants, respectively). The crystallite easy magnetization directions are randomly distributed over a sphere. The exchange coupling between neighboring crystallites and crystallographic anisotropy of individual crystallites compete in the magnetic structure formation. If there is no uniform macroscopic anisotropy the magnetization field is a conglomerate of the so-called stochastic domains (SDs) or magnetic blocks (MBs) [11–15]. New length δ_S corresponding the SD size was detected in real experiments by different authors using different experimental tools [16–18]. But magnetostatics defines favorable direction of magnetization along the long axis of the crystallites chain.

2. Induced stochastic anisotropy

It is know the SDs exhibit the pronounced uniaxial anisotropy [15] with its effective constant and effective axis direction. To calculate the effective anisotropy constant for a block, we write the torque from the side of the random anisotropy field of an ensemble of crystallites contained in the SD:

$$M_\vartheta = \frac{\partial}{\partial\vartheta}\sum_{n=1}^{N} v_n K_n (\mathbf{m}_n \mathbf{e}_n)^2. \quad (1)$$

where v_n and K_n is the volume and local anisotropy constant for the nth crystallite, $\mathbf{e}_n$ are the easy magnetization axis (EMA) direction orts, and N the number of crystallites in a SD, ϑ - polar angle of the magnetization. The same torque should be induced by the effective anisotropy of the SD that involves the block crystallites. We can write the effective anisotropy torque as

$$M_{\vartheta_{ef}} = \frac{\partial}{\partial\vartheta} V K_{ef} (\mathbf{m}\mathbf{e}_{ef})^2. \quad (2)$$

where K_{ef} and $\mathbf{e}_{ef}$ are the effective anisotropy constant and effective anisotropy axis (EAA) direction vector of the block, and $V = \sum v_n$ is the block volume. We equalize expressions (1) and (2) and obtain

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http://dx.doi.org/10.1016/j.jmmm.2016.12.053
Received 15 August 2016; Received in revised form 2 November 2016; Accepted 18 December 2016
Available online 23 December 2016
0304-8853/

$$K_{ef} = \left[\frac{<K^2> - \mu^2 <K>^2}{N} (\sigma_v^2 + 1) + \mu^2 <K>^2 \right]^{\frac{1}{2}}. \quad (3)$$

where $\mu = <\cos(2(\alpha_n - \alpha_m))>$, crystallite EMA polar angle α, and σ_v is dimensionless crystallite volume dispersion. It should be noted that when the volumes and constants K of crystallites are identical, expression (3) acquires the well-known form $K_{ef} \approx K/\sqrt{N}$.

The exchange extracts a certain mode from the random picture of the easy axes anisotropy distribution. To study the features of the distribution of the SD effective easy axes (EAA) directions, we return to Eqs. (1) and (2). Using this equation, we obtain the expression for the effective direction of the anisotropy axis

$$\sin(2\alpha_{ef}) = \frac{K}{K_{ef}} \sum_{n=1}^{N} \sin(2\alpha_n) = s_0. \quad (4)$$

Let us calculate the density of distribution of the quantity $s = \sin(2\alpha_{ef})$, which can be presented in the form

$$\rho(s) = \int_{-\alpha_0}^{\alpha_0} \dots \int_{-\alpha_0}^{\alpha_0} \prod_{n=1}^{N} \rho(\alpha_n) \delta(s - s_0) d\alpha_n. \quad (5)$$

where $\rho(\alpha_n)$ is the density of distribution of the EAA polar angles, α_0 is a half of the polar angle of cone opening in the EAA distribution. In this expression the δ-function excludes the implementations α_n from integration, that do not satisfy condition (4). To obtain the final form of (5), we use the refining technique described in [19] (Fourier-transform with the free parameter). The calculated $\rho(\alpha_{ef})$ values for $\rho(\alpha_n) = 1/(2\alpha_0)$ are presented in Fig. 1 in comparison with the Gaussian approximation.

The exchange coupling strengthens the fragile stochastic regularity. Thus, the self-organized area arises, where the exchange coupling ensures the quasi-homogeneous magnetization. When the magnetostatic interaction starts working, SDs become invisible. Classical domains and domain walls appear. Meanwhile, the magnetization self-organization is observed in nanowires in the presence of the uniform macroscopic anisotropy induced by magnetostatics. Stochastic domains are analogous to the normal modes of interacting oscillators and exist as a structural unit.

3. Self-organization manifestation upon magnetization switching

The computations were made using the gradient descent technique [20]. Let the wire be magnetized along the long axis direction. The magnetic structure is almost homogeneous, except for weak oscillations of the EAA direction. Below we show that some parts of the inhomogeneities are initial nuclei of inverse domains. The observations show

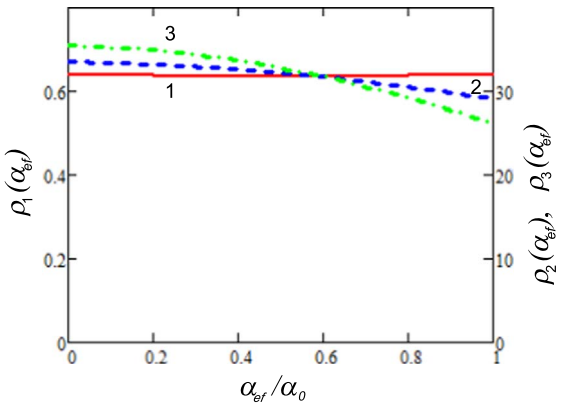

Fig. 1. Distribution of the polar angle of the effective anisotropy axis of a stochastic domain. Plot 1 shows the uniform distribution of local axes in a cone from $-\pi/2$ to $+\pi/2$; plot 2, in a cone from $-\pi/100$ to $+\pi/100$; and plot 3, the Gaussian approximation for a cone from $-\pi/100$ to $+\pi/100$.

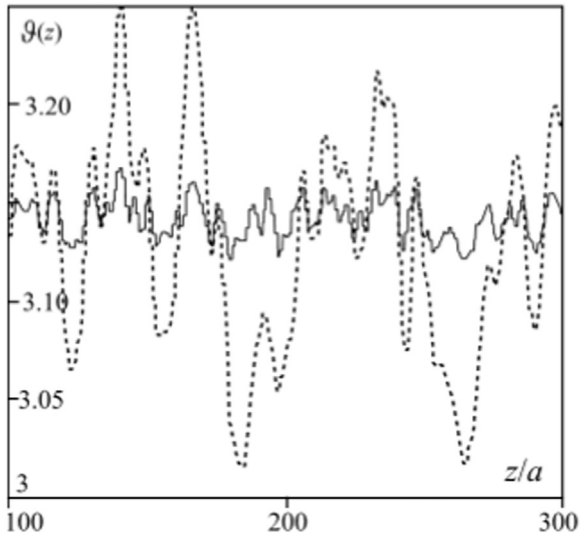

Fig. 2. Enhancement of magnetization fluctuations with an increase in the external magnetic field. The solid line corresponds to $h = H/H_S = 0$ and the.

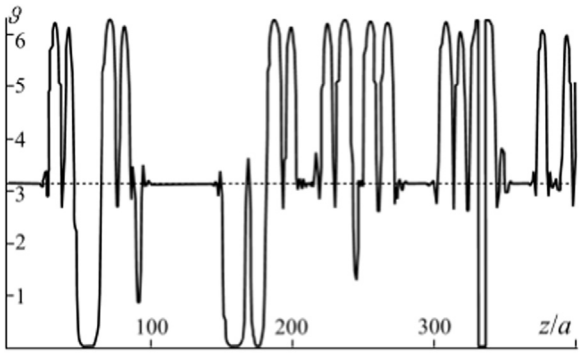

Fig. 3. Domain structure formed at attaining the critical field.

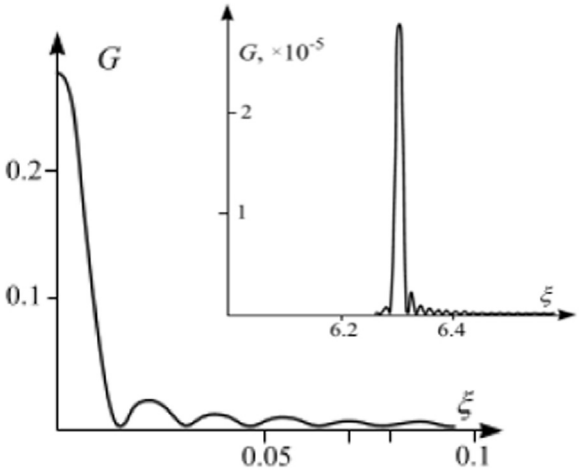

Fig. 4. Characteristic spectral density of the distribution of the polar angle for a magnet at $b = a/\delta_0 = 0.1$.

that the sizes of these parts are similar to those of SDs.

We apply an external magnetic field in the direction opposite to the average magnetization. The applied field increases deviations of the magnetization from the z axis direction. The beginning of this process is illustrated in Fig. 2.

When the external field attains a critical value of $H_{nucl} \approx 0.16\mu_0 M_S$, the magnetization of separate nuclei drastically rotates, which results in the occurrence of 180- or 360-degree domain walls [20]. Fig. 3

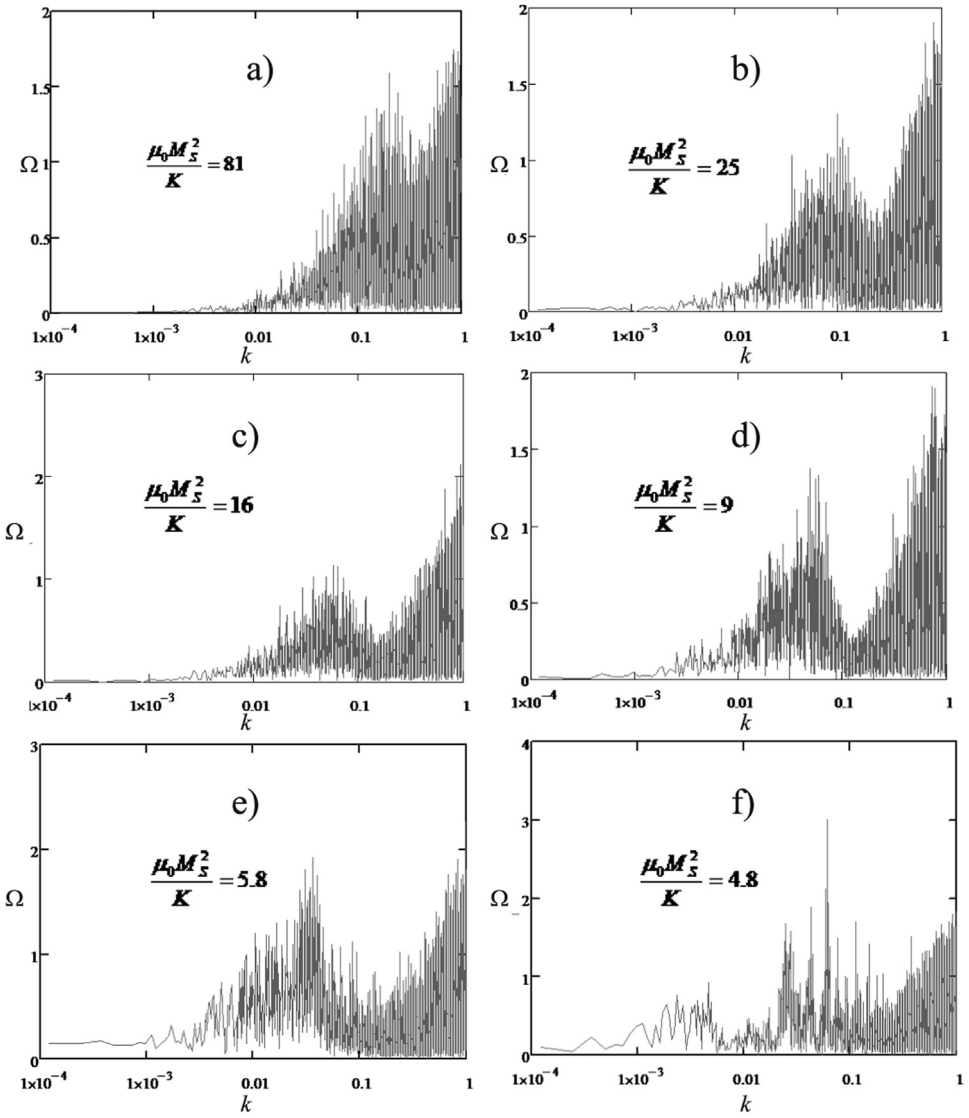

Fig. 5. Spectral density $\Omega(k)$ of the force relief for samples with different M_S values. The EMA directions are distributed randomly and uniformly over a sphere. Here, $k \approx 1/\lambda$, where λ is measured in units of a.

illustrates the end of this process.

The frequently occurring 360-degree domain walls and some of 180-degree walls do not move upon variation in the external magnetic field. The low mobility originates from the fact that at large saturation magnetizations M_S of a material, the demagnetizing field creates satellite domains with the opposite magnetization at the domain edges (Fig. 3). The domain wall continuation in the satellite works as a part of the 360-degree wall, pinning the latter [20]. The nuclei domain walls have the anomalously low mobility. The obtained domains are located in the places where SDs would be located if the induced magnetostatic anisotropy were absent. Thus, the information about SDs is stored, despite the effect of such a strong masking factor as the anisotropy induced by magnetostatics. The phenomenon of pinning the domain walls that separate the regions related to SDs can apparently be observed in experiments. The experiment should follow the scenario described above.

Spectral study of the magnetization distribution function makes it possible to consider the structure in more detail without switching the sample magnetization. Let us consider the spectral density $G(\xi)$ of the spatial distribution of the polar angle $\vartheta(z)$

$$G(\xi) = \frac{1}{4\pi^2}\left(\left(\int_0^L \vartheta(z)\cos(z\xi)dz\right)^2 + \left(\int_0^L \vartheta(z)\sin(z\xi)dz\right)^2\right). \quad (6)$$

The spatial magnetization distributions $\vartheta(z)$ shown in Figs. 2 and 3 were obtained at the same implementation of the stochastic anisotropy field at different external fields. These distributions were subjected to the spectral analysis.

It can be seen that with an increase in the field, the functions $\vartheta(z)$ exhibit the common features. The peaks and dips in the $\vartheta(z)$ curves are positioned at the same places and only have different values. However, in the critical external fields, one can observe significant differences. It is remarkable that the spectral densities at any external field values completely coincide. The effects masking the self-organization are not reflected in the spectral density. The form of $G(\xi)$ is determined by the primary interactions (crystallographic anisotropy and exchange), i.e., by SDs. The main contribution to the spectral density is made by the long-wavelength region (SD size). It is important that, as expected, the spectral density plot contains a noticeable maximum corresponding to the crystallite sizes (a/δ_0 value) Fig. 4.

4. Spectral analysis of domain wall pinning

The authors of [21] theoretically discussed domain wall pinning in ultradispersed 1D materials on the force relief of magnetic inhomogeneities and statistical properties of this relief. In this study, we simulated the nanowire magnetization switching to investigate the pinning force spectrum. In computer simulation the magnetic field applied along the z axis was increased. The equilibrium distribution of magnetization searched by gradient descent. The initial distribution of magnetization chosen so as to form one domain wall. The total SD energy E_W was detected. The pinning force was defined as the ratio of the changes of energy of wall to its displacement at the distance a: $F = -\Delta E_W/a$.

Fig. 5 presents the result of the spectral analysis of the force relief of wires with the same cross section and parameter $a/\delta_0 = 0.1$, but different ratios $\mu_0 M_S^2/K$. This ensured approximately the same SD size, but different widths of domain walls between classical domains. The maximum corresponding to the large k values is determined by the magnetization ripples upon tuning to the local anisotropy of separate crystallites. The other maximum is, in our opinion, complex and contains peaks responsible for the domain wall width and SD size (in this case, their characteristic sizes are comparable). It can be seen from the Fig. 5 that with decreasing M_S, the maximum splits and the peak responsible for the increasing domain wall width becomes pronounced. In this case, the peak responsible for the SD is nearly invariable.

Thus, the force relief has at least three pronounced harmonics: two long-wavelength - SD size and domain wall size with short-wavelength mode - crystallite size.

5. Conclusions

The spectral analysis of magnetization and pinning force allowed us to determine the long-wavelength harmonic, which is attributed to the existence of the so-called stochastic domains (magnetic blocks). The wavelength of this harmonic coincides with the stochastic domain size.

The parameter characterizing the new self-organization is the induced stochastic anisotropy. We derived the universal expression for the induced stochastic anisotropy, which involves fluctuations of the crystallite size, fluctuations of the local constants, and arbitrary distribution of the local anisotropy axes directions.

Acknowledgments

This study was supported by RFBR, Project no. 14-02-00238-a.

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