Magnetic domains and the process of technical magnetization

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Abstract. This article presents the results of the formation of a domain structure and the process of technical magnetization of weak ferromagnets. It has been determined that for a given film thickness, the characteristic dimensions of the domain structure depend on the energy density of domain boundaries and the magnetic dipole energy density.

1 Introduction

The range of substances in which a stable domain structure is observed includes crystals and alloys with various types of magnetic ordering: ferromagnets, ferrimagnets, antiferromagnets with weak ferromagnetism. For the first time, the hypothesis about the existence of regions of spontaneous magnetization – domains – in ferromagnets was put forward by Weiss at the beginning of the 20th century. The famous work of Landau and Lifshitz in 1935 (see [1]) provided a theoretical justification for the Weiss hypothesis about domains and it also outlined the first specific model of the domain position of a ferromagnet.

2 Research methods

Within the framework of the phenomenological theory developed in [1], the question of formulating isostatic spin relationships in magnets with a domain structure (DS) is reduced to solving equations that specify the minimum of the equilibrium thermodynamic potential,

$$F = \int \Phi dV = \int [f(M(r), L_v(r), \frac{\partial M}{\partial x_i}, \frac{\partial L_v}{\partial x_i}) - M(r)H - \frac{1}{2}M(r)H_m(r)]dV, \quad (1)$$

together with the magnetostatic equations:

$$rotH_m = 0,$$

$$divH_m = 4\pi\rho_m, \quad (2)$$

$$\rho_m = -divM$$

L_v- the value of the internal parameters of the ferromagnet;
M - general magnetization;

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$H_m(r)$– magnetostatic field;
ρ_m- density of magnetostatic charges;
V– body volume;
H– external magnetic field;
f - a function that represents part of the internal energy of the magnet.

3 The results obtained and their discussions

Obtaining a solution to this system in a general form at the present stage of development of the physics of magnetic phenomena represents the "super task" of the theory of micromagnetism. However, in experimentally observed DS the following inequality is usually satisfied:

$$X_0 \leq D \leq L,$$

where X_0 - is the thickness of the domain wall,
D - is the characteristic size of the domain,
L - is the characteristic size of the sample.

This size ratio allows one to significantly simplify functional (1), and as a consequence, to simplify the very task of determining the equilibrium domain structure of a magnet. A fairly large number of works have been devoted to theoretical studies of the types of various domain configurations (see review [2]), on the basis of which we can conclude that the internal state of a magnet is mainly determined by the magnitudes of exchange, magnetic dipole-dipole and anisotropic interactions, the magnitude of the Dzyaloshinsky interaction and the magnitude of the internal field

$$H^{(1)}(r) = H + H_m(r).$$

The homogeneity of internal states in domains implies the spatial homogeneity of the internal field $H^{(1)}(r)$ in them. In the case of a regular DS, when the magnetization $\langle \mathrm{M}(r) \rangle$, averaged over the dimensions $\lambda\ (L >> \lambda >> D)$, is uniform over the sample

$$H_m(r) = -4\pi\widehat{N}\langle M \rangle,$$

$\widehat{N}$- tensor of demagnetizing coefficients.

In the case of homogeneous domains, the internal magnetostatic charges can be concentrated exclusively at the domain boundaries, which leads to a jump in the normal charge to the domain boundary

$$\Delta M_n = M_n^{(1)} - M_n^{(2)},$$

where $M_n^{(1)}$and $M_n^{(2)}$are the equilibrium magnetizations in neighboring domains. The requirement for a minimum thermodynamic potential (1) when condition (2) is met in the case of uniaxial anisotropy of the magnet leads to the condition $\Delta M_n = 0$ [3], i.e. to antiparallel orientation of magnetization vectors in neighboring domains (to 180-degree DS).

As is known, in a homogeneous state, the saturation magnetization $M_s$of a magnetically ordered sample of finite dimensions is parallel to the axis of easy magnetization (A.E.M.), while the internal field of the sample $H_i = -4\pi M_s$, and its free (magnetostatic) energy per unit volume equal to $2\pi M_s^2$ [3]. Since the vectors $H_i$and $M_s$are antiparallel, this state of the sample is metastable, and, obviously, there is a magnetic structure with lower free energy. In this case, it is energetically advantageous for the sample to split into domains - regions of finite sizes with the opposite direction of the $M_s$vector; each of them is magnetized spontaneously to saturation, but the sum of the resulting moments throughout the entire volume of the sample is zero. At the boundary of two domains, the $M_s$vector gradually changes its orientation from a direction parallel to the magnetization of the first domain to a direction parallel to the magnetization vector of the second. Such a transition layer (where the direction of $M_s$changes) is called a domain boundary (wall). Since the parallelism of the

spins of neighboring atoms in the domain boundary is disrupted, and their direction differs from that specified by the magnetic crystal anisotropy, the appearance of domain walls leads to an increase in the energy of the sample both due to an increase in the exchange energy and the anisotropy energy. Therefore, the emerging domain structure will be determined by the balance between the demagnetizing effect of the sample surface and the energy of domain boundaries [4].

There are two main types of domain boundaries: Bloch and Néel. In the first of them, when passing through the boundary, the spin rotates in the plane of the boundary and the normal component of the spins does not change, so the total magnetostatic energy is minimal. However, if the magnetization vector lies in the plane of the sample (films or thin single-crystal plates), with such a spin distribution, magnetic poles appear on the sample surface at the exit of the domain wall and the magnetostatic energy increases. In this case, it turns out to be more advantageous to rotate the spins in the domain wall in a plane parallel to the surface of the sample. Such a domain wall is called Néel's [5].

When an external magnetic field is applied, the (technical) magnetization of a multi-domain sample is carried out by two main processes of changing its domain structure. Firstly, domains with a magnetization direction closer to the direction of the applied magnetic field will grow due to a decrease in the volume of less favorably magnetized domains. This process is carried out by shifting domain boundaries. Secondly, in each of the domains there will be a rotation of magnetization towards the direction of the external magnetic field. The latter occurs mainly at the end of the process of technical magnetization of the sample.

One of the parameters that determines the orientation of the M_s vector in domains is the quantity $R = \frac{K}{2\pi M_s^2}$, where K - is the anisotropy constant, characterizing the volumetric anisotropy energy density. If $R > 1$, then in [4] it is shown that the formation of closing domains is energetically unfavorable; domain boundaries are Bloch boundaries (as already noted, such boundaries are characterized by the constancy of the projection of M_s onto the normal to the domain boundary) and are located along the A.E.M., vector M_s in domains is also parallel to A.E.M.

In the case of $R \leq 1$, the vector M_s occupies an intermediate position between the A.E.M. and the plane of the sample (in this case, a stripe domain structure or the so-called stripe structure appears). Such a magnetic structure was comprehensively studied in [6 – 8]. It was shown that there is a critical thickness, below which it is advantageous for the sample to be in a single-domain state with magnetization lying in its plane. The most characteristic feature of a stripe structure is the presence in the sample plane of a preferential direction in the formation of domain boundaries, which can be caused by anisotropy in the sample plane, the tilt of the anisotropy axis or the direction of the external magnetic field relative to the normal to the sample surface. In particular, this situation arises if the direction of easy magnetization lies in the sample plane, which is achieved, for example, by a slight deviation of the anisotropy axis from the normal to the surface when cutting a plate from a single-crystal sample. In this case, the domain boundaries are located parallel to the A.E.M., since the deviation from this direction is associated with an increase in the free energy of the system by an amount $\sim M^2$.

The period of the domain structure D depends both on the characteristic size of the sample along the A.E.M. ($D \sim L^{1/2}$), and from the external magnetic field. The theory of magnetization processes in multidomain crystals has been developed both for orienting the direction of the external magnetic field along [9,10] and perpendicular to A.E.M. crystal [9-10], as well as for arbitrary orientation of the vector H relative to A.E.M. [11, 12]. The first two cases differ qualitatively from each other in the nature of the behavior of the domain structure in a magnetic field.

In [9], the stripe domain structure of a thin plate (L~3 μm) of $BaFe_{12}O_{12}$ ferrite was studied. Direction A.E.M. coincided with the direction of the hexagonal axis C_3, perpendicular to the sample plane. The H field was applied parallel to the C_3 axis. With increasing external magnetic field strength, the width of domains with $M_s$oriented along the field, d_1, increased due to a decrease in the width of domains d_2 with opposite magnetization orientation. It was found that in weak fields the period of the domain structure $D = (d_1 + d_2)$ remained approximately constant. When the value of H approached the saturation field value, the width d_1 increased sharply with increasing field, while the width d_2 decreased very slowly. In this case, domains with a magnetization orientation opposite to the field disappeared not by reducing their width to zero, but as a result of reducing their extent. By minimizing the total energy of the plate, which consists of the energy of domain boundaries, the energy of interaction with the field H and magnetostatic energy, the dependences of the structure period D and domain width d_2 on H were calculated in [9], which were in good agreement with the experimental results. It was shown that the value of D increased with increasing field, tending to infinity in fields close to the saturation field. Those. it was found that in a magnetic field parallel to the A.E.M., there is both a change in the volume occupied by some domains at the expense of others and an increase in the period of the domain structure.

The dependence of the period of the domain structure on the magnitude of the external magnetic field perpendicular to the A.E.M. was studied on various materials (for example, in [6] studies were carried out on permalloy films). A theoretical consideration of the available experimental results, carried out on the basis of ideas about small deviations of magnetization from A.E.M., was carried out in [7]. In [8], from the condition of a minimum thermodynamic potential of the system, an equilibrium distribution of magnetization in thin ferrite films was found in the presence of an external magnetic field applied in the plane of the sample. In [9], based on the Bloch domain wall model, a theory of changes in the period of the domain structure in a magnetic field perpendicular to the A.E.M. was proposed, which was subsequently refined in [10] using the twisted domain wall model.

In accordance with the results of these works, the dependence of the equilibrium period of the domain structure on the magnitude of the reduced field $h = \frac{H}{H_A}$ (where $H_A = \frac{2K}{M_S}$) and film thickness L can be represented as:

$$D(h) = \left[\frac{\varepsilon_0 L}{1{,}2M_S^2}\right]^{\frac{1}{2}} g(h),$$

$$g(h) = \frac{1-2h}{(1-h^2)^{\frac{1}{2}}\, arccos(1+h)^{\frac{1}{2}}(1-h^2)^{\frac{1}{4}}},$$

$\varepsilon_0 = 4\,(A\,K)^{1/2}$,

where ε_0 – is the energy density of the domain wall;

A - is the exchange constant;

K – anisotropy constant.

Thus, for a given film thickness, the period of the domain structure is determined by the ratio of the energy density of domain boundaries to the magnetic dipole energy density. Moreover, since the energy of domain boundaries decreases with increasing field H faster than the energy of demagnetization fields, the period of the domain structure decreases with increasing value h almost linearly. Consequently, under the influence of the field H applied perpendicular to the A.E.M., only a change in the period of the domain structure occurs without a change in the volume occupied by some domains due to domains with the opposite direction of magnetization.

However, in real magnetic films, the period of the domain structure may not change in a magnetic field, which was observed experimentally, for example, in [5]. This was associated with pinning of domain boundaries at various defects and inhomogeneities.

The region of intermediate angles between the field direction H and A.E.M. To date, in the general case, it has not been studied due to significant difficulties that arise when taking into account changes in the magnetic structure of the material and the energy of domain boundaries in an external magnetic field. The use of a number of simplifying assumptions made it possible to analyze some special cases. Thus, in [13], changes in the parameters of the domain structure in thin ferromagnetic plates were considered under the assumption that the type of domain structure in the field H remains unchanged (i.e., the domains remain plane-parallel), and the plane of the domain boundaries is parallel to the direction of magnetization. A similar problem was considered in [12], and then developed in for the case when the component of the vector H, parallel to the surface of the plate, is perpendicular to the plane of the domain boundaries. The equilibrium values of the domain widths d1 and d2, as in previous cases, were found from the condition of the minimum energy density of the system, which included the energy of magnetic anisotropy, the intrinsic magnetostatic energy of surface charges, the Zeeman energy of interaction with the field H and the energy of domain boundaries. To solve this problem, numerical methods were used.

4 Conclusion

In [13], the calculated dependences of the half-period of the domain structure D/2 and the domain width d2 on the value of the reduced field $h = \frac{H}{H_A}$ (H perpendicular to the plane of the domain boundaries) are given for various values of the angles β between the vector H and A.E.M. Experimental D(H) curves for this case were obtained in [14]. It was found that in fields close to Hk (Hk is a field in which the multi-domain state of the sample disappears), the period of the domain structure increases indefinitely, while the domain width d2 tends to a finite value. The exception is the angle $\frac{\pi}{2}$, for which the change in the value of D is limited: for a domain structure in which the plane of the domain boundaries is parallel to the field, this limitation is due to the abrupt transition of the magnetic system from a multi-domain to a single-domain state. It was found that with increasing field H, the width of domains with vector $M_s$antiparallel to the field direction always decreases, while the decrease in period D depends on the orientation of vector H relative to A.E.M. At angles β, close to $\frac{\pi}{2}$, a decrease in the period of the domain structure with increasing H is first observed, and then its rapid increase. The range of angles β, which are characterized by this behavior of the value D for the case when the vector H is perpendicular to the plane of domain boundaries, is significantly smaller than in the case when H lies in their plane.

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