Onset of singular lines in the magnetization distribution of a uniaxial ferromagnet with a dislocation

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We analyze the conditions for the onset of linear singularities of the anisotropy field of a uniaxial ferromagnet with a dislocation. The mechanism that produces domains of a new phase at the dislocations and is due to the existence of these singularities is discussed.

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Crystal-structure defects are known to influence strongly the initial stage of domain-structure formation in magnets (see, e.g., Ref. 1). In crystals of the yttrium-iron-garnet type, having a large magnetostriction, this influence can be due to dislocation strains ε_{ij} that form[2-4] a local crystallographic magnetic anisotropy.

A detailed description of the distribution of the magnetization **M** in a crystal with a defect calls for taking into account (besides the magnetostriction and magnetic-anisotropy energies) the exchange, magnetostatic, and elastic energies. If, however, the thickness δ of the domain wall in a defect-free crystal is less than the length of the characteristic inhomogeneity connected with the strain tensor $\varepsilon_{ij}(\mathbf{r})$, the exchange can be neglected. It is also possible to neglect the elastic strains due to the inhomogeneity of **M**. Their relative contribution is proportional to the magnetoelastic-interaction constant, which is[5] of the order of 10^{-3} to 10^{-5} for most materials, and is small compared with the magnetic-anisotropy energy. It is important to take into account the stray fields due to the magnetization gradients. For simplicity, however, we shall also neglect them completely.

The problem reduces thus to a description of the (vector) field of the magnetic anisotropy in an inhomogeneous ferromagnet. We consider in this communication the general regularities of its distribution in ferromagnets with linear crystal-structure defects. We show that this field can acquire linear singularities that lead to multidomain states, and discuss the conditions for the existence of these singularities with account taken of the inhomogeneous-exchange energy.

We consider the simplest case, namely a uniaxial ferromagnet of the easy axis type, containing a straight edge dislocation. The magnetic-anisotropy energy density of a defect-free unbounded crystal is

$$w_a = K_1\alpha_z^2, \quad K_1<0, \quad \boldsymbol{\alpha}=\mathbf{M}/|\mathbf{M}|. \tag{1}$$

The dislocation strains $\varepsilon_{ij}(\mathbf{r})$ introduce in the magnetic-anisotropy energy local changes that are comparable in magnitude with w_a or may even exceed it.[2] For a dislocation parallel to the **x** axis with a Burgers vector **b** || **y** the nonzero components are ε_{yy}, ε_{zz}, and ε_{yz} (Ref. 6). With account taken of the induced magnetic anisotropy, the energy density of the latter in a crystal with a dislocation is

$$w_a' = \tilde{K}_1\alpha_z^2 + \tilde{K}_{yy}\alpha_y^2 + \tilde{K}_{yz}\alpha_y\alpha_z, \tag{2}$$

$$\tilde{K}_1 = K_1 + B_1\varepsilon_{yy} + B_2\varepsilon_{zz}, \tag{3}$$

$$\tilde{K}_{yy} = B_3\varepsilon_{yy}, \quad \tilde{K}_{yz} = B_4\varepsilon_{yz}, \tag{4}$$

where B_i are the magnetoelastic-coupling constants. The magnetic-anisotropy field is in fact produced at the distribution of $\boldsymbol{\alpha}_0(\mathbf{r})$ at which w_a' is a minimum. Far from the defect, this field is uniform ($\alpha_{0z}=\pm1$) and can be described by a single angle $\psi(\mathbf{r})$ ($\alpha_{0x}\equiv0$) reckoned in the yz plane from the **z** axis, with $\psi\in[-\pi,\pi]$. Then

$$\mathrm{tg}\,2\psi(\mathbf{r}) = -\tilde{K}_{yz}/\tilde{K}_1', \tag{5}$$

where $\tilde{K}_1'$ is defined by Eq. (3) in which B_1 is replaced by B_1-B_3, and **r** is the radius vector in the yz plane: in the case considered ε_{ij} does not depend on one of the coordinates (x), and the problem is two-dimensional.

If the renormalization of the magnetic-anisotropy constant is weak, namely if the signs of $\tilde{K}_1'$ and K_1 are the same, then the maximum (at $|\tilde{K}_{yz}|\gg|\tilde{K}_1'|$) deviation of ψ from $\psi_0=0$ and $\psi_0=\pi$ (the equilibrium value far from the defect) does not exceed $\pi/4$. The deflection angle α is correspondingly likewise smaller than $\pi/4$. The existence of solutions of this type was noted also in Ref. 7.

The situation is different when the magnetic-anisotropy renormalization is strong. It was shown earlier[2] that the sign of $\tilde{K}_1'$ can change near the dislocation. The intersections of the contour $\tilde{K}_1'=0$ with the lines $y=\pm z$ and $y=0$, on which the sign of $\tilde{K}_{yz}(\sim\varepsilon_{yz})$ changes, determine the singular points of Eq. (5) (in three-dimensional space, lines parallel to the x axis). On tracing a closed circuit around each of the singular points located outside the dislocation, ψ acquires a coordinate-independent increment

$$\Delta\psi = \psi_+ - \psi_- = \pm\pi, \tag{6}$$

where ψ_+ and ψ_- are the values of ψ at the start and end of the circuit. The dislocation line is also singular, and the value of $\Delta\psi$ following a circuit around this line does not depend on the shape of the region in which the sign of $\tilde{K}_1'$ is changed. If the contour does not enclose any of the singular points, $\Delta\psi=0$.

The shape of the contour $K_1'=0$, and hence the number and positions of the singular points, depends on the ratio of the constants B_i in (3) and (4). Figure 1 shows

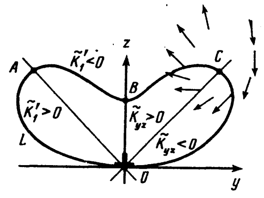

FIG. 1. Distribution of $\boldsymbol{\alpha}_0(\mathbf{r})$ near the singular line C.

one of the possible contours $\tilde{K}_1' = 0(L)$, the singular points A, B, C, and O; to be specific, the signs of $\tilde{K}_{yz}$ are indicated. The change of $\boldsymbol{\alpha}_0(\mathrm{r})$ following a circuit around the point C is shown; all the singular points are equivalent (apart from the sign). If the contour L is a trifolium,[2] $\Delta\psi = \pm 3\pi$ following a single circuit around the singularity O.

Thus, a linear defect in an elastic subsystem (edge dislocation) can "induce" linear singularities in a magnetic subsystem if the magnetostriction is large enough. Since the condition (6) is satisfied for certain contours around the points, the $\boldsymbol{\alpha}_0(\mathrm{r})$ directions parallel and antiparallel to the z axis (as $|\mathrm{r}| \to \infty$) are found to be coupled. This is illustrated by the solid curves in Fig. 2(a). The solid lines in Figs. 2(a) and 2(b) characterize the position of $\boldsymbol{\alpha}_0$ (of the easy-magnetization axis) in a defect-free crystal (l is the distance along the corresponding contour from an arbitrarily fixed point).

If now the magnetization direction is fixed far from the dislocation (e.g., $\boldsymbol{\alpha} \parallel \mathrm{z}$), this direction should follow $\boldsymbol{\alpha}_0(\mathbf{r})$ near a singular line, since the magnetostriction is (by assumption) strong. Since $\boldsymbol{\alpha}_0$ acquires an increment (equal to $-2\boldsymbol{\alpha}_0$) on going around the linear singularity, and $\boldsymbol{\alpha}$, unlike $\boldsymbol{\alpha}_0$, is continuous, there should exist a region of space in which $\boldsymbol{\alpha}$ turns away from a direction close to that of $\boldsymbol{\alpha}_0(\mathbf{r})$ to a direction that almost coincides with $-\boldsymbol{\alpha}_0(\mathbf{r})$. The 180° domain walls produced in this manner should obviously have a thickness $\sim\delta$ and bear against the singular lines.

The distance between the singular lines is determined by the characteristic dimension r_0 of the region in which the sign of $\tilde{K}_0'$ is changed. If $r_0 < \delta$, the singular lines are not resolved: the core of one singularity (a cylindrical region of diameter $\sim\delta$) overlaps the core of another. The magnetization distribution should in this case be quasihomogeneous. If, however, $r_0 \gg \delta$ the gradients of α are small and the singular lines can be regarded as isolated (and it is precisely in this case that one can speak of domain-wall formation).

To determine the structure of the produced domain wall and the location of its center, we must solve the exact problem. It is clear, however, that in the ab-

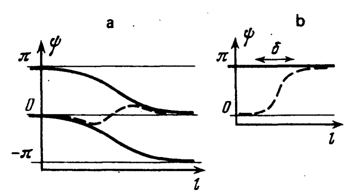

FIG. 2.

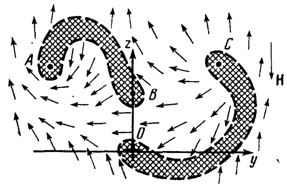

FIG. 3. One of the possible distributions of $\boldsymbol{\alpha}(\mathbf{r})$ around an edge dislocation, with formation of a domain structure. The shaded regions are domain walls.

sence of external perturbations the length of the domain wall should be a minimum. It is therefore obvious that in the absence of other dislocations, the produced domain walls should bear against singular lines having opposite sign and induced by one dislocation (and not go off to infinity). In addition, even in this case one can expect a quasihomogeneous distribution of $\alpha(\mathrm{r})$: the magnetization rotation due to the change of $\alpha_0(\mathrm{r})$ is almost offset in the region inside L by the rotation due to the transition of $\alpha(\mathrm{r})$ from one local minimum of the magnetic-anisotropy energy to another. The resultant distribution of $\alpha(\mathrm{r})$ is illustrated by the dashed curve of Fig. 2(a). We emphasize that a domain wall does exist for this quasihomogeneous magnetization distribution: $\alpha(\mathrm{r})$ goes over from one local magnetic-anisotropy minimum to another. When the domain wall is displaced from the position shown in Fig. 2(a), the magnetization distribution in it becomes the same as in a domain wall in a defect-free crystal [see the dashes in Fig. 2(b)]. Regions are then produced with almost opposite magnetizations—domains. One of the possible domain structures is shown in Fig. 3 for the case when an external magnetic field H is applied antiparallel to the z axis.

Thus, it is precisely because of the existence of linear defects induced in the magnetic subsystem by a dislocation that one can expect the appearance of domains with opposite magnetizations, or of their seeds. Their appearance should be expected on dislocations with edge components in materials with large magnetostriction and small δ (e.g., in gadolinium). In materials with large anisotropy (cobalt) a similar effect can be exerted by disclination dipoles—high-energy linear defects produced at large degrees of plastic deformation. The elastic field of a disclination dipole can be approximately regarded as a dislocation field with a large (of the order of the grain size) Burgers vector.

We note in conclusion that we have used the analogy between the behavior of **M** and of the elastic-displacement field of a screw dislocation. In addition, our analysis of the onset of singular lines is valid also in the case of an arbitrary vector order parameter that interacts with the elastic subsystem in analogy with (2) (for example for an antiferromagnet or a ferroelectric). The problem of a dislocation as a singular line in an antiferromagnet was considered in Refs. 8 and 9. It follows from our work, in addition to the results of Refs. 8 and 9, that in antiferromagnets with large magneostriction an edge dislocation can produce several linear singularities of the order-parameter vector field, and each such singularity can be analyzed in accord with Refs. 8 and 9.

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