Magnetization curves of antiferromagnets with several antiferromagnetism axes: Irreversible processes

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Magnetization processes in antiferromagnets with several mutually perpendicular antiferromagnetism axes were investigated theoretically and experimentally for an FeG_2 single crystal. It is shown that for a magnetic field H oriented along the antiferromagnetism axis both reversible and irreversible displacements of interdomain walls are possible. Parameters are introduced for describing the magnetic hysteresis and the H dependence of the reversible and irreversible susceptibilities.

1. As shown in Ref. 1, magnets with several mutually perpendicular antiferromagnetism axes exhibit anisotropy not only of the magnetic properties but also of the processes which determine them. That is, in the case of magnetization along a direction that is symmetric with respect to the antiferromagnetism axes, irreversible intradomain processes occur, while in the case of magnetization along one of the antiferromagnetism axes both reversible and irreversible displacement of 90-degree interdomain walls occur together with intradomain processes. In Ref. 1 a theory is constructed for irreversible magnetic susceptibility. The results of this theory have been confirmed experimentally for $FeGe_2$ tetragonal single crystals, in which at temperatures $T < T_1$ ($T_1 = 265$ K) two mutually perpendicular (110) axes lie in the basal plane. It was also found that both irreversible and reversible displacements of walls occur in this antiferromagnet.

In the present paper we present and interpret the results of further investigations of experimentally observed regularities governed by irreversible processes.

2. Measurements of the magnetization I and the differential susceptibility $\chi^{\rm dif}$ and its components—the reversible susceptibility $\chi^{\rm rev}$ and the irreversible susceptibility $\chi^{\rm irr}$—were performed along the antiferromagnetism axis on a vibrating-coil magnetometer in fields of up to 18 kG. The standard deviation of the measurements was less than 0.1%.

Figure 1 shows magnetization curves $I_\alpha(H)$ at $T = 77$ K of a single crystal of $FeGe_2$. The index $\alpha = 1$ corresponds to the virgin curve (curve 1), measured after the sample was cooled in a field $H = 0$ from a temperature above the Néel temperature $T_N = 290$ K down to $T = 77$ K. The index $\alpha = 2$ corresponds to the descending branch of the hysteresis loop (curve 2), measured with the magnetic field intensity H decreasing down to zero from values at which on the virgin curve the dependence $I_1(H)$ is already linear. The index $\alpha = 3$ corresponds to the ascending branch of the hysteresis loop (curve 3).

It is obvious from Fig. 1 that the virgin magnetization curve $I_1(H)$ is nonlinear. However the curve does not contain any indications of homogeneous phase transitions, namely, the transition from nonlinear to linear curves is smooth.

Figures 2 and 3 show curves of the reversible

$$\chi_\alpha^{\rm rev} = \Delta I_\alpha / \Delta H_2$$

and irreversible

$$\chi_\alpha^{\rm irr} = \chi_\alpha^{\rm dif} \ni \chi_\alpha^{\rm rev}$$

susceptibilities as a function of H. Here $\chi_\alpha^{\rm diff}$ is the differential susceptibility, determined from the relation $\chi_\alpha^{\rm diff} = \Delta I_\alpha / \Delta H_1$, where the value $\Delta H_1 = |\Delta H|$ on the virgin curve and the ascending branch of the hysteresis loop and $\Delta H_1 = -|\Delta H|$ on the ascending hysteresis loop. In determining $\chi_\alpha^{\rm rev} \Delta H_2 = -\Delta H_1$. For measurements on the virgin curve $|\Delta H| = 30$ G, while for measurements on the branches of the hysteresis loop $|\Delta H| = 60$ G.

The important characteristics for analyzing the curves $\chi_\alpha^{\rm rev}(H)$ shown in Fig. 2 are the values of $\chi_\alpha^{\rm rev}$ at $H = 0$ and in the limit $H \to \infty$ and the fields $H_\alpha^{\rm max}$ in which $\chi_\alpha^{\rm rev}$ reach the maximum value.

It is obvious from Fig. 3 that $\chi_\alpha^{\rm irr} \to 0$ holds in both limits $H \to 0$ and $H \to \infty$. The distinguishing feature of these curves is the existence of the critical fields H_α^0, in which the susceptibilities $\chi_\alpha^{\rm irr}$ reach the maximum value.

3. We recall[1] that in the hypothetical case when there is no domain structure and the magnetization is in the direction of one of the antiferromagnetism axes, we have

$$I = \chi_\perp H, \quad \chi = \chi_\perp, \tag{1}$$

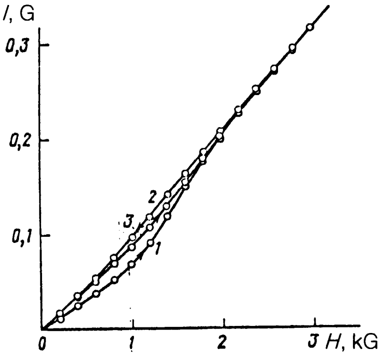

FIG. 1. Magnetization curves of a $FeGe_2$ single crystal at $T = 77$ K: *1*—virgin curve, *2*—descending branch of the hysteresis loop, and *3*—ascending branch of the hysteresis loop.

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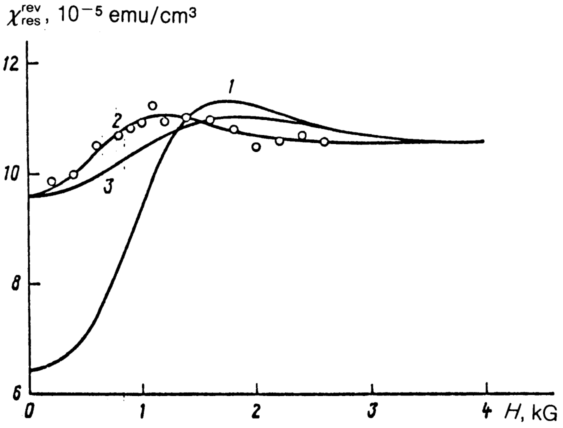

FIG. 2. Reversible differential susceptibility χ^{rev} as a function of H: *1*—on the virgin curve, *2*—on the descending branch of the hysteresis loop, and *3*—on the ascending branch of the hysteresis loop ($T = 77$ K).

if the antiferromagnetism vector **L** is initially oriented perpendicularly to **H** and

$$I=\chi_{\parallel}H, \quad \chi=\chi_{\parallel} \quad \text{for} \quad H\leqslant H_0,$$
$$I=\chi_{\perp}H, \quad \chi=\chi_{\perp} \quad \text{for} \quad H\geqslant H_0, \tag{2}$$

if initially $\mathbf{L}\|\mathbf{H}$ holds, where

$$H_0^2=\frac{2K_4}{\chi_{\perp}-\chi_{\parallel}}. \tag{3}$$

The reversal field H_0 is insensitive to structure. It is determined by the constant K_4 which characterizes the crystallographic magnetic fourth-order anisotropy of the perpendicular and parallel (with respect to the field) susceptibilities $\chi_\perp$ and $\chi_\parallel$, which are fundamental constants.

It follows from Eqs. (2) that at $H = H_0$, in the latter case, a first-order homogeneous orientational magnetic phase transition occurs and the antiferromagnetism vector jumps from the state $\mathbf{L}\|\mathbf{H}$ into the state $\mathbf{L}\perp\mathbf{H}$.

We now examine the case when the antiferromagnet is initially (for $H = 0$) divided into domains. We introduce the concentrations of the magnetic phases $n_\parallel$ and $n_\perp$ of the domains separated by 90-degree walls. In what follows a 90-degree wall will be referred to as simply a wall. Each phase can be homogeneous or it can contain domains separated by 180-degree walls, which are not shifted by a magnetic field. In these phases the antiferromagnetism vector is parallel and perpendicular to **H**, respectively.

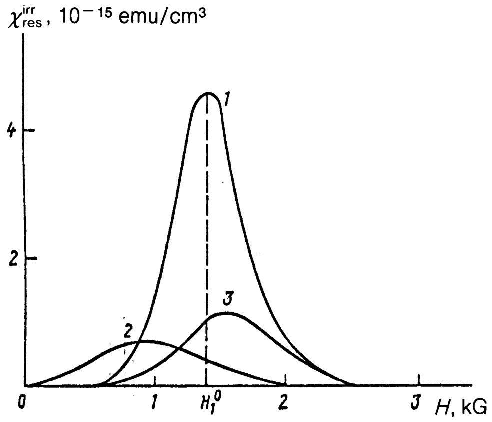

FIG. 3. Field dependences of the irreversible differential susceptibility χ^{irr} at $T = 77$ K: *1*—on the virgin curve, *2*—on the descending branch of the hysteresis loop, and *3*—on the ascending branch of the hysteresis loop.

If the walls between the phases are pinned, then wall displacements occur together with intradomain processes. Walls in which a phase transition should occur $H = H_0$ with increasing H are absorbed by energetically more favorable domains of the second phase. In the case when absorption ends in a field $H < H_0$, which happens in $FeGe_2$, a first-order homogeneous phase transition is not realized. A heterogeneous magnetic phase transition occurs. This analysis shows that domain structure exists in $FeGe_2$.

We now give a theoretical description of the magnetization processes. The free energy of the two-phase system under study consists of the free energies of the magnetic phases in the field of the external forces $\int (F_{ex})_i dV_i$, the volume internal magnetoelastic anisotropy energy $\int (F_{in})_i dV_i$, and the surface energy of the interdomain walls

$$\Gamma=\int \gamma_{ik}\,dS_{ik},$$

where γ_{ik} is the wall energy density and S_{ik} is the area of the wall separating these phases in a unit volume. The indices i and k characterize the phases: i is the phase in which $\mathbf{L}\perp\mathbf{H}$ and k is the phase in which $\mathbf{L}\|\mathbf{H}$.

When the wall is displaced by a distance δn_{ik} the total work performed by the pressure produced by the difference of the free energies of the phases $(F_{ex})_i - (F_{ex})_k$, should cover the increase in the internal energy F_{in} and should compensate the change in the surface free energy. As a result, we obtain for the total change in energy accompanying virtual displacements of the interphase boundary δn_{ik} (Ref. 1)

$$\delta\Phi=\left\{\int\left[\Delta F_{ex}+\Delta F_{in}+\frac{\partial\gamma}{\partial n}\right]dS+\gamma\frac{\partial S}{\partial n}\right\}\delta n. \tag{4}$$

Here, as a simplification, we have omitted the phase indices i and k in the quantities γ_{ik}, S_{ik}, and n_{ik} and we have introduced the quantities

$$\Delta F_{ex}=(F_{ex})_i-(F_{ex})_k \text{ and } \Delta F_{in}=(F_{in})_i-(F_{in})_k.$$

Equilibrium occurs when $\delta\Phi = 0$. The equilibrium is stable if as ΔF_{ex} increases the quantities

$$\int [\Delta F_{in}+\partial\gamma/\partial n]\,dS+\gamma\,\partial S/\partial n$$

for each element of the surface dS also increase. When these quantities reach their maximum values, the equilibrium is destroyed for each element of the surface and irreversible Barkhausen jumps can occur.

For the case when the external force is the intensity of the magnetic field we have

$$\Delta F_{ex}=-(\chi_{\perp}-\chi_{\parallel})H^2. \tag{5}$$

Barkhausen jumps will occur for some local values of the critical fields H^0_{loc}. In real antiferromagnets there is a distribution of fields H^0_{loc} around a critical field H^0, in which irreversible processes will be most pronounced. A maximum should be observed in the curve of the irreversible susceptibility at the field $H = H^0$; we observed this experimentally.

In order to estimate the critical field H^0 we introduce, instead of the values of $(\Delta F_{in})_{max}$, $(\partial\gamma/\partial n)_{max}$, and $(\partial S/\partial n)_{max}$ the average values over the surface S. Then, using Eq. (5), we obtain

$$(H^0)^2 = \frac{\overline{B_{max}}}{\chi_\perp - \chi_\parallel}, \tag{6}$$

where

$$B = \Delta F_{in} + \frac{\partial\gamma}{\partial n} + \frac{\gamma}{S}\frac{\partial S}{\partial n}. \tag{7}$$

It is obvious from Eqs. (6) and (7) that the critical field H^0, characterizing the irreversible displacements of the walls, is sensitive to the structure of the crystal. It is determined by the nonuniformities of a) the internal stresses, b) the concentrations of foreign impurities or components of the alloy, and c) the distribution of inclusions.

We recall that the reversible susceptibility χ^{rev} consists of two terms[1]

$$\chi^{rev} = \chi_{in} + \chi^{rev}_{dis}, \tag{8}$$

where χ_{in} is the susceptibility governed by intradomain processes

$$\chi_{in} = \chi_\perp n_\perp + \chi_\parallel n_\parallel, \tag{9}$$

and χ^{rev}_{dis} is the susceptibility governed by reversible displacements of the walls

$$\chi^{rev}_{dis} = 2(\chi_\perp - \chi_\parallel)(H/H^*)^2 n_\perp n_\parallel, \tag{10}$$

where $n_\perp + n_\parallel = 1$,

$$n_\perp = \{1 + \exp[-[(H/H^*)^2 - a]]\}^{-1},$$
$$n_\perp n_\parallel = {}^1/_2\{1 + \mathrm{ch}\,[(H/H^*)^2 - a]\}^{-1}, \tag{11}$$

$$(H^*)^2 = \frac{n_\perp{}^0 n_\parallel{}^0}{(\chi_\perp - \chi_\parallel)\overline{C}S^0}, \tag{12}$$

$$C^{-1} = \frac{\partial B}{\partial n} = \frac{\partial F_{in}}{\partial n} + \frac{\partial^2\gamma}{\partial n^2} + \gamma\left[\frac{1}{S}\frac{\partial^2 S}{\partial n^2} - \frac{1}{S^2}\left(\frac{\partial S}{\partial n}\right)^2\right], \tag{13}$$

and $n^0_\perp$, $n^0_\parallel$, and S^0 are the initial concentrations and the area of the interphase wall (at $H = 0$). The averaging is performed over the entire surface separating the phases. According to Eqs. (8)–(11), the field H^* and the field H^{max}, in which χ^{rev} is maximum and irreversible displacements occur most actively, are related with one another by the relation

$$\left(\frac{H^{max}}{H^*}\right)^2 = \frac{3}{2}\,\mathrm{cth}\left[\left(\frac{H^{max}}{H^*}\right)^2 - a\right], \tag{14}$$

where

$$a = \ln\frac{\chi_\perp - \chi(0)}{\chi(0) - \chi_\parallel}, \tag{15}$$

and $\chi(0)$ is the reversible susceptibility at $H = 0$.

In the derivation of the relations (11) it was assumed that the integration constant a does not depend on the magnetic field intensity. However, because of the existence of irreversible processes, the integration constant can depend on H. For this reason, the relation (14) holds only for the case $a = \text{const}$, and the theoretical dependences (8)–(11) for $\chi^{rev}(H)$, in the general case, can describe the phenomena only qualitatively.

The field H^*, in contrast to H^0, is sensitive not only to the crystalline structure ($\overline{C}$) but also the magnetic structure (n^0_α, S^0) of the initial state.

According to Eqs. (6) and (12), the fields H^* and H^0 are related to one another by the relation

$$\left(\frac{H^*}{H^0}\right)^2 = \frac{n_\perp{}^0 n_\parallel{}^0}{S^0\overline{C}\overline{B_{max}}}. \tag{16}$$

We note in passing that in contrast to ferromagnets, in which χ^{rev} usually decreases monotonically with increasing H, the antiferromagnets maxima are observed in the $\chi^{rev}_\alpha(H)$ curves. According to Eq. (8), the existence of these maxima is associated with the existence of maxima in the $\chi^{rev}_{dis}(H)$ curves, since χ_{in} increases monotonically with H while we have $\chi^{rev}_{dis} \to 0$ for both $H \to 0$ and $H \to \infty$. The susceptibility χ^{rev}_{dis} drops to zero as $H \to \infty$ because of the presence of the factor $n_\perp n_\parallel$, since $n_\perp \to 0$ for fields $H \gg H^*$. But $H^{rev}_{dis} \to 0$ as $H \to 0$ because of the factor H/H^*. This factor appeared because, unlike ferromagnets, in which **H** acts on the spontaneous magnetization, in antiferromagnets the field **H** is also necessary for producing the magnetization.

4. We now discuss the experimental results.

We found experimentally that the formulas (8)–(11), with the corresponding parameters, accurately describe reversible processes on the ascending ($\alpha = 3$) and descending ($\alpha = 2$) branches of the hysteresis loop. The agreement with the experimental data on the H dependence of the reversible susceptibility on the virgin curve ($\alpha = 1$) is achieved by taking into account the H dependence of the integration constant a. Using Eq. (15), we estimated the value of a for a given field H_q from the value of $\chi(0)$ on the descending branches of the partial hysteresis loops measured up to the field H_q.

Figure 2 shows the theoretical $\chi^{rev}_\alpha(H)$ curves. For convenience, the experimental data are presented only for $\chi^{rev}_2(H)$. It was found that on the virgin curve we have $H^{max}_1 = 1.8$ kG, $H^*_1 = 1.55$ kG, and $n^0_\perp = n^0_\parallel = 0.5$. On the descending and ascending branches of the hysteresis loop we have $H^*_2 = 0.96$ kG, $H^{max}_3 = 1.9$ kG, $H^*_3 = 1.5$ kG, $(n^0_\perp)_2 = (n^0_\perp)_3 = 0.88$.

Comparing the values of H^*_α with the values of H^0_α estimated from the plots in Fig. 3 we conclude that the values of H^*_α and H^0_α are close to one another for each value of the index α.

It is obvious from a comparison of the plots presented in Figs. 2 and 3 that $\chi^{rev}_\alpha > \chi^{irr}_\alpha$.

The irreversible susceptibility is maximum in ferromagnets in fields equal to the coercive force H_c. Accordingly, the coercive force can be taken as the half difference of the fields in which the irreversible susceptibility reaches maximum values on the ascending and descending branches of the hysteresis loop. For this reason, the analog of the coercive force for antiferromagnets can be taken as the half-difference of the critical fields in which the irreversible susceptibilty is maximum on the ascending and descending branches of the hysteresis loop

$$H_c=(H_3{}^0-H_2{}^0)/2. \tag{17}$$

It was found that $H_c = 270$ G.

By analogy to the concept of residual magnetization in the case of ferromagnetism, we introduce the concept of the residual concentration of magnetic phases n^{res}, expressing it in terms of the concentration of the magnetic phase $(n^0_\parallel)_2$ or $(n^0_\perp)_3$ in the field $H=0$ on the descending or ascending branches of the hysteresis loop $[(n^0_\parallel)_2 = (n^0_\parallel)_3]$,

$$n^{res} = 2(n_\parallel{}^0)_2. \tag{18}$$

The factor of 2 was introduced in order that n^{res} vary over the same limits $0 \leqslant n^{res} \leqslant 1$ as does the relative residual magnetization in the case of ferromagnetism.

We determine the concentrations of the magnetic phases for $H=0$ from the values of $\chi_\alpha(0)$ according to the relation

$$(n_\parallel{}^0)_\alpha = \frac{\chi_\perp - \chi_\alpha(0)}{\chi_\perp - \chi_\parallel}. \tag{19}$$

The quantities H_c and n^{res} determine the shape and area of the magnetization hysteresis loop. As $n^{res} \to 0$ the area approaches zero, and the branches of the hysteresis loop close into a straight line, which is a continuation of the function $I(H) = \chi_\perp H$ (for $H \gg H^*$) into the region $H < H^*$. The area of the loop is maximum for $n^{res} = 1$. It was found that in $FeGe_2$ we have $n^{res} = 0.24$.

The fields H^*_α were found by the least-squares method from the relations (8)–(11), where all other parameters were determined experimentally.

We now discuss why the fields H^*_α and H^0_α are close to one another in magnitude.

We first study qualitatively the case when H^0 and H^* are determined by the nonuniformity of the internal stresses on which the internal magnetoelastic energy depends.

Real antiferromagnets contain regions of stretching and compression. Consider a plane-parallel structure of domains, separated by walls whose planes are perpendicular to the x axis. Let the intensity **H** of the magnetic field and the internal tensile stresses $(\sigma > 0)$ or compressive stresses $(\sigma < 0)$, which vary according to the very simple law

$$\sigma = \sigma_0 \sin\left(\frac{\pi x}{d}\right), \tag{20}$$

be oriented along the y axis. Then, from symmetry considerations, it follows for the isotropic magnetostriction in the basal plane that

$$\Delta F_{in} = 2|\lambda||\sigma|, \tag{21}$$

where λ is the saturation magnetostriction in the basal plane.

When the wall is displaced along the x axis by the distance $\delta n = \delta x$, according to Eqs. (7) and (13), we obtain

$$\bar{C} = \frac{d}{2\pi|\lambda|\sigma_0}, \quad \overline{B_{max}} = 2|\lambda|\sigma_0. \tag{22}$$

Using also Eq. (16), we obtain

$$\left(\frac{H^*}{H^0}\right)^2 = \frac{\pi n_\perp{}^0 n_\parallel{}^0}{dS^0}. \tag{23}$$

In order that this ratio be close to unity in accordance with the experimental results, the condition $dS^0 \approx 1$ must be satisfied. This condition is satisfied, if the half-period d of the change in stress is equal to the dimensions D of the domains or groups of domains in which the antiferromagnetism vectors are parallel to one another,

$$d = D, \tag{24}$$

since, according to estimates of D and S^0, it follows that $DS^0 \sim 1$.

The condition (24) is satisfied if the initial domain structure is governed by the distribution of internal stresses, since in this case the walls are located where the stresses change sign.

The second consequence of the relation (23) is that the fields H^0 and H^* must have the same temperature dependence. In Ref. 1 it is shown that the experimental temperature dependence $H^*(T)$ can be explained well, if it is assumed that the field H^* is determined by the nonuniformity of the magnetoelastic energy. From these two independent circumstances it follows that the initial domain structure $(H=0)$, at least in the antiferromagnet investigated, is determined by the distribution of internal stresses. The "amplitude" of the internal stresses can be estimated starting from Eqs. (6) and (22), whence

$$\sigma_0 \approx \frac{(\chi_\perp - \chi_\parallel)(H^0)^2}{2|\lambda|}. \tag{25}$$

Since at $T = 77$ K we have $\chi_\perp - \chi_\parallel \sim 8 \cdot 10^{-5}$ emu/cm^3, $\lambda \sim 10^{-5}$ (Ref. 2), and $H^0 \sim 15 \cdot 10^2$ Oe, we obtain $\sigma_0 \sim 10^7$ ergs/cm^3. The anisotropy caused by these stresses is equal to $\lambda\sigma_0 \sim 10^2$ ergs/cm^3, while the crystallographic magnetic anisotropy constant is $K_4 \sim 10^4$ ergs/cm^3 (Ref. 1) Thus we have $K_4 \gg \lambda\sigma_0$, and therefore the directions of the antiferromagnetism axes are determined by the crystallographic magnetic anisotropy, while the internal stresses only distinguish the "easiest" ones.

It follows from the relations (12), (22), and (24) that if the initial domain structure is determined by the distribution of internal stresses, then H^* and therefore, according to Eq. (10), also the reversible susceptibility, governed by the displacement of the walls, should not depend on the initial area of the interphase boundary, i.e., on the disperseness of the domain structure.

Finally, we study the case when the fields H^0 and H^* are determined by variations of γ and S. The coordinate dependences of γ and S should satisfy at least two conditions in this case. First, when the initial susceptibility is calculated the walls should be in the initial state. Second, γ and S at other locations should have their maximum values. This requirement is used to calculate the critical fields. In the simplest case the functions

$$\gamma = \gamma_0 + \gamma' \sin^2\left(\frac{\pi x}{d_1}\right) \text{ and } S = S^0 + S' \sin^2\left(\frac{\pi x}{d_2}\right) \tag{26}$$

meet the above requirements. Then, according to Eqs. (16), (7), and (13), we obtain correspondingly,

$$\left(\frac{H^*}{H^0}\right)^2 = \frac{2\pi}{d_1 S^0} \text{ and } \left(\frac{H^*}{H^0}\right)^2 = \frac{2\pi}{d_2 S^0}. \tag{27}$$

In order that (H^*/H^0) be close to unity in accordance with experiment, the conditions $d_1 S^0 \sim 1$ and $d_2 S^0 \sim 1$ must be satisfied. But there are no reasons for the periods d_1 and d_2 of the changes in γ or S to be related to the dimensions of the domains. This circumstance also suggests that the initial domain structure is governed by the nonuniformity of the magnetoelastic energy. The nonuniformity of this energy also determines the displacement of the boundaries. In addition, it was shown in Ref. 1 that the variation in γ cannot explain the form of the temperature dependence of H^*.

The above model, however, does not make it possible to understand the mechanisms responsible for the irreversible processes.

This model does not explain the reasons for a) the difference between the quantities H_2^0 and H_3^0 (which determines the coercive force), b) the difference between the fields H_2^* and H_3^*, and c) the relation $\chi^{rev} > \chi^{irr}$.

This model also does not explain a) why even for magnetization along the antiferromagnetism axis, the residual concentration n^{res} is less than unity but at the same time greater than zero; b) why the formulas (11), determining the H dependence of the reversible susceptibility with $a = \text{const}$, quantitatively describe the experimental dependences $\chi_a^{rev}(H)$, obtained on the branches of the hysteresis loop, while for the virgin curve of magnetization the agreement is only qualitative.

In order to answer these questions, we examine a more realistic form of the function $\sigma(x)$.

Suppose that the antiferromagnet contains tensile ($\sigma > 0$) and compressive ($\sigma < 0$) internal stresses in the direction [110] which alternate along the x-axis, which is perpendicular to [110]. In addition, assume that additional extrema are present in the stretched and compressed regions (Fig. 4). If, for example, we have $\lambda < 0$, then for $H = 0$ in the compressed region (region II) the vector **L** will be oriented parallel to [110] axis and in stretched regions (I and III) the vector **L** will be oriented perpendicular to [110]. The boundaries between the domains will be located where $\sigma = 0$.

In the case of magnetization along [110] the domains initially located in the stretched regions (regions I and III) will grow by displacement of walls at the expense of the domains initially located in the compressed regions (region II).

As the field H increases from the value $H = 0$ the wall initially in the position *1* will move continuously until it reaches the position *2*. As the field is increased further the wall jumps into the position *3*. Then the wall moves continuously into the position *4*, jumps into the position *5*, and finally reaches, in a continuous manner, the position *6* [the greatest extremum of $\sigma(x)$], where it encounters the wall moving continuously from the position *11* into the position *6*.

If, in the process, domains where the vectors **L** are oriented parallel to one another were present in the regions I and III, then the colliding 90-degree walls annihilate one another, and there arises a single domain in which the vector **L** is perpendicular to **H**. If, however, the **L** vectors are antiparallel, then the colliding 90-degree walls form a 180-degree wall, separating domains with antiparallel vectors **L**. This unique wall, existing only in quite strong fields, should not be confused with the 180-degree walls which are also present in the absence of a field ($H = 0$). It is a two-dimensional seed for magnetic reversal occurring as H decreases. The term "magnetic reversal seed" is introduced in order to distinguish such nuclei from nuclei [180-degree walls existing also in the absence of a field ($H = 0$)] of a transitional domain structure in magnetically uniaxial antiferromagnets with increasing H.[3-7]

As H decreases further this two-dimensional nucleus once again decomposes into two 90-degree walls moving in opposite directions. One wall will move from the position *6* continuously not up to the position *5* but rather up to the position *7*, from which it jumps into the position *8*, etc. As a result of this the magnetization will change according to the curve shown schematically in Fig. 5 and consisting of a collection of microhysteresis loops. The other 90-degree wall will return continuously from the position *6* at $H = 0$ into the initial position *11*. The collection of microhysteresis loops from all domains forms the resulting hysteresis loop.

The difference of the quantities H_3^* and H_2^* on the ascending and descending branches of the hysteresis loop is apparently associated with the fact that some reversible sections, which pass through walls in the process of magnetization along the ascending (*10–2*, *8–4* in Fig. 4) and descending branches of the hysteresis loop (*5–7*, *3–9*), are different. For this reason, the average quantities $\overline{C}$ and therefore H_3^* on the ascending and H_2^* on the descending branches of the hysteresis loop are different.

The difference between the quantities H_3^0 and H_2^0 on the ascending and descending branches of the hysteresis loop

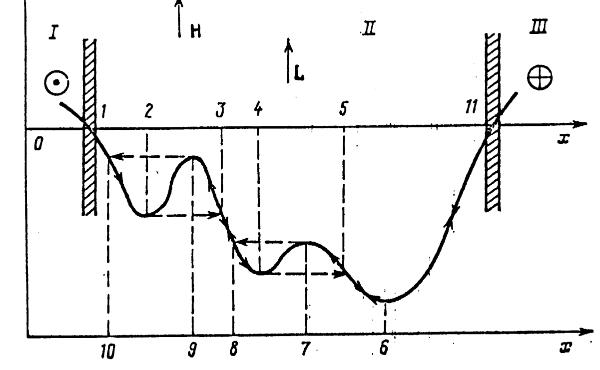

FIG. 4. Schematic distribution of the internal stresses along the x axis, determining the character of the displacement of interdomain walls accompanying cyclical changes of the field from zero to H.

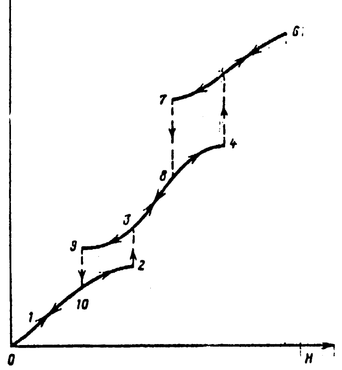

FIG. 5. Schematic magnetization dependence corresponding to the model of Fig. 4.

is associated with the fact that the location of the additional extrema in $\sigma(x)$, at which abrupt changes of the magnetization occur, and their values on the ascending (position of the boundaries *2* and *4*) and descending branches of the hysteresis loop (positions *7* and *9*) are different. For this reason, the average values of B_{max} and therefore H_3^0 and H_2^0 are different.

The resulting changes produced in the magnetization and therefore also in the susceptibilities by the irreversible processes are less than these values in the case of reversible processes because the number of regions in tension and compression, where additional extrema are present, is apparently smaller than the number of regions in which these extrema do not occur.

Thus two irreversible processes occur: Barkhausen jumps, caused by nonuniformities of the antiferromagnet, and annihilation of interdomain walls.

In order for the first process and the irreversible susceptibility and hysteresis associated with it to exist, the function $\sigma(x)$ must have additional extrema in the regions of compression and tension. A collection of these extrema is necessary in order for a hysteresis loop to form.

We now discuss the consequences of the second reason for the existence of irreversible processes.

The number N_{mr} of wall pairs formed by nuclei of magnetic reversal and the number N_{an} of pairs of annihilating walls are related by

$$N_{mr} + N_{an} = N/2 ,$$

where N is the total number of 90-degree walls. These quantities are related to the residual concentration n^{res} by

$$n^{res} = 2\frac{N^{mr}}{N}. \tag{28}$$

For $N_{an} = 0$, we have $n^{res} = 1$, which corresponds to a hysteresis loop with the maximum area; for $N_{mr} = 0$ we have $n^{res} = 0$, which corresponds to absence of hysteresis.

The value $n^{res} = 24$ obtained for the residual concentration in the experiment indicates, according to Eq. (23), that in the antiferromagnet under study in the initial state there exist both walls which annihilate with increasing H and walls which form two-dimensional nuclei of magnetic reversal for $H \gg H^*$. Apparently, even the necessity of taking into account the dependence of a on H in the formulas (11) in order to give a quantitative description of the virgin curve of magnetization is associated with the fact that as the magnetization changes on the virgin curve annihilation of walls occurs, while such processes are absent on the branches of the hysteresis loop.

In magnetically uniaxial ferromagnets, in the process of magnetization two 180-degree walls approaching one another can annihilate if their polarization is parallel, or they can form 360-degree n-walls if their polarization is antiparallel, in which case they can act as two-dimensional seeds for magnetic reversal.[8] In ferromagnets (for example, in cobalt), however, in contrast to antiferromagnets, the relative residual magnetization is close to unity if the magnetic reversal in them occurs along the axis of easy magnetization. This difference is apparently determined by the fact that as 90-degree walls in an antiferromagnet approach one another a repulsive force arises between them owing to the nonuniformity of the magnetoelastic energy, while in the case when 180-degree walls approach one another, because of evenness of the phenomenon of magnetostriction no repulsive force arises. Accordingly, 360-degree n-walls become unstable in fields $H < 0$, while two-dimensional seeds for magnetic reversal in antiferromagnets are stable only in fields above H^*.

5. Thus our work, including also Ref. 1, has established the following.

We have observed experimentally magnetic hysteresis arising through irreversible displacements of interdomain walls, the possibility of which is mentioned in Ref. 8, in antiferromagnets with several equivalent mutually perpendicular antiferromagnetism axes with magnetization along one of the antiferromagnetism axes. In fields H_α^{max} and H_α^0 maxima are observed on the curves of the reversible susceptibility χ_α^{rev} and irreversible susceptibility χ_α^{irr}, respectively, as a function of H on the virgin curve of magnetization ($\alpha = 1$) and the descending branch ($\alpha = 2$) and ascending branch ($\alpha = 3$) of the hysteresis loop. The form of the dependences $\chi_\alpha^{rev}(H)$ is determined by the fields H_α^* and the initial concentrations (for $H = 0$) of the magnetic phases $(n_\perp^0)_\alpha$. The form and area of the hysteresis loop are determined by the coercive force $H_c = (H_3^0 - H_2^0)/2$ and the residual concentration of the magnetic phases n^{res}.

From analysis of the observed experimental fact that the ratios of the fields H_α^0 (which are sensitive to the nonuniformities of the crystal structure) to the fields H_α^* (which are also sensitive to the magnetic structure) are close to unity and do not depend on the temperature and from analysis of the form of the temperature dependence of H_1^* it follows that the initial domain structure is determined by internal stresses, and the displacements of the walls are caused by the nonuniformity of the stresses. The magnitude of the magnetic anisotropy from these stresses, which is estimated from H_1^*, was found to be significantly smaller than the crystallographic magnetic anisotropy.

The existence of hysteresis (differences in the values of not only H_2^0 and H_3^0, but also H_2^* and H_3^*) are associated with the existence of additional extrema in the coordinate dependence of the internal stresses in both regions of tension and compression in the crystal. Annihilation of 90-degree walls as well as formation of two-dimensional nuclei of magnetic reversal from them (unique 180-degree walls existing only in fields $H \gg H^*$), which occur when the walls approach one another as H increases, lead in $FeGe_2$ implying that even in the case of magnetization along the antiferromagnetism axis the residual concentration of magnetic phases falls in the range $0 \leqslant n^{res} \leqslant 1$. The limits of this interval correspond to maximum area of the hysteresis loop ($n^{res} = 1$) and absence of hysteresis ($n^{res} = 0$). The irreversibility owing to the annihilation of the walls, in contrast to the irreversibility determining the Barkhausen jumps, is manifested only for magnetization on the virgin curve.

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