INVESTIGATIONS OF BOUNDARY LAYERS BETWEEN DOMAINS IN FERROMAGNETS

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The distribution of magnetization in the main types of boundaries (walls) between domains in transformer steel, nickel, and cobalt crystals was investigated by a method in which the polar Kerr effect was used. It is shown that the agreement with the available theoretical calculations is good for those parts of domain walls where the main change of the spontaneous-magnetization orientation takes place. The dimensions and shapes of the walls are determined by the nature of the neighborhoods which the wall separates. For similar walls the wall thickness in iron silicate is approximately an order of magnitude greater than in cobalt and about as much smaller than in nickel. The effect of mechanical stresses and of temperature was also investigated. With increase of temperature the wall thickness increases and, at temperatures at which the anisotropy constant vanishes or changes sign, the boundary "dissolves" in the domains which it separates. Mechanical stresses not only change the spin-orientation distribution in the walls but also the wall thickness.

FERROMAGNETIC substances not magnetized to saturation split up into the so-called regions of spontaneous magnetization or domains. In each such domain the magnetization is uniform but in different domains the direction of the magnetization vector is different. Domains with different directions of magnetization are separated by transition or boundary layers. These boundaries (domain walls) play a very important role in processes of technical saturation and magnetic hysteresis.

The first step in the study of domain walls was made by Bloch, [1] who showed that the walls are not geometrical surfaces on one side of which the magnetization has one direction and another on the other side. A wall is a transition layer of finite thickness inside which the magnetization gradually changes its direction. The final solution of this problem was given by Landau and Lifshitz [2] for the case of a uniaxial crystal. Following the method of Landau and Lifshitz, various authors subsequently developed the theory of domain walls for multiaxial crystals both in the free state and during magnetization and mechanical stressing. [3-8]

Owing to the small dimensions of domain walls, experimental studies of them meet with considerable difficulties, and the available data [9-11] give only some approximate information on the wall thickness. Reliable results would permit a check of the correctness of the theoretical representations developed for ideal crystals, as well as give information on walls in real materials. Some special cases, for example 71° and 109° neighborhoods, have not even been considered theoretically.

In our earlier work [12] we were able, by a technique based on the use of the polar Kerr effect, to obtain automatic-potentiometer records from which not only the wall thickness but also the distribution of magnetization in the walls could be determined.

In the present work we give experimental results of a study of the main types of walls in transformer steel, nickel and cobalt. The apparatus was, in principle, the same as before, [12] but the photomultiplier and amplifier noise was reduced to minimum and, moreover, the glass polaroids, used as polarizer and analyzer, were replaced by the better Nicol prisms. As a result of this the sensitivity of the apparatus increased considerably. Records of the walls were obtained beginning from a normal magnetization component of about 15 G, which represents spin deviation from the easy magnetization axis by 1.5—2° in nickel and by less than 0.5° in iron and cobalt. Thus we may assume that in practice the walls were recorded completely by the apparatus and that the maxima of the recorded curves represented the total saturation magnetization of the samples. In the figures given below the abscissa gives the wall thickness and the ordinate gives a quantity proportional to the normal saturation-magnetization component, $A = kI_{sn}$, at the corresponding point in the wall.

1. INVESTIGATIONS OF SAMPLES IN THEIR INITIAL STATE

Silicon iron. Samples were cut from fine-grained transformer steel (grain diameters up to 1—2 mm) containing 3% silicon; the samples were strips measuring 20 × 5 × 0.3 mm. In such samples it is always possible to find grains with a crystallographic orientation of the surface such that the simplest domain structure is observed. The samples were first carefully polished and then, to relieve the stresses, annealed in vacuum at 1000° C for 3 hours.

Figure 1 shows a record of the distribution of the normal component of the saturation magnetization I_S in 180° walls emerging on the (110) and (100) surfaces, as well as in 90° walls enclosing the prismatic domains on the (100) surface. All the curves in Fig. 1 were obtained from the same sample. The records of the walls of many crystals show that the wall thickness varies both from crystal to crystal and even in the same crystal. The thickness of the 180° walls emerging on the (110) surface varies within the limits 0.40—0.70 μ and the thickness of the walls emerging on the (100) surface lies within the limits 0.32—0.36 μ. Such a scatter of the wall thicknesses may be due to local singularities in crystals and, in the case of the (110) plane, also to the angular direction at which the walls emerge on the surface.

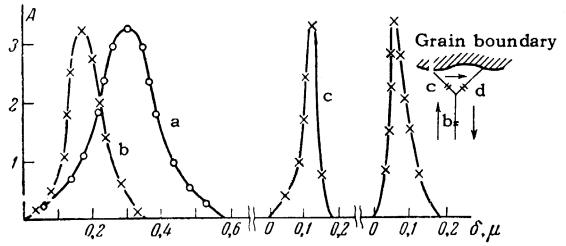

FIG. 1. Distribution of magnetization in walls of different orientations in silicon iron crystals: a) 180° wall in the (110) plane; b) 180° wall in the (100) plane; c) and d) 90° walls of prismatic domains. The points at which the walls were recorded are shown schematically on the right.

As shown in earlier work, [13] the walls in silicon iron emerge on the (110) surface at angles of about 10—30° to the normal. In the case of the (100) plane the walls emerge more or less exactly perpendicular to this plane (following the direction of the third easy magnetization axis), and the scatter of the wall thicknesses is considerably smaller. Much better agreement between wall thicknesses is observed for walls of the same type (those separating domains with the same neighborhood and the same orientation of the crystal surface) in the upper parts of the magnetization distribution curves where the main change of the spin orientation takes place.

The structure of the 90° walls forming a prism is such (Fig. 1c and 1d) that if these walls are brought together they form the one 180° wall from which they originate. A more careful comparison of the areas under the curves shows that the area under the 180° curve is slightly larger than the areas under the two curves representing the 90° walls, in agreement with theoretical predictions. Smooth variation of the magnetization in the 90° walls occurs on the side of the main domains.

On the side of the prismatic domains the direction of I_S in the walls changes almost discontinously from 0 to 90°. Exactly the same distribution of magnetization occurs in walls of herringbone ("Christmas-tree") domains observed in crystallites having the (100) plane inclined slightly to the surface.

Records were also made of walls in the (110) plane in single-crystal samples. A comparison with polycrystals showed no important difference for thin walls.

Nickel. Electrolytic nickel was used, in which fairly large crystallites (up to several millimeters in diameter) were grown by plastic deformation followed by annealing. Since the domain structure of nickel is very sensitive to stresses, annealing was carried out very thoroughly: about 30 hours at 1000—1100° C. After shorter annealing the records of the walls showed random deformation.

The simplest domain structure in nickel, as in the other materials, is observed on crystallographic planes containing one or two directions of easy magnetization. In nickel such planes are (110) and (211). The former contains two directions of easy magnetization, the latter only one. Since the angle between the axes of easy magnetization in the (110) plane is 71° or 109°, this plane may contain, in addition to 180° domain neighborhoods, also 71° or 109° neighborhoods. The (211) plane contains only one easy magnetization axis and only 180° neighborhoods are possible in this plane. Figure 2 shows the magnetization distribution curves for walls separating all these types of neighborhoods. The nature of the neighborhood was determined first from the characteristic powder patterns, described in detail in the work of Yamamoto and Iwata. [14] The wall thickness measured at the base of the I_S distribution curves was found to be 2.2 μ for 71° neighborhoods, about 4 μ for 109° neighborhoods, 6 μ for 180° neighborhoods on the

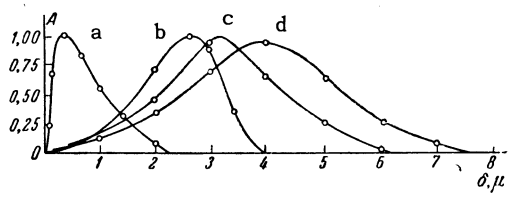

FIG. 2. Distribution of magnetization in domain walls is nickel: curves a, b, c represent, respectively, 71°, 109° and 180° walls in the (110) plane; d is a 180° wall in the (211) plane.

(110) plane and 7.8 μ on the (211) plane.

The 71° and 109° walls brought together form roughly a single 180° wall. In the (110) plane, which has two directions of easy magnetization, the 180° neighborhood extends over a smaller region than in the (211) plane, which has only one easy-magnetization axis. This is similar to the structure of walls in silicon iron crystals. Symmetrical walls, as in silicon iron, are only the 180° walls, while the highest asymmetry occurs for 71° walls.

Cobalt. A fine-grained sample was at the present authors' disposal. Before the walls were recorded the sample was polished mechanically and then lightly electropolished until good powder patterns appeared. The sample was not annealed since this would have altered its crystal structure. Two crystallites were found having surfaces parallel to the hexagonal plane and containing 180° walls. In one of the crystallites the thicknesses of different walls ranged from 0.05 to 0.08 μ, in the other they ranged from 0.8 to 0.10 μ. All the curves had similar shape.

Figure 3 shows two I distribution curves, for the walls with greatest and least thickness. The large difference between the thicknesses is obviously due to the crystallographic orientation of the surfaces of the two grains being not quite identical; this was also noticed in the powder patterns. The somewhat flattened shape of the curves in the top part indicates the presence of strong mechanical stresses. The effect of stresses (for other crystals) will be discussed below.

Comparison with Theory. According to the calculations of Landau and Lifshitz, [2] the effective thickness of a 180° wall in a uniaxial crystal is given by

$$\delta = \sqrt{A/2aK}, \qquad (1)$$

and the spin orientation is given by

$$\cos\vartheta = -\operatorname{th}(x/\delta), \qquad (2)^*$$

where A is the exchange integral, a is the lattice constant, K is the anisotropy constant, ϑ is the angle of deviation of the spin in the wall from the direction of easy magnetization, and x is the coordinate along the direction perpendicular to the plane of the wall.

For a triaxial crystal, Néel deduced the thickness of a 180° wall perpendicular to the tetragonal axis:

$$\delta \approx 15a\sqrt{E/6K}, \qquad (3)$$

and the orientation of spins in the wall:

$$x = a\sqrt{\frac{E}{6(K+K')}}\operatorname{argsh}\left(\sqrt{\frac{K+K'}{D}}\operatorname{ctg}\vartheta\right), \qquad (4)^{**}$$

where E is the molecular-field energy per unit volume, and K′ and D are the constants occurring in the definition of the magnetoelastic energy of the crystal. For iron $E = 8.6 \times 10^9$, $K' = 1780$, and $D = 820$ erg/cm^3.

Measurements on cobalt are the most suitable for comparison with the theory of Landau and Lifshitz. For $a = 2.5 \times 10^{-8}$ cm, $K = 5 \times 10^6$ erg/cm^3 and $A = 1.5 \times 10^{-13}$ erg we obtain $\delta \approx 8 \times 10^{-7}$ cm. The large difference between this calculated value and the observed wall thicknesses (cf. Fig. 3) is, to a considerable degree, due to the fact that Eq. (1) gives an effective wall thickness which includes only the spins with a large deviation from the direction of easy magnetization. The experimental values give the total wall thickness. The records of the domain walls in cobalt were obtained for an unannealed sample and, therefore, their top portions are flattened out. Due to this the plotted distributions of the values of $\cos\vartheta$ and $\tanh(x/\delta)$ differ considerably, with $\cos\vartheta$ practically equal to zero over a large part of the wall.

Crystals of silicon iron with surface orientation along the (110) plane, which contains one easy-magnetization axis, are similar in many aspects of their domain structure to cobalt crystals. Therefore, a check of Eq. (2) was also carried out for 180° walls of silicon iron. The results are shown in Fig. 4. The $\cos\vartheta$ curve is almost linear in the middle of the wall and the value of $\cos\vartheta$ rapidly

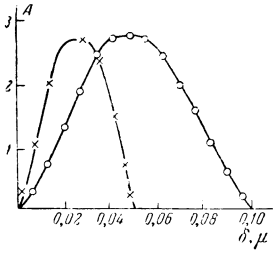

FIG. 3. Distribution of magnetization in domain walls in cobalt (thinnest and thickest walls).

*th = tanh.

**sh = sinh, ctg = cot.

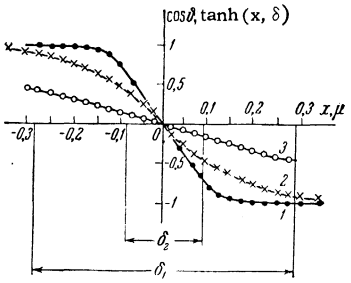

FIG. 4. Variation of the spin orientation in a 180° wall in silicon iron: 1) cos ϑ; 2) tanh(x/δ_2); 3) tanh (x/δ_3). The cos ϑ curve is plotted from Fig. 1a.

approaches unity. On the other hand, tanh(x/δ) lags considerably behind. For some walls the values of the cosine and the hyperbolic tangent are very nearly equal if the wall thickness is taken to be 5—6 times smaller than the experimental value. Thus Eq. (2) describes quite accurately the change in the spin orientation in those portions of the walls where the deviation of the spin from the easy-magnetization axis is sufficiently large. For iron containing 3% silicon, $K \approx 3.7 \times 10^5$ erg/cm^3, A $\approx 10^{-13}$ erg, and $a = 2.86 \times 10^{-8}$ cm, and therefore from Eq. (1) we have $\delta = 7 \times 10^{-5}$ cm, in good agreement with experiment.

The most suitable case for comparison with Néel's theory is a 180° wall emerging on the (100) plane in silicon iron. Since no calculated values of the constants K′ and D are available for iron with 3% silicon, we made a comparison for pure iron. Figure 5 gives, on the same scale, two curves plotted from the dependence of ϑ on x, given by Eq. (4), and from experimental observations. The curves are quite close to one another, particularly where the deviations of spin from the easy-magnetization direction are sufficiently large. The greatest disagreement between the curves is observed at the extreme portions of the wall.

2. EFFECT OF TEMPERATURE

The main energies which determine a boundary layer between domains are the exchange energy and the energy of magnetic crystalline anisotropy. If the exchange integral for a given material is regarded as constant, then the wall will depend on the anisotropy. The magnetic anisotropy can be altered by mechanical stresses and consequently such stresses may influence the wall structure. The effect of temperature on domain walls is also governed by the variation of anisotropy constants with temperature.

To prevent the samples from being oxidized by heating during temperature tests, they were placed in a special chamber which was evacuated to an order of 10^{-4} mm Hg. The samples were heated by means of a copper rod which itself was heated by passing current through a bifilar spiral. Light from a microscope reached the sample through a plane-parallel optically polished glass window. In order to protect the glass from distortion on heating, it was cooled by running water like the rest of the chamber casing. Temperature was measured with a thermocouple whose junction was in direct contact with the sample surface. Before the walls were recorded the sample was kept at a given temperature for 8—10 min. In each case the sharpness of focus of the microscope image of the sample surface was checked in case it was disturbed by thermal deformation. After the walls had been recorded at a given temperature the sample was heated to the next temperature without going back to the initial state. An objective with long focal length was used in the microscope. Although the apparatus permitted measurements at low temperatures, records were obtained only on heating: the region of high temperatures is more interesting because of the special temperature dependence of the anisotropy constants of the crystals investigated.

Silicon Iron. The 180° walls were recorded, at various temperatures, on the surface of a single crystal which coincided with the (110) plane. The results are shown in Fig. 6 for temperatures up to slightly above 700° C. The general nature of the variations observed is as follows. First, the am-

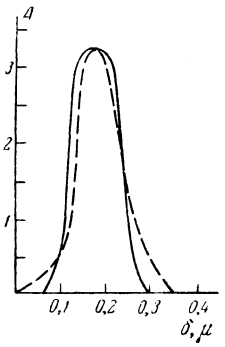

FIG. 5. Distribution of spin orientation in a wall perpendicular to the tetragonal axis in iron: the continuous curve is theoretical, according to Néel; the dashed one is experimental (from Fig. 1b).

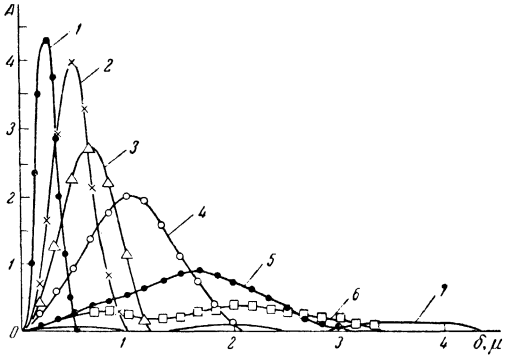

FIG. 6. Orientation of spins in a 180° wall in silicon iron at various temperatures: 1) 15°C; 2) 400°C; 3) 600°C; 4) 650°C; 5) 680°C; 6) 700°C; 7) 710°C.

plitude of the curves is reduced due to decrease of the magnitude of I_S with temperature and, second, the walls become thicker. At 710° C the apparatus recorded only single "islands" with walls. On further slight increase of temperature the remaining traces of the walls disappeared.

Nickel. A study was made of the 180° walls emerging on the surface along the crystallographic plane (110). The variation with temperature of one of the walls is shown in Fig. 7. In general this variation is similar to that observed for walls in silicon iron. At 100° C and 150° C the wall in nickel was not observed. It reappeared at 200° C but it was then thinner than at 80° C. At 250° C the wall thickness decreased still further and it disappeared again at 300°C.

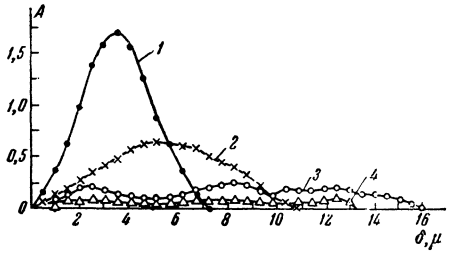

FIG. 7. Orientation of spins in a 180° wall in nickel at various temperatures: 1) 15°C; 2) 50°C; 3) 80°C; 4) 200°C. At 100 and 150°C the wall was not observed.

This behavior of the domain walls in nickel is related to the special temperature dependence of the anisotropy. Between 100° C and 200° C the anisotropy constant of nickel changes sign and the tetragonal axes become the directions of easy magnetization. In the 100—200° C region the absolute value of the anisotropy is least and this leads to the disappearance of the walls. On further increase of temperature the absolute value of the anisotropy increases but it changes sign. This may be responsible for the reduction in the wall thickness at 200° C and 250° C. In general, at these temperatures the domain structure of nickel should be established in accordance with a new easy-magnetization axis of tetragonal type. However, because of the experimental technique employed (only gradual heating) the domain structure remained unaltered, although it may possibly have been metastable. [15,16]

Cobalt. The 180° walls observed on a hexagonal plane were investigated. The temperature variation of one of these walls is shown in Fig. 8. The behavior of these walls is similar to that in iron and nickel. The highest temperature at which the walls in cobalt could still be recorded was 250° C. At slightly higher temperatures the walls "dissolved" completely in the domains. In precisely the same range of temperatures the anisotropy of cobalt vanishes and then reappears with negative sign. In the region of negative anisotropy values no walls were observed, in contrast to nickel. Obviously at these temperatures the domains are already rearranged in accordance with a new easy-magnetization axis which is displaced to the basal plane of the crystal. [17]

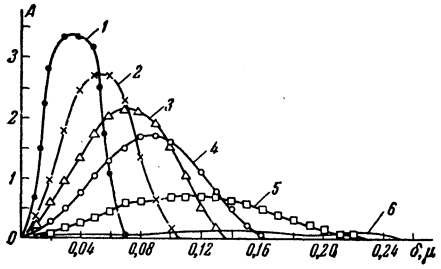

FIG. 8. Orientation of spins in a domain wall in cobalt on heating: 1) 15°C; 2) 60°C; 3) 100°C; 4) 130°C; 5) 200°C; 6) 250°C.

Discussion. From the curves given here, we may conclude that with increase of temperature the domain wall thickness increases in all these ferromagnets and the nature of the spin distribution in the walls is altered. Increase of the wall thickness is related to a reduction of the anisotropy of the crystals with increase of temperature. The spin distribution curves reflect quite accurately the qualitative changes in the anisotropy constants related to the reversal of sign. The reduction of the amplitudes of the curves represents a reduction of I_S with temperature. However, the reduction of the curve amplitude is considerably greater than the reduction of I_S at corresponding temperatures. For example, in the case of cobalt at 200°C the magnitude of I_S decreases by only 5%, while the amplitude of the curves decreases by a factor greater than 5. The same can be said of nickel. A similar discrepancy, though somewhat smaller, between I_S and the curve amplitude is also observed for silicon iron.

The reduction of the sensitivity of the apparatus is related to a reduction of the Kerr rotation constant on heating of the ferromagnets. This is confirmed by the usual records of the domain structure obtained by means of the Kerr effect. For example Kirenskiĭ and Degtyarev [15] found that clear contrast between oppositely magnetized domains in silicon iron was retained to 300° C. The contrast was considerably weakened on increase of temperature to 400° C, while at 500° C it fell very sharply, although the reduction of I_S was still small at this temperature. Consequently the Kerr

effect is of limited use in temperature tests and in many cases, particularly in studies of domain walls, it can give only qualitative results. For quantitative studies it is necessary to know the exact dependence of the Kerr rotation constant on temperature.

3. EFFECT OF STRESSES

A study was made of the effect of unidirectional stresses (tensile and compressive) on the walls between domains. When such stresses are applied to crystals magnetoelastic energy is added to the anisotropy energy. Thus the effective anisotropy energy then consists of the intrinsic crystal anisotropy energy and the magnetoelastic energy E_σ. If the spontaneous magnetization is directed along the easy-magnetization axis, then in the case of iron (and silicon iron) along the [100] axis and in the case of nickel along the [111] axis we have, respectively:

$$E_\sigma = -\tfrac{3}{2}\lambda_{[100]}\sigma\cos^2\varphi, \quad (5)$$

$$E_\sigma = -\tfrac{3}{2}\lambda_{[111]}\sigma\cos^2\varphi, \quad (6)$$

where $\lambda_{[100]}$ and $\lambda_{[111]}$ are the saturation magnetostrictions along the [100] and [111] axes, φ is the angle between the directions of magnetization and stress, and σ is the magnitude of the applied stress. The change in the crystal anisotropy under the influence of stress should affect also the domain walls. The effect should depend on the relative magnitudes of the intrinsic anisotropy and the applied stress. Since nickel has the lowest anisotropy, the largest changes in the walls for a given stress should be observed in nickel. Conversely, in cobalt, whose anisotropy is very high, such changes should be minimal. The effect of stress was investigated on silicon iron and nickel crystals. The authors did not possess cobalt suitable for this investigation.

Silicon iron. The samples consisted of single-crystal plates with the surface along the (110) plane; stresses were produced in them by a special stretching device which uses a motor. The spin distribution in the walls was recorded at certain fixed values of tensile stresses, measured with a dynamometer.

Figure 9a shows the appropriate curves in the initial state and under a stress (along the easy-magnetization direction) of 26 kg/mm^2, which is close to the elastic limit. The curves for lower stresses σ lie between the two curves shown in Fig. 9a. The addition to the anisotropy energy is in this case given by Eq. (5) where $\varphi = 0$. The curves of Fig. 9a indicate that the wall thickness

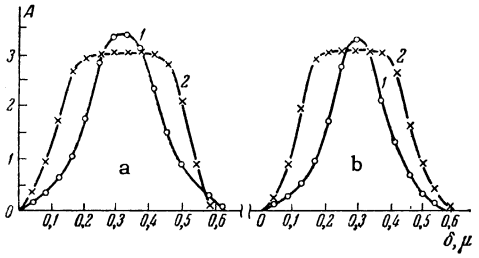

FIG. 9. Effect of tension on a domain wall in silicon iron. The load was applied: a) along the wall; b) at right angles to the wall. Curves 1 represent walls in unloaded state, curves 2 under a load.

decreases on stressing, although this decrease is slight: from 0.66 to 0.60 μ. If we assume that the wall thickness depends only on the effective anisotropy and that it is inversely proportional to the square root of the effective anisotropy, then for $\lambda_{[100]} = 24 \times 10^{-6}$ and $K = 3.7 \times 10^5$ erg/cm^3 a calculation gives approximately this slight reduction in the wall thickness. Main effects of stresses are observed in the distribution of magnetization. The upper part of the curve is smoothed out and becomes practically flat. This indicates that the spins in the middle of the wall, where they are most unfavorably directed with respect to σ, deviate from their normal direction toward the sample surface. Judging by the magnitude of the reduction in the curve amplitude this deviation amounts to 34°. The spins in the middle of the wall act on the side spins and consequently the remaining part of the wall "swells" considerably. The shape of the wall becomes approximately the same as that of a round rubber cord under a flat object. The existence of a flat upper part of the curve may indicate that in this part of the wall there is no continuous variation of the spin direction but that at some point there is a big jump between the directions of two neighboring spins.

Figure 9b shows the change in the wall on stretching along the average direction of magnetization, i.e., at right angles to the wall. The nature of the spin distribution is in this case the same as on stretching along a wall, but the wall thickness increases somewhat; this is now due to the reduction of the effective anisotropy constant compared with its initial value. Under stresses greater than 4.5 kg/mm^2 the walls cannot be recorded, because the whole domain structure begins to rearrange itself in accordance with a new easy-magnetization axis imposed by stretching.

Nickel. Since we possessed only small pieces of nickel it was more convenient to compress rather than to stretch them. For this purpose samples were cut in the form of square plates

with 6 mm side and thickness about 1.5 mm. The two sides of the square were made perpendicular to the direction of easy magnetization [111]. The same device as was used to stretch silicon iron, causing little rearrangement, was employed for compression along the direction of easy magnetization. The addition to the anisotropy energy is now given by Eq. (6) with $\varphi = 0$. Crystallites with the (110) plane were selected and only the 180° walls were studied.

As pointed out above, nickel is very sensitive to mechanical stresses because of its large magnetostriction and weak anisotropy. Consequently the annealing of samples must be very thorough. Figure 10 gives the spin distribution records for one of the wal under stresses of 0, 0.5, 2 and

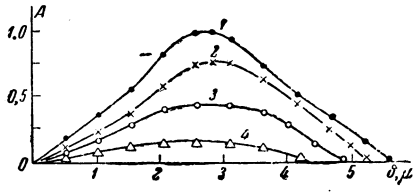

FIG. 10. Effect of compression on a 180° wall in nickel. The direction of the compression is along the wall. Curve 1 – zero load; 2) $\sigma = 0.5$ kg/mm^2; 3) $\sigma = 2$ kg/mm^2; 4) $\sigma = 4$ kg/mm^2.

4 kg/mm^2. With increase of the stress the wall thickness decreased from 5.6 μ to, respectively, 5.2, 4.9 and 4.3 μ. For nickel $\lambda_{[111]} = 25 \times 10^{-6}$, $K = 5 \times 10^4$ erg/cm^3, and appropriate calculations give 5.4μ, 5.2μ and 5.1μ for the wall thickness under stresses of 0.5, 2 and 4 kg/mm^2. Thus the wall thickness was observed to decrease faster than would be expected from the calculations. As in the case of silicon iron, the shape of the spin distribution in the wall changes and in the middle of the wall the curve has a horizontal part, indicating the absence of spins directed at right angles to the sample surface. At $\sigma \approx 13$ kg/mm^2 the magnetoelastic energy becomes equal to the anisotropy energy. We may expect that at these (or slightly larger) stresses all the spins align themselves along the direction of compression and there are no leakage fields above the wall. However, records could not be obtained under such loads since stresses slightly larger than 4 kg/mm^2 began to produce plastic deformation in the samples.

From investigations of the spin distribution curves in the walls under stress we may conclude that for the same crystal and the same values of the intrinsic and effective crystal anisotropy constants the wall structure is not the same. In theoretical calculations on this problem no distinction is made between these constants, although in fact the influence of the induced anisotropy on the walls is essentially different from the influence of the intrinsic anisotropy.

Stresses in closure domain walls. Under favorable conditions there are prismatic closure domains at the crystal edges. In the case of iron (or silicon iron) crystals the magnetization in the prisms is perpendicular to the magnetization of the main domains. The spontaneous magnetostriction stresses in such domains lie along the same direction as the magnetization. Consequently at the walls separating domains with different directions of magnetization there should be tensile or compressive stresses.

To check this hypothesis we recorded walls of prismatic domains in various parts of silicon iron and nickel crystals (cf. Fig. 11). In the case of iron region 1 at the vertex of the prism has the thickest wall, the thickness decreasing in the middle of the wall (region 2) and becoming smallest at the base of the prism (region 3). Comparing the curves in Fig. 11a with those obtained earlier (Fig. 9) we may conclude that the 90° wall runs along points with gradually changing stresses. Judging by the nature of the curves the stresses

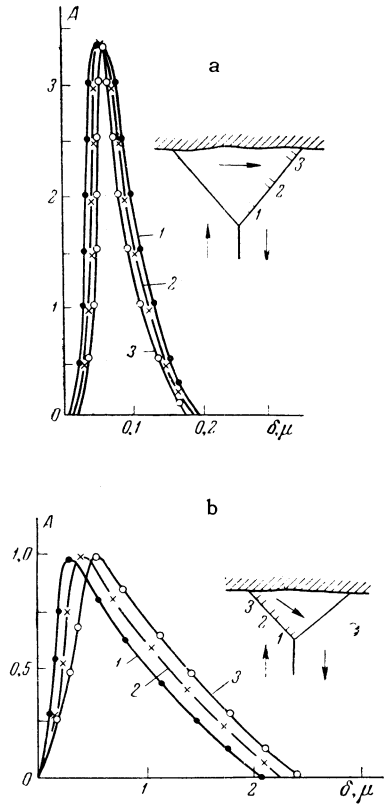

FIG. 11. Orientation of spins in walls of closure domains: a) in silicon iron, and b) in nickel. The schematic drawings show the points at which walls were recorded.

are tensile along the wall. Qualitatively the same conclusion may be reached by taking into account the positive sign of magnetostriction for directions along which the main and closure domains are magnetized. Figure 11b also shows various portions of a 71° wall of a closure domain in the (110) plane of nickel. Comparison with Fig. 10 permits us to assert that in the case of nickel the stresses along the wall are compressive. The same conclusion may be reached from the negative sign of the magnetostriction of nickel.

CONCLUSIONS

Finally, we shall compare the behavior of domains and domain walls in various states of ferromagnets. As pointed out above, the structure of the walls, in contrast to the domains themselves, does not depend on the shape and dimensions of crystals. If a crystal is subjected to any treatment (temperature, mechanical stresses, etc.) the walls always reach a state corresponding to the energy of the crystal without any additional treatment of the crystal. On the other hand the domain structure is not altered by such treatments although it becomes metastable. The domain structure corresponding to a new energy balance of the crystal is established only after reaching an equilibrium state which may be achieved, for example, by magnetization and demagnetization of the sample by an alternating field or by heating it above the Curie point.

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