SOVIET PHYSICS JETP VOLUME 37(10), NUMBER 3 MARCH, 1960

ON THE MAGNETIZATION PROCESS IN FERROMAGNETS

L. V. KIRENSKIĬ, M. K. SAVCHENKO, and I. F. DEGTYAREV

Physics Institute of the Siberian Division, Academy of Sciences, U.S.S.R.

Submitted to JETP editor March 31, 1959

J. Exptl. Theoret. Phys. (U.S.S.R.) **37**, 616-619 (September, 1959)

The dynamics of the domain structure during magnetization were studied in crystals of silicon iron containing 3% silicon, using the powder figure method and the magneto-optical Kerr effect. It is shown that magnetization is achieved in the general case by the following processes: displacement of the domain walls, rearrangement of the domain structure, rotation of the magnetization vector in the direction of the field, and the paraprocess. The rotation process terminates technical magnetization; the process of boundary displacement precedes the rearrangement of the domain structure and completes it.

INTRODUCTION

IN the absence of a magnetic field, according to contemporary ideas, a ferromagnetic crystal is divided into separate regions of spontaneous magnetization — domains. The domains are separated from one another by a bounding layer of thickness $0.6 - 0.9\,\mu$.[1] The domain configuration in a given crystal is determined from the minimization of its free energy.[2] The domain structure is adequately revealed by the method of powder figures,[3] and the domain configurations obtained in experiments are very close to those required by the theory.

The magnetization of a ferromagnet, according to contemporary views,[4] is composed of the process of boundary displacement, the rotation process and the paraprocess. The process of boundary displacement can be both reversible and irreversible. During irreversible boundary displacement uneven changes of the magnetization occur — the Barkhausen jumps.

On the completion of the displacement process the crystal is magnetized to saturation as a whole along one of the axes of easy magnetization closest to the direction of the field; the rotation process is considered complete when the magnetization vector is parallel to the field vector.

The processes of boundary displacement and rotation partially overlap in some comparatively small portion of the technical part of the magnetization curve.

The processes of boundary displacement and rotation undoubtedly occur and can be easily revealed by motion pictures of powder figures.[5] The paraprocess is observed in strong fields and is completely irreversible.

If the process of magnetization does, in fact, take place as described above, then when studying the Barkhausen effect in a single crystal disc with positive anisotropy constant — the disc being cut in a plane of the type (110) — the following picture should apply.

Since the domain structure of such a crystal consists of plane-parallel domains magnetized along and in the opposite direction to the [001] axis lying in the plane of the disc, then a Barkhausen jump will correspond only to a portion of the ferromagnet, the magnetic moment of which undergoes an irreversible rotation through 180°.

Therefore, a measuring coil detecting the Barkhausen jumps detects such a jump completely if the axis of the coil coincides with the [001] direction and only partially for any other direction. Since an apparatus for studying Barkhausen jumps detects only those above a certain size, then the maximum number of jumps should be detected in the direction of the easy axis, while in a direction normal to this axis no jumps should in general be detected by the coil.

It is essential to dispose the detecting coil accurately, but not the direction of the magnetizing field. For the latter it is important that the component along the axis of easy magnetization be different from zero.

However, detailed studies of the Barkhausen effect lead to directly contrary results.[6] The maximum number of jumps appears in the [110] direction, perpendicular to the axis of easy magnetization. In the direction of easy magnetization the number of jumps is a minimum.

The experimental fact given above cannot be explained by assuming that the mechanism of the jumps is an irreversible displacement of part of the boundary held up somewhere at magnetic inhomogeneities in the crystal. Also, the maximum number of jumps corresponds approximately to the maximum value of the magnetic permeability, which for a uniformly increasing magnetic field should depend only on the speed of displacement of the boundaries between domains, because only in these places in a ferromagnetic single crystal is the magnetic permeability essentially greater than unity — being close to it anywhere inside the domains.

However, direct measurement of the speed of boundary motion in a uniformly increasing field shows that the maximum speed of boundary motion corresponds to the initial portion of the magnetization curve,[5] which does not as a rule correspond with the maximum magnetic permeability.

The said divergences of some of the experimental data from the theoretical scheme of magnetization show that experiments should be made aimed at finding more precisely the mechanism of the magnetization process in ferromagnets.

EXPERIMENTAL ARRANGEMENT

The investigation was carried out on crystals of silicon iron with 3% silicon content. The specimens were cut in the form of plates 30 x 6 mm or discs of diameter 20 mm. The specimen thicknesses were 0.3 mm or less. The specimen surfaces coincided with the (110) planes or were close to them. In the plates the long side coincided with the [001] direction. The specimens were annealed in vacuum for two to three hours at a temperature of 1000° C, were subsequently cooled slowly in the furnace, and then polished electrolytically.

The change of the domain structure of the specimens in a magnetic field of increasing strength was studied by the powder-figure method and the method of meridional magneto-optical Kerr effect.[7] For visual observations and photography of the domain structure by the magneto-optical method, the specimens were coated with a uniform layer of iron oxide.[7] The domain structure was studied by the powder method simultaneously on opposite surfaces of

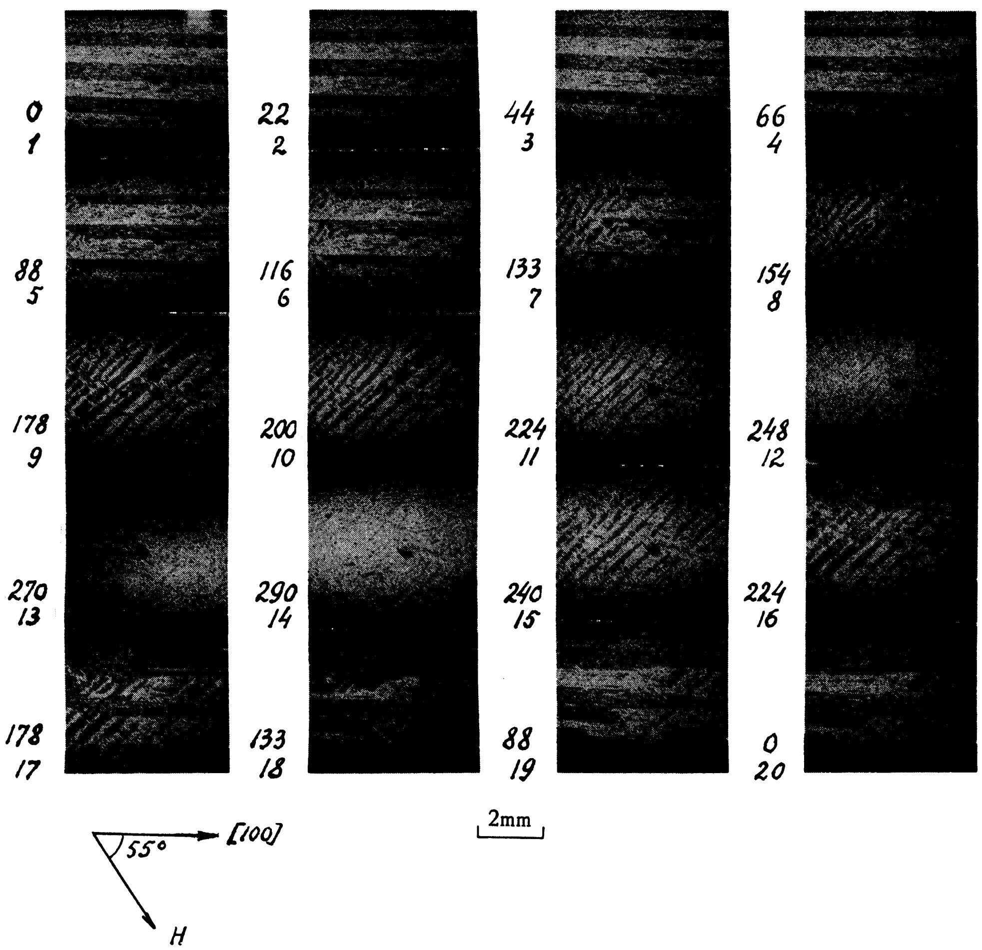

FIG. 1. Dynamics of the domain structure in a changing magnetic field inclined at an angle of 55° to the axis of easy magnetization. Numbers on the left: values of the external field in oe; below them, serial numbers of the frames.

a specimen. The observations were made using two MIM-6 microscopes, arranged vertically with objectives pointing towards each other, so that the optical axes of the microscopes coincided accurately.

OBSERVATIONAL RESULTS AND THEIR ANALYSIS

Magneto-optical observations: Using a specimen in the form of a disc of diameter 20 mm and thickness 0.3 mm, observations were made on the dynamics of the domain structure during magnetization along different directions in the plane of the specimen. For magnetization in the easy direction only displacements of the 180° boundaries were observed. In Fig. 1 the change of domain structure is shown during magnetization of the same specimen at an angle of 55° to the easy axis. With no field the original appearance is of parallel dark and light strips, which correspond to domains magnetized along and opposite to the [001] axis (Fig. 1, Frame 1). Apart from the main features, small wedges are seen, showing that the surface of the specimen has a small inclination to a crystallographic plane of the type (110). In fields less than 100 oe, widening of the light strips is mainly observed (Fig. 1, Frames 2 — 5). In fields of 100 — 200 oe, rearrangement of the domain structure occurs (Fig. 1, Frames 6 — 10). By visual observation of this rearrangement, its clearly pronounced erratic nature was apparent.

With further growth of the field up to 300 oe the displacement of the domain walls of the newly

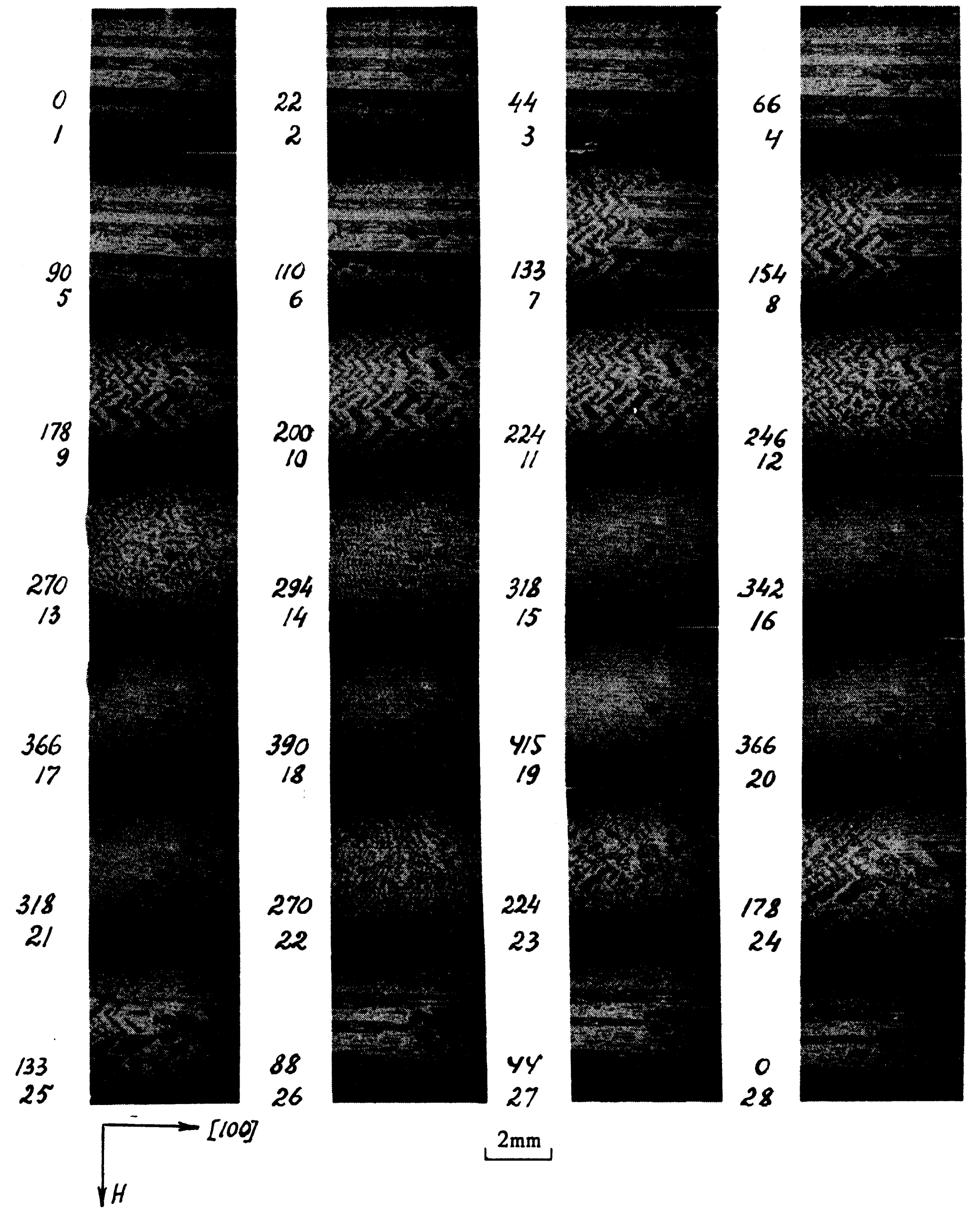

FIG. 2. Dynamics of the domain structure in a changing magnetic field directed along an axis of the type [110] perpendicular to the axis of easy magnetization. Numbers on the left: values of the external field in oe, and below them serial numbers of the frames.

formed structure is observed (Fig. 1, Frames 11 — 14).

In fields above 300 oe no structure is observed, since technical saturation has been reached. On diminishing the value of the field the process takes place in the reverse order (Fig. 1, Frames 15 — 20). The domain walls observed at the end are considerably distorted (Fig. 1, Frame 20). After demagnetization by an alternating field, the domain structure returns again to the original.

Similar changes of the domain structure are also observed during magnetization along other different angles — greater than 30° — to the easy axis. A typical feature of the structures arising due to rearrangement is that the direction of the dark and light strips in them is perpendicular to the difficult axis closest to the magnetic field vector. Thus, on changing the angle between the vector **H** and the [001] direction from 0 to 360°, new structures can be observed with only two directions of the strips, perpendicular to the two axes of difficult magnetization lying in the plane of the specimen.

A considerably more complicated rearrangement of the domain structure is observed during magnetization at an angle of 90° to the easy axis, i.e. along the [110] direction. The results of these observations are given in Fig. 2. On applying the magnetic field the process of boundary displacement is hardly noticeable (Fig. 2, Frames 1 — 4). In fields from 90 to 200 oe, rearrangement of the domain

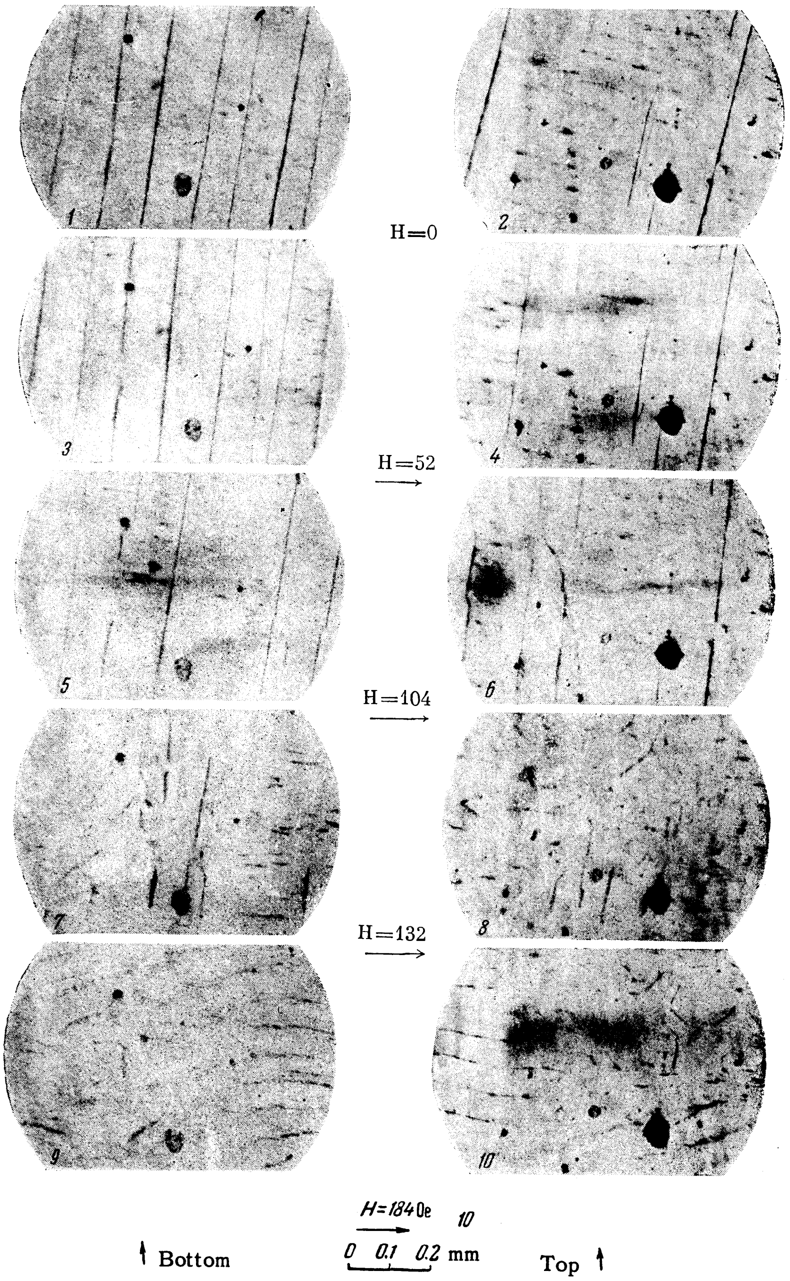

FIG. 3. Dynamics of the domain structure on opposite sides of a crystal in an increasing magnetic field. The domain structure does not penetrate the crystal.

structure takes place. Structures arise consisting of broken strips (Fig. 2, Frames 5 — 10). In this case both directions, characterising structures of this kind, appear simultaneously. With further increase of the field, sub-division into smaller domains takes place and the figures take the form of fine winding strips with preferential direction along the [110] axis, i.e., along the field (Fig. 2, Frames 11 — 19). On reducing the field the process takes place in the reverse order, but the characteristic directions are less clearly displayed (Fig. 2, Frames 20 — 28). As is seen from this figure and also from visual observations, throughout the entire process of magnetization in fields up to 400 oe boundary displacement is not observed, and the rearrangement of the structure which occurs takes place in the form of jumps during which separate volumes of the specimens reverse their magnetization.

It is apparent that such sharp structure changes are caused by major changes of the domain structure inside the crystal.

Similar changes of domain structure were observed by the magneto-optical method on several specimens. On specimens of thickness 200 — 400 μ the rearrangement of domain structure already described was, as a rule, observed. On specimens of thickness 100 μ and less, such complicated changes of structure were not often observed, and displacement of the boundaries of the original figures predominated; only during magnetization in a direction close to an axis of the type [110] did new structures arise in the form of fine winding lines oriented along the [110] axis.*

Powder-figure observations: In Fig. 3 are shown powder-figures taken on opposite sides of the same crystal. As is seen from this figure, the domain structure does not go right through and undergoes a significant change inside the crystal. On the upper surface the entire width of one domain and parts of two others are seen, whereas on the lower surface are seen a large number of parallel domains of approximately equal thickness. On increasing the field (directed horizontally) the structures also change in different fashions. The structure on the upper surface is almost unchanged up to a field of 100 oe; then destruction of the domains commences, and finally in very strong fields a new structure appears. On the lower surface boundary displacement is more clearly observed, which is broken up in the end by rearrangement of the domain structure.

It is interesting to remark that the domains that were getting smaller as the field increased directly before the rearrangement of the entire domain structure, increased somewhat in volume and were then destroyed.

Thus, the magnetization process in a ferromagnetic crystal is not restricted to the processes of boundary displacement, rotation and the paraprocess. The process of domain structure rearrangement plays an important role in the magnetization process; it is accompanied by a large number of Barkhausen jumps and corresponds to the maximum magnetic permeability.

*The changes of domain structure described are observed most clearly on looking through the motion-picture films taken during the work on the magneto-optical effect.

[1] L. V. Kirenskiĭ and V. V. Veter, JETP **35**, 819 (1958), Soviet Phys. JETP **8**, 568 (1959).

[2] L. D. Landau and E. M. Lifshitz, Sow. Phys. **8**, 153 (1935).

[3] F. Bitter, Phys. Rev. **38**, 1903 (1931); N. S. Akulov and M. V. Dehtjar, Ann. physik, 750 (1932).

[4] S. V. Vonsovskiĭ and Ya. S. Shur, Ферромагнетизм (Ferromagnetism) Gostekhnizdat (1948); R. Bozorth, Ferromagnetism, Van Nostrand, N. Y., 1951.

[5] L. V. Kirenskiĭ and V. D. Dylgerov, Физика металлов и металловедение (Physics of Metals and Metal Research) **3**, 216 (1956); Kirenskiĭ, Dylgerov, and Savchenko, Izv. Akad. Nauk SSSR, Ser. Fiz. **21**, 1168 (1957), Columbia Tech. Transl. p. 1157.

[6] Ivlev, Il'yushenko, and Aseeva, Izv. Akad. Nauk SSSR, Ser. Fiz. **21**, 1250 (1957), Columbia Tech. Transl. p. 1239.

[7] L. V. Kirenskiĭ and I. F. Degtyarev, JETP **35**, 584 (1958), Soviet Phys. JETP **8**, 403 (1959).

Translated by K. F. Hulme
123