which has to form the basis for a correct interpretation of experimental results on transport, optical, and Fermi-surface experiments.

It is a pleasure to thank Dr. W. Schneider and Dr. H. J. Wiesmann for useful discussions and Professor A. R. Ubbelohde, F.R.S., for interesting suggestions and comments in the final stage of our work.

[1]G. R. Henning, Prog. Inorg. Chem. 1, 125 (1959); A. R. Ubbelohde and L. A. Lewis, *Graphite and Its Crystal Compounds* (Oxford Univ. Press, Oxford, 1969).
[2]F. L. Vogel, Bull. Am. Phys. Soc. 21, 262 (1978).
[3]*Intercalation Compounds of Graphite*, edited by F. L. Vogel and A. Hérold (Elsevier Sequoia, Lausanne, 1977).
[4]For a review and discussion see paper by G. Dresselhaus and M. S. Dresselhaus, in Ref. 3.
[5]M. S. Dresselhaus, G. Dresselhaus, and J. E. Fischer, Phys. Rev. B 15, 3180 (1977).
[6]I. L. Spain and D. J. Nagle, in Ref. 3.
[7]L. A. Girifalco and N. A. W. Holzwarth, in Ref. 3.
[8]C. Kittel, *Quantum Theory of Solids* (Wiley, New York, 1963).
[9]J. W. McClure, Phys. Rev. 108, 612 (1957); J. C. Slonczewski and P. R. Weiss, Phys. Rev. 109, 272 (1958).
[10]H. Venghaus, Phys. Status Solidi 81, 221 (1977).
[11]A. S. Bender and D. A. Young, J. Phys. C 5, 2163 (1972).
[12]D. D. L. Chung and M. S. Dresselhaus, Solid State Commun. 19, 227 (1976).
[13]D. A. Platts, D. D. L. Chung, and M. S. Dresselhaus, Phys. Rev. B 15, 1087 (1977).

Magnetization Reversal of a FeSi Picture-Frame Crystal Measured by the Time-Dependent Neutron-Depolarization Technique

F. J. van Schaik and M. Th. Rekveldt
Interuniversitair Reactor Instituut, Delft, The Netherlands
(Received 23 June 1978)

The magnetization-reversal process within a [100] [010] [001] picture-frame FeSi (3.5 wt% Si) crystal has been investigated by means of the time-dependent neutron-depolarization technique, applying a periodic block-shaped magnetic field. Various distinct states are observed in the magnetization-reversal process: firstly, nucleation of regions of reversed magnetization; subsequently, the merging of these regions into two wavy domain walls according to a sandwich structure and the motion of these straightening walls towards the center.

It has long been recognized that magnetization reversal in a ferromagnet under the influence of a pulsed magnetic field can be described in terms of nucleation regions of reversed magnetization (denoted reversed regions) and eddy-current-controlled domain-wall motion.[1,2] However, the experimental information about the reversal process is restricted by the detection techniques used up to now: pickup coils to measure the average magnetization of the bulk material combined with Kerr-effect observations of the surface behavior of the domain walls. In contrast, polarized neutrons are a unique probe for investigating magnetic domains within the volume of a ferromagnet.[3,4] Time-dependent neutron-depolarization technique[5,6] (TDNDT) gives information with a spatial resolution of several microns about the internal magnetization distribution and the local direction of the magnetization. In this Letter we report the results of applying the newly developed TDNDT to study the magnetic reversal processes within a single-crystal picture-frame specimen of silicon(3.5 wt%) iron.

In the neutron-depolarization technique[4] the polarization direction of a monochromatic neutron beam impinging in the x direction on the sample can be adjusted before and analyzed after transmission along any of the three orthogonal directions x, y, and z (Fig. 1). The polarization change D_{ij} by the sample is defined by $D_{ij}=(I_s-I_{ij})/(I_s-I_0)$, in which I_s is the intensity of a fully depolarized beam, I_{ij} the intensity with analyzation and polarization directions i and j (i, $j=x,y,z$), and I_0 the intensity of the undisturbed polarized beam.

The polarization direction of the neutron beam rotates with the Larmor precession frequency around the magnetization direction in the crystal. The total rotation angle ϕ is given by $\phi=\gamma B_s d/v$, where γ is the gyromagnetic ratio of the neutron ($\gamma=1.80\times10^8$ s^{-1} T^{-1}, mksa units), B_s the spontaneous magnetic induction, v the velocity of the neutrons, and d the crystal thickness. The length $|D|$ and rotation angle ϕ of the polarization vector

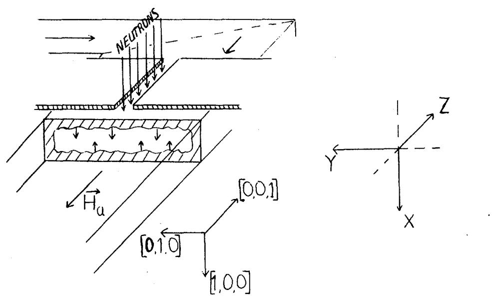

FIG. 1. Schematic view of a part of the picture frame crystal with neutron diaphragm. The coordinate system, crystal orientation, and direction of the applied field and magnetization are indicated. The arrows in the cross section indicate how the wavy-structured domain walls move towards the center of the specimen (sandwich model).

for a rotation around the z axis are calculated by

$$|D| = (D_{xx}{}^2 + D_{yx}{}^2)^{1/2}, \quad \phi = \tan^{-1}(D_{yx}/D_{xx}). \qquad (1)$$

In expressions (1) the (x, y, z) coordinates are as indicated in Fig. 1 and the initial polarization direction is parallel to the x axis.

The polarized neutron beam with a wavelength of 1.6 Å and a velocity $v = 2500$ m/s is transmitted through one long leg (width 2.9 mm) of the crystal of dimensions $15\times10\times0.26$ mm^3, a part of which has been drawn in Fig. 1. The crystallographic orientations are indicated in the figure. For the crystal investigated and magnetized at saturation with $B_s = 2.05$ V s/m^2, the rotation angle ϕ of the polarization vector amounts to 6.1 times 2π. A rectangular 5×0.3 mm^2 Cd-B_4C diaphragm is mounted in a fixed position in front of the crystal with its slit direction parallel to the z axis. A 49-turns/cm coil is wound around the long leg of the crystal and the crystal is magnetized by a block-shaped magnetic field with a risetime of 12 μs and ranging from 200 up to 2250 A/m. The intensity of the transmitted neutron beam is recorded synchronously with the block-shaped magnetic field using a multichannel analyzer. The time resolution of 15 μs of the experimental setup is mainly caused by the neutron path length of 2.5 cm in the ^{3}He-filled detector.

From the time-dependent neutron intensities measured at applied fields of 700 and 1350 A/m the time spectra obtained for D_{xx}, D_{yx}, and D_{zz} are shown in Figs. 2(a) and 2(b) together with the block-shaped applied field as a function of time. The length $|D|$ and the net rotation angle

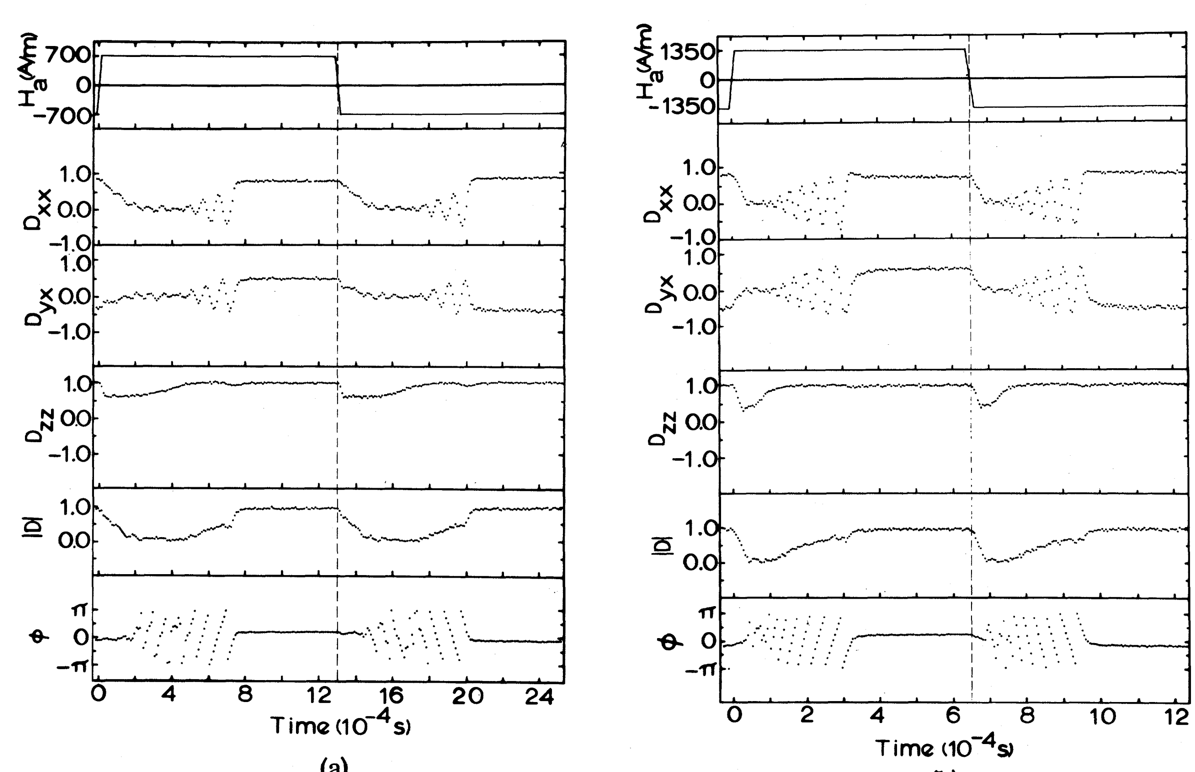

FIG. 2. (a) Time spectra of the applied block-shaped field, the polarization components D_{xx}, D_{yx}, and D_{zz}, the length $|D|$, and the rotation angle ϕ of the polarization vector.

ϕ of the polarization vector in the x-y plane defined by (1) are given also. The spectra obtained at higher applied fields are qualitatively the same. The shape of the D_{xx}, D_{yx}, D_{zz} time spectra and hence the dependence of $|D|$ and ϕ in the first half-period of the applied field are identical to those in the second half-period.

In the D_{xx} and D_{yx} spectra it appears that before reversal of the applied field both D_{xx} and D_{yx} have a constant value corresponding to a rotation of + or -6.1 times 2π. In both half-periods these levels are the same for D_{yx}. This is because only D_{yx} is sensitive to the sign of the magnetization $[\sin(-\phi) = -\sin(+\phi)]$. It is evident that then $|D|$ and $|\phi|$ are constant, too.

After reversal of the applied field we observe a drastic change in the three polarization components. The component D_{zz} decreases most abruptly with time to a constant minimum level of 0.1 and 0.03 ms duration at 700 and 1350 A/m, respectively. In the same time intervals the length of the polarization vector $|D|$ decreases to zero while the net rotation angle ϕ remains about the same. We attribute the decrease of D_{zz} and $|D|$ with time to the creation and growth of small reversed regions at the moment of reversal of the applied field. Because of eddy-current considerations these regions will mainly grow at the surface of the crystal.[1,2] The stray fields caused by the reversed regions are in all directions and therefore they depolarize the neutron beam as observed in $|D|$ and D_{zz}. In particular D_{zz} is decreased only by stray fields not parallel to the z axis. The length $|D|$ is not only affected by stray fields but by the size and number of the reversed regions being transmitted also. The latter follows from the rotation of the polarization vector in a reversed region which is proportional to the size of that region. The decrease of $|D|$ by the transmission through the regions should be accompanied by a change in the net rotation angle of the polarization vector, in contrast to the depolarization by stray fields of the reversed regions.

The initial decrease of D_{zz} suggests that the formation of the reversed regions apparently takes place within the experimental resolution time. The nearly constant value of ϕ immediately after reversal of the applied field indicates that the decrease in $|D|$ in this time interval is mainly caused by stray fields. The constant minimum levels of D_{zz} of 0.1 and 0.03 ms at 700 and 1350 A/m, respectively, and the simultaneous decrease of $|D|$ indicate that in this time interval the stray fields with directions different from the z axis remain constant, while the stray fields in the z direction, and therefore also the reversed regions, are still growing.

As the magnetization-reversal process progresses in time the D_{zz} and $|D|$ values gradually increase to 1.0 and at the same time the D_{xx} and D_{yx} spectra show oscillations which increase in amplitude. The oscillations in D_{xx} and D_{yx} have a phase difference of $\pi/2$ with respect to each other and, calculating ϕ, several complete 2π rotations of the polarization vector around the z direction are found as shown in the $\phi(t)$ curve of Fig. 2.

These results can be interpreted by means of the sandwich domain model originally proposed by Rodwell and Bean.[1] According to this model the magnetization reversal takes place by two domain walls parallel to the crystal surface, traveling from the surface towards the inside of the sample. When the walls are moving the net rotation angle ϕ of the neutron polarization vector will become time dependent as observed in the spectra. The walls are created by the joining together of neighboring reversed regions. However, upon creation these walls are not straight, but have a wavy structure, which causes local differences in the net rotational angle of the polarization vector. As long as $|D|$ remains zero we suppose that the wavy structure of the two walls depolarizes the beam completely and hence discrete oscillations cannot be observed. As $|D|$ is increasing towards $+1.0$ in time, the walls are gradually straightened out during their inward motion, and in this time interval we see also that D_{zz} increases to $+1.0$, which is in agreement with the picture of straightening walls, causing less stray fields. Straightening of the walls while moving inwards is favored because they are affected by the wall surface tension and because, due to eddy currents, the more inner parts of the walls move slower than the outer ones.

Rather suddenly the oscillations have disappeared and the various polarization components become constant. This apparently occurs when both walls have met each other and, according to the sandwich model, they will vanish at the end of the magnetization reversal. Just before the end of the reversal process small minima are observed in D_{zz} and $|D|$, indicating that stray fields arise in the crystal. A possible explanation for these minima may be the presence of distinct areas with right- and left-handed–

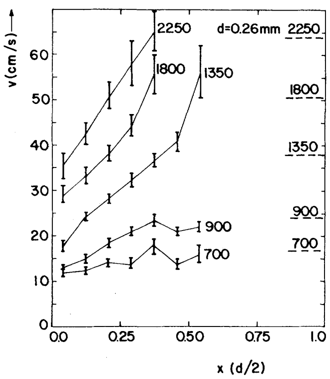

FIG. 3. The velocity of the domain wall in the sandwich model as a function of the distance of the wall to the center of the crystal (units relative to the half-crystal thickness). The parameter in the figure is the applied field (in amperes per meter). The horizontal stripe lines are defined in the text.

turning magnetizations within the moving walls forming a kind of patchwork. These areas are supposed to be separated by Néel lines and they find their origin in the linking process of neighboring nucleation regions. When the two walls meet each other, some opposing areas will attract each other and they collapse immediately because of surface energy minimalization, but other parts will repel each other. In this way an inhomogeneous magnetization with stray fields arises which will remain for a finite time in the crystal.

Assuming that the walls vanish in the middle of the crystal the velocity and the position x of the domain walls can be calculated from the $\phi(t)$ spectrum. Figure 3 gives the wall velocity as a function of the distance x to the center of the crystal. The distance x has been expressed in units relative to half the crystal thickness d, with parameter the applied field. The wavy structure of the walls, whenever they are formed, inhibits the determination of the wall motion in the outer layers. The velocity decreases when the walls are approaching the center. This can also easily be seen from the slopes of $\phi(t)$ in Figs. 2(a) and 2(b). The decrease is most pronounced at high applied fields. The higher velocities are less accurately determined due to the limited detector resolution time. The retardation of the walls may be caused by the eddy-current increase as the reversed layers become thicker. Another reason may be the increasing interaction between the two approaching walls by means of the eddy currents.

In comparing Figs. 2(a) and 2(b) we note that the entire duration of the magnetization reversal as observed in the spectra is shorter at the higher applied field. The time needed for entire reversal has been translated into a mean velocity of two approaching walls, sandwiching the crystal, in order to compare it with the observed sandwich-wall velocity. This mean wall velocity is indicated in Fig. 3 with horizontal stripe lines. It turns out that the velocities of the sandwich walls during the last stage of the magnetization-reversal process are less than the mean wall velocities, indicating that the reversal due to the nucleation regions happens much faster than the reversal by the sandwich-structure motion.

In the experiments sharp oscillations are measured, which proves that the magnetization reversal in the crystal effectuated by the sandwich motion takes place in a reproducible way. It should be stressed that in view of periodic data collection small deviations in the motion would have caused a strong smearing out of the oscillations.

In summary, we note that the TDNDT gives detailed information about the magnetization-reversal processes in the bulk of a FeSi picture frame crystal. Two stages in the reversal process can be distinguished from the measurements, which agree with the model given by Rodwell and Bean.[1]

We should like to thank Dr. M. Schlenker, Laboratoire de Magnétisme, Centre National de la Recherche Scientifique–Institut Laue-Langevin, Grenoble, France, for lending the picture-frame crystal, Professor Dr. J. J. van Loef for helpful discussions, and the Foundation for Fundamental Research of Matter, The Netherlands, for the financial support of this work.

[1]D. S. Rodbell and C. P. Bean, J. Appl. Phys. 29, 1318 (1958).

[2]J. E. L. Bishop, J. Phys. D 9, 2095 (1976); W. J. Carr, Jr., J. Appl. Phys. 47, 4176 (1976).

[3]F. Mezei, Physica (Utrecht) 86–88B, 1049 (1977).

[4]M. Th. Rekveldt, J. Phys. (Paris), Colloq. 2–3, C1-579 (1971), and J. Magn. Magn. Mat. 1, 342 (1976), and J. Phys. (Paris), Colloq. 38, C1-23 (1977).

[5]F. J. van Schaik, M. Th. Rekveldt, and J. J. van Loef, to be published; F. J. van Schaik and M. Th. Rekveldt, Phys. Lett. 66A, 77 (1978).

[6]F. J. van Schaik, M. Th. Rekveldt, and J. J. van Loef, J. Magn. Magn. Mat. 6, 233 (1977).