tion of the continuity of normal component of magnetization at the boundary should be satisfied. Mathematical deduction of the hysteresis loop and of the initial curve can be carried out in quite an elementary way. Figure 10 shows the dependence of the shape of the hysteresis loop thus calculated on the orientation of applied field, where θ denotes the angle between the field and the wall normal. Explanation will be given here only in one typical case, where the magnetic field is applied parallel to one of the uniaxial axes ($\theta=\frac{1}{4}\pi$). As shown in Fig. 11, the descending branch of the loop is divided into four sections *a*, *b*, *c*, and *d*, and three abrupt decreases of magnetization (*ab*), (*bc*), and (*cd*) exist between them. The change of domains in each

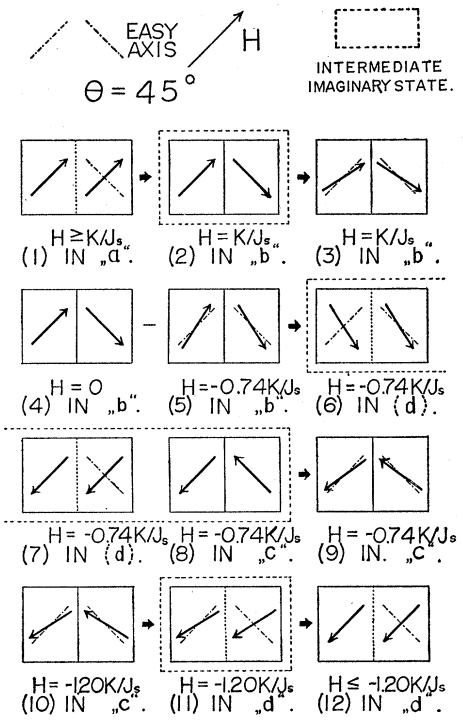

FIG. 12. Schematic diagram of the transitions of neighboring domains, when magnetization varies along the descending hysteresis curve.

stage is illustrated in Fig. 12. Following the decreasing applied field, an abrupt change (*ab*) will be initiated, if the energy of configuration (2) becomes smaller than that of configuration (1), and this will be carried out by the creation of a new boundary. Since the energy of configuration (3) is smaller than that of configuration (2), the transition (2) and (3) will be completed simultaneously.

At the abrupt change (*bc*), the transition is (5) to (9), and this will be analyzed into four intermediate transitions, of which (5) to (6) means annihilation of boundary and (7) to (8) means its creation. In the actual case of an abrupt change, creation or annihilation of a domain boundary would be accompanied with some difficulties associated with nucleation, but we have neglected this effect in this calculation. The field intensity, at which the abrupt change (*bc*) occurs, can be interpreted as the coercive force H_c and this amounts in this case to 0.73 K_u/J_s. If we substitute $K_u=1000$, H_c becomes 0.73 oersteds.

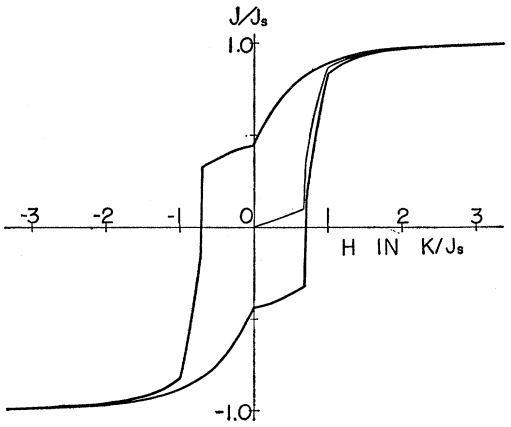

FIG. 13. Calculated hysteresis loop of polycrystalline material.

The initial curve can be easily obtained, by superposing the two branches of hysteresis loop, $P_1Q_1R_2R_1$ and $P_2Q_2Q_1R_2R_1$. Initial permeability μ_0 is expressed in this case:

$$\mu_0=1+\tfrac{1}{2}\pi(J_s^2/K_u),$$

and this furnishes us: $\mu_0=1500$, with $K_u=1000$, $J_s=1000$. Both H_c and μ_0 accord well with the experimental values.

It will be emphasized here, that, in some orientations of applied field, the initial curve extends out of the hysteresis loop. Figure 13 illustrates the initial and hysteresis curve of polycrystalline material, deduced by taking the average value, when the orientation of applied field varies from 0° to 90°. This agrees qualitatively with the experimental one shown in Fig. 5. Quantitatively some discrepancies exist between theories and experiment. For instance, the remanence J_r is 0.45 J_s, while the experimental value is much smaller. This discrepancy is probably due to the simplicity of the adopted model. In a more complete theory, a three-dimensional assemblage of domains, which, in the absence of an external field, would permit flux closure, should be adopted.

DISCUSSION

J. E. GOLDMAN, *Carnegie Institute of Technology, Pittsburgh, Pennsylvania:* There are two alternative possibilities in approaching an explanation of the effect of the magnetic anneal on the properties of Permalloy in certain specific composition ranges. One of these is to suppose that the certain characteristic properties of

the effective composition range, e.g., anisotropy, magnetostriction or presence of order, cause the alloy to be sensitive in some way to the presence of the field and, when such effects are present, the magnetic properties of the alloy are affected. Such would be the case in Chikazumi's suggestion that the magnetic annealing effect in Permalloy is the result of a directional order governed by the orientation of the annealing field. The alternative supposition is that, in general, a magnetic field present during annealing and cooling nearly always affects the possible orientations of the domains, but that only at certain specific compositions can this preferred domain orientation be reflected in major changes of the macroscopic magnetic properties.

Evidence obtained a few years ago by the writer and A. I. Schindler tends to support the latter alternative. Strips of $4\frac{1}{2}$ percent silicon iron were annealed at 650°C in a magnetic field directed along the long axis of the strip in this field. No significant changes were observed in the permeability at various inductions or in the coercive force. But the magnetostriction as measured along the axis showed a radical change on annealing in a field. The magnetostriction curves obtained on samples treated in an identical manner but with the field not present were virtually parabolic with a magnetostriction at saturation of the order of $5\text{–}7\times10^{-6}$. In the case of the samples annealed in a field, at low inductions the magnetostriction was very small and negative and increased slowly becoming positive at approximately 11 000 gauss and reaching a maximum value of the order of 1×10^{-6} at saturation. This effect is readily understood if one assumes that the field present during annealing and cooling brings about a preferred domain orientation in which all domains tend to be oriented in the direction of easy magnetization nearest that of the field. Thus the process of magnetization takes place almost exclusively by 180° boundary displacements. Since these do not contribute to the magnetostriction, the net effect is to decrease the magnetostriction.

Whether this can result in a significant change in other magnetic properties depends on the energy required to move such a 180° boundary. In the theory of Becker and Kersten, this would depend principally upon the magnetostriction. Miss Goetz of the Bell Telephone Laboratories does, in fact, observe a large effect of a magnetic anneal on the properties of an alloy containing 6–7 percent silicon where the magnetostriction tends toward zero. We believe that this is probably the case in Permalloy as well. Thus it appears on the basis of the foregoing that the effect of the field present during annealing and cooling in determining the domain distribution is not limited to the specific compositions at which large magnetic effects are observed but is rather there at other compositions as well. Where large effects of the macroscopic magnetic properties are observed, these must be because of the fact that, where only 180° boundaries exist, the magnetoelastic energy is the principal cause of resistance to domain motion and this is minimized when the magnetostriction is zero. Such an explanation is also consistent with the sensitivity of the alloys in the Permalloy range to rate of cooling, for, as first shown by the writer,[1] the magnetostriction is very sensitive to cooling rate near the composition Ni_3Fe owing to its strong dependence on the state of the order.

[1] J. E. Goldman, Phys. Rev. **76**, 471 (1949).

J. M. HASTINGS, *Brookhaven National Laboratory, Upton, Long Island, New York:* Following a suggestion of Dr. Bozorth, based on a proposal of S. Chikazumi, we have carried out a preliminary neutron diffraction investigation of the ordering in a single crystal of 68 Permalloy. The sample, which he kindly furnished us, was carefully annealed, in the presence of a magnetic field directed along a (110) normal, from 600°C to 200°C at the rate of 2°/hour. The objective of this experiment was to see if there was any difference in the degree of ordering, as measured by the relative intensities of superlattice reflections, for directions both parallel and perpendicular to that of the magnetic field applied during the annealing.

The intensity of the superlattice lines is proportional to the square of the difference of the scattering amplitudes for iron and nickel. Unfortunately, the nuclear scattering amplitudes for these two elements differ by only 7 percent so that nuclear contribution to the superlattice reflections is small. However, there is an appreciable difference in the coherent magnetic scattering amplitudes which adds to the intensity and, therefore, enables one to perform the experiment rather readily. In order to obtain the maximum magnetic scattering, it is necessary that the atomic magnetic moments be lined up perpendicularly to the scattering vector of the particular reflection being observed. This is an important consideration for the case at hand, for the domains are all spontaneously magnetized along the (110) normal parallel to the magnetic field used in the annealing.

The integrated intensity, nuclear plus magnetic, from the set of (110) planes whose normals were along the direction of magnetic anneal was measured by applying an external field to orient the moments perpendicular to their spontaneously aligned direction. Then the external field was removed and the integrated intensity from a set of (110) planes having normals perpendicular to the direction of magnetic anneal was measured. After making an absorption correction, these two intensities were the same, and hence, to within the precision of our measurement, approximately 10 percent, there is no difference in the degree of long range order in these two directions.

E. B. STONER, *University of Leeds, England:* There are many difficulties in the way of making *a priori* calculations of the magnetization curves of polycrystalline materials. This may be illustrated by considering the three main types of elementary change in turn. (1) The change of intrinsic magnetization with field is small, but where it is usually assumed that after-effects are negligible (i.e., in high fields), the experimental variation of I with H does not agree satisfactorily with that given by any of the current theoretical treatments. This means that other factors are involved possibly connected with the effect of "small domains" or with the "fading out" of domain walls. (2) For a random aggregate of crystals free from strain, the change of magnetization with field in a reversible rotational region can in principle be calculated if the single crystal anisotropy coefficients are known. The result should apply most closely for well-annealed material. There is, however, no completely satisfactory method of taking into account the interaction between the crystal grains; the forms and the orientation distribution of the crystals are in general unknown; and the degree and character strain distortion is not known and, even if it were, the effect on the magnetic properties could not be estimated with any accuracy. It is not surprising that the agreement between calculated and observed curves is very poor except under special conditions. (3) The detailed character of the boundary movement processes depends in a complex way, via the localized disperse fields, on the detailed localized structural irregularities, caused by inclusions, holes, and strains. The detailed character of these is again not known and, even if it were, calculation of their effect would present prohibitive difficulties.

The above three types of process are superposed and since the extent to which each has taken place is determinative of the subsequent course of the changes with further change of field, it is virtually impossible to calculate magnetization curves *a priori* except over particular ranges of field for materials in a well-defined state or under special conditions (e.g., under strong tension).

It is because of these difficulties that the carrying out of supplementary measurements, magnetic and magnetothermal, and the consideration of the combined sets of results have been put forward in the paper as the only sound means at present of obtaining definite information about the character and proportions of the elementary changes occurring along any part of a magnetization curve. When the magnetization curves of a number of representative materials have been satisfactorily analyzed, it may be hoped that the general course of the changes will become much clearer quantitatively as well as qualitatively, and that the way will be opened for a more fruitful attack on the complex groups of theoretical problems involved. Reasonably accurate prediction as well as interpretation of the forms of magnetization curves may then gradually become possible.

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[1] L. R. Aronin, J. Appl. Phys. **23**, 642 (1952).

L. R. ARONIN, *Massachusetts Institute of Technology, Cambridge, Massachusetts:* Dr. Kaya has shown a two-step behavior in the order-annealing kinetics of Ni_3Fe at 580°C as compared with a simple behavior at 510°C. In this connection I should like to point out that we have recently observed,[1] through resistivity and saturation induction measurements, an anomalous kinetic behavior in Ni_3Mn which we have interpreted as indicating changes in local order accompanied by somewhat slower growth of order domain size.

Reheating at 425°C an alloy, previously cooled through the ordering range and held isothermally at 400°C and 375°C, resulted in a dip in saturation induction followed by a subsequent increase. The dip may be considered as a decrease in local order with the subsequent rise indicating antiphase domain growth. The magnitude of this reversal appears dependent on the relative extents of local order and domain size. In low temperature treatment for ordering, the value of saturation induction attainable exhibits dependence on domain growth previously obtained at higher temperatures.

G. W. RATHENAU, *N. V. Philips' Gloeilampenfabrieken, The Netherlands:* Experiments which are related to those of Dr. Kaya have been performed at Eindhoven by the late Dr. Snoek, and lately by Mr. Smit.

We have found that an alloy of the composition Ni_3Fe does not show an energy of anisotropy ($E_{\text{perpendicular}} - E_{\text{parallel}}$) to field, if, before performing the cooling in a magnetic field, the alloy has been ordered.

Some difficulties remain if one assumes that the effect of cooling in a field is to form, only along the field direction, cigar-shaped particles of ordered phase within the disordered matrix, the anisotropy of shape being the only cause of ($E_{\text{perpendicular}} - E_{\text{parallel}}$).

(1) The anisotropy of shape calculated in the extreme case that the alloy as a whole has been transformed into the cigar shaped bodies is 1000 ergs/cm_3. Experimentally more than 2000 ergs/cm_3 are found.

(2) The high initial permeability found for alloys which have been field cooled is astonishing. Why are the 180° walls not hampered in their movement by the inclusions? Is it because the diameter of these ordered particles is so small compared to the wall thickness?

(3) Anisotropy resulting from field cooling has been found to occur also with NiCo binary alloys and very strongly in FeNiCo+alloys; yet no ordering has been reported as yet for the NiCo alloys.