# Virtues and Weaknesses of the Domain Concept

WILLIAM F. BROWN, JR.
*Naval Ordnance Laboratory, Navy Yard, Washington, D. C.*

FIRST I will review the standard description of the magnetization process in terms of domains. Then I will discuss the experimental basis of the domain concept and the attempts to justify it by theory. Finally I will draw some conclusions.

## STANDARD DESCRIPTION

Figure 1 illustrates the standard description. It goes thus:[1] A ferromagnetic specimen consists of a number of small regions, each spontaneously magnetized to saturation. These regions are called "domains." In a demagnetized specimen (state 1 in the figure), the directions of magnetization of the individual domains are distributed at random among various possible directions. These directions are determined by the crystalline anisotropy; they are called "directions of easy magnetization." As the specimen is subjected to larger and larger fields, at first (state 2) the magnetization remains along directions of easy magnetization, but domains magnetized close to the field direction grow at the expense of those magnetized away from the field direction. This process corresponds to the steep part of the magnetization curve. Eventually (state 3) only the directions of easy magnetization nearest the field direction are occupied. At still higher fields (state 4), the magnetization rotates toward the field direction.

## EXPERIMENTAL BASIS

The experimental basis of the domain concept includes four separate phenomena.

First, there is the fact that magnetic specimens require a field to saturate them. The Weiss theory[2,3] says they should always be saturated. The theory is too successful in other respects to be discarded; therefore, we assume that the predicted spontaneous magnetization exists on a microscopic scale but varies in direction from one point to another, so that its macroscopic average may be small or zero. Single crystals, like ordinary specimens, can be demagnetized; therefore, the direction of magnetization presumably varies within each microcrystal of an ordinary specimen. But crystals show strong magnetic anisotropy, which favors magnetization along certain directions; therefore, we expect the direction of magnetization to remain close to one of these directions over a considerable distance, then hurry rapidly past other directions. Thus we arrive at the concept of *Weiss domains*, each saturated along a direction of easy magnetization, with rather thin transition layers or "walls" between them. The existence of such domains is not predicted by the theory; it is separately postulated to reconcile theory and experiment.

Second, there is the Barkhausen effect.[4] As a specimen traverses a hysteresis loop, irreversible changes of magnetic moment occur in discrete jumps. Apparently small regions are undergoing abrupt changes in their directions of magnetization. These *Barkhausen domains* are not necessarily identical with the Weiss domains. They may be parts of them or groups of them.

Third, there are Bitter's magnetic field patterns, formed on surfaces of specimens.[5,6] Figure 2 is an example from Elmore. There have been attempts to relate these patterns to an assumed internal magnetic structure, but no complete or unique explanation has been produced. These *Bitter domains* may be purely a surface effect.

Fourth, there are the experiments of Sixtus and Tonks.[7] In certain materials under tension, reversal of the field produces a region of reversed magnetization which grows until it engulfs the specimen. By assuming that some of the properties of these *Sixtus-Tonks domains* are possessed also by the Weiss domains, one gets a qualitative theory of the coercive force.

[1] R. Becker and W. Döring, *Ferromagnetismus* (Verlagsbuchhandlung Julius Springer, Berlin, 1939), pp. 101–112.
[2] F. Bitter, *Introduction to Ferromagnetism* (McGraw-Hill Book Company, Inc., New York, 1937), pp. 34–40, 126–143.
[3] Reference 1, pp. 25–33, 83–101.
[4] Reference 2, pp. 290–291; reference 1, pp. 176–182.
[5] Reference 2, pp. 59–66; reference 1, pp. 331–336.
[6] W. C. Elmore, Phys. Rev. **62**, 486 (1942).
[7] Reference 1, pp. 182–187; reference 2, p. 290, footnote 3.

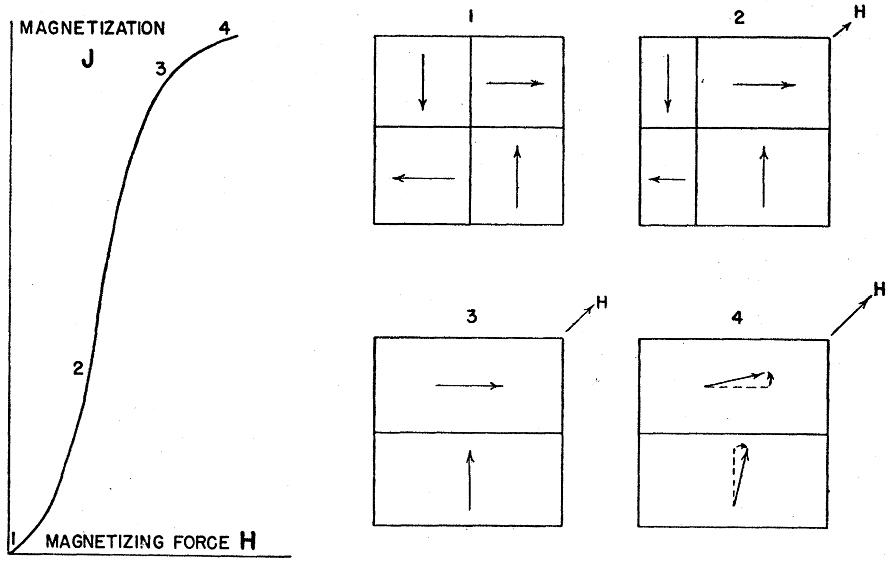


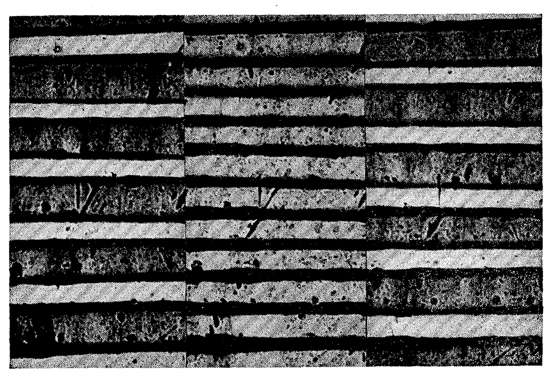

FIG. 1. Domain description of magnetization. The diagrams numbered 1, 2, 3, 4 at the right show schematically the distribution of magnetization directions of the domains and the relative sizes of the domains, with the specimen at points 1, 2, 3, 4 respectively of the magnetization curve at the left.

These four phenomena lead to four separate "domain" concepts; the relations between them are not clear. The standard domain picture is based on a sort of *all-purpose domains* that combines the properties of the other four in whatever way is convenient for calculation. It is assumed to be cubical, spherical, ellipsoidal, needle-like, or plate-like, as the theorist prefers. It undergoes changes of volume or of its direction of magnetization, whichever may be convenient. It responds to small applied fields but ignores large local fields. It responds to stresses but ignores anisotropy, or *vice versa*. This highly adaptable domain has yielded a number of formulas that can be fitted to experimental data by empirical evaluation of undetermined constants, such as the "internal stress."[8] The successes of such a model are not conclusive evidence of its correctness. For every model is subject to certain requirements of thermodynamics and symmetry, and any model that satisfies these and contains an adjustable constant has a fair chance of fitting the experimental data.

## THEORY

The vagueness of the domain concept is due to the lack of satisfactory theoretical basis for it. The existence of domains is inferred from four different sets of experimental facts which have not been clearly related to each other because nobody has explained why there should be domains at all.

In the early attempts at theory,[9] it was assumed that the domains have fixed volumes, and that they change their magnetization from one



a b c

FIG. 2. Patterns of magnetic colloid on a cobalt surface approximately perpendicular to the basal plane with applied normal field (a) outward; (b) zero; (c) inward. The lines run parallel to the hexagonal axis. Magnification approximately 65×. (From W. C. Elmore, Phys. Rev. **53**, 757 (1938); his Fig. 3, p. 759.)

[8] Reference 1, pp. 101 ff.

[9] Reference 1, pp. 216–217.

easy direction to another by rotation of the magnetization under the influence of the applied field. If this were so, the field would have to overcome the anisotropy throughout a domain in order to produce a reversal. The result is a coercive force value much too large.

Bloch[10] investigated the transition layer between two regions assumed to be magnetized along different directions of easy magnetization. He concluded that upon change of the field, this interdomain wall would be displaced. In this process only a small volume is ever magnetized in a difficult direction. Therefore, Bloch's model overcomes the coercive force difficulty. It also gives a plausible explanation of the Barkhausen process: a Barkhausen jump supposedly occurs when a wall reaches a point of instability and moves irreversibly through a finite distance. But the theory does not explain why the domains should exist in the first place.

Frenkel and Dorfman[11] attempted to explain the existence of domains as the result of a conflict between forces of two types. The first are the interatomic coupling forces responsible for spontaneous magnetization. These act only between neighboring atoms and tend to keep their moments parallel. The second are the magnetic dipole interactions. These are weaker than the other forces at short distances but more effective at large distances. They allegedly tend to produce magnetization in closed paths so as to make the pole field zero. A more detailed calculation by Landau and Lifshitz[6,12,13] takes account also of anisotropy forces. Figure 3 shows the Landau-Lifshitz model with its domains separated to make the structure clear. The specimen has a single pair of directions of easy magnetization, horizontal in the diagram. It is assumed to consist mainly of plate-like domains magnetized alternately in these two opposite directions. The surface energy of the interdomain walls is calculated by means of the Bloch theory. At the ends, poles are avoided by introducing auxiliary domains in the shape of triangular prisms; they are magnetized in difficult directions and therefore contribute anisotropy energy. Finally, the domain thickness is found which makes the total energy smallest, and this is interpreted as the actual thickness.

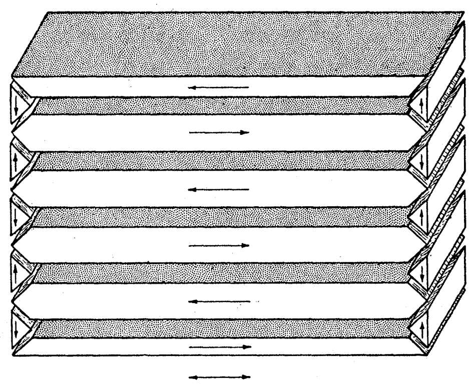



FIG. 3. Landau-Lifshitz model.

This calculation merely compares the energies of slightly different models of the same type; it does not prove that that type of model minimizes the energy. However, the fundamental assumption of the theory has not usually been questioned. That assumption is that domains originate through interplay of three types of force—the interatomic coupling forces which preserve saturation on a microscopic scale; the magnetic interactions which prevent macroscopic saturation; and the anisotropy forces which keep the magnetization in or near the easy directions except in rather thin transition layers.

To show that even that assumption is questionable, I will present a simple calculation that takes account of all these forces and yet produces no domains.

Figure 4 shows the case to be considered. The specimen is an ellipsoid with a direction of easy magnetization along a principal axis. We begin with the specimen saturated in this direction by a large applied field $H_0$. We ask: to what value may we reduce the field without causing a deviation from saturation? To answer this question, we must find the value of field for which saturation in the field direction ceases to minimize the energy. We therefore imagine the spontaneous magnetization $J_s$ to deviate slightly from the

[10] F. Bloch, Zeits. f. Physik **74**, 295 (1932); reference 1, pp. 187–192, 147–154.

[11] J. Frenkel and J. Dorfman, Nature **126**, 274 (1930).

[12] L. Landau and E. Lifshitz, Physik. Zeits. d. Sowjetunion **8**, 153 (1935).

[13] E. H. Kennard, Phys. Rev. **55**, 312 (1939).

field direction, the $z$ axis, so that its direction cosines with respect to the $x$ and $y$ axes have small values $\alpha$ and $\beta$; these may vary from one point to another. For given $H_0$, we calculate the variation of energy, due to the deviation, to the second order in small quantities and in their spatial derivatives. If this variation is positive for $\alpha$ and $\beta$ arbitrary functions of $x$, $y$, and $z$, the original direction of magnetization still minimizes the energy and no deviation from saturation will occur.

We assume only the three types of force mentioned and follow that assumption to its conclusion.

The energy variation is then given by[14]

$$W=\int\{\tfrac{1}{2}C[(\nabla\alpha)^2+(\nabla\beta)^2]+\tfrac{1}{2}[g_{11}\alpha^2+g_{22}\beta^2]$$
$$+\tfrac{1}{2}J_s[H_0-NJ_s][\alpha^2+\beta^2]\}d\tau$$
$$+\frac{1}{8\pi}\left\{\int(\nabla U)^2d\tau+\int(\nabla U')^2d\tau'\right\}.$$

Here the term in $C$ is due to interatomic coupling forces and is positive if the magnetization direction varies with position, since $C$ is positive. The terms in $g_{11}$ and $g_{22}$ are due to anisotropy; the $x$ and $y$ axes have been chosen to eliminate the $\alpha\beta$-term, and $g_{11}$ and $g_{22}$ are positive constants, since the $z$ axis is a direction of easy magnetization. The term in $H_0$ is the energy in the applied field. The remaining terms are magnetic interaction energy: $N$ is the demagnetizing factor for the $z$ direction, and $U$ and $U'$ are the magnetic scalar potentials of the transverse part of the magnetization, inside and outside the body.

The sum of the terms in $C$, $U$, and $U'$ is always positive unless $\alpha$ and $\beta$ are zero; for a constant $\alpha$ or $\beta$ different from zero produces a transverse demagnetizing field and, therefore, positive terms in $U$ and $U'$, and a variable $\alpha$ or $\beta$ produces a positive term in $C$. The sum of the terms in $\alpha^2$ and $\beta^2$ is positive unless $J_s(H_0-NJ_s)$ has a negative value numerically greater than $g_{11}$ or $g_{22}$, whichever is smaller. Therefore no deviation from saturation can occur until this negative value is reached. Now as long as the specimen

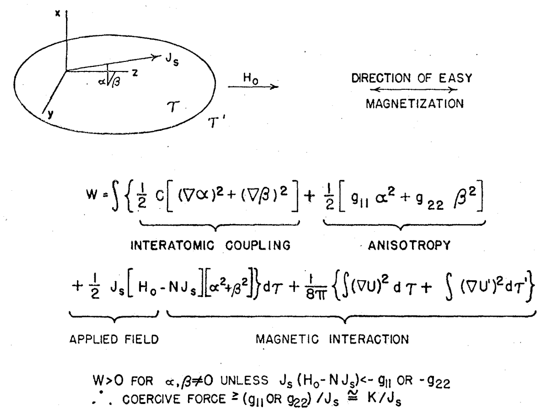



FIG. 4. Ellipsoidal crystal initially saturated along a direction of easy magnetization coincident with a principal axis of the ellipsoid.

remains saturated, $H_0-NJ_s$ is the magnetizing force $H$; therefore we conclude that the coercive force is at least as great as $(g_{11}$ or $g_{22})/J_s$. But the $g$'s are of the order of magnitude of the anisotropy constant $K$; and this coercive force value, of order $K/J_s$, is the same much-too-high value given by the early rotation theory.

Remember that the low coercive force is explained by Bloch's theory if the domains exist, but that their existence is not explained by that theory. We have attempted to explain their existence on the basis of the three types of force supposed to be responsible for them. We have taken account simultaneously of all those forces, and they have failed to produce domains in time to do any good.

It is possible, of course, that the crystals that have been measured were never really saturated, but always contained vestigial domains; and that they would indeed be found to have a high coercive force if they were initially subjected to a field of, say, 100 kilogausses—large enough to overcome any possible internal magnetic fields.

If this is not the explanation, then something else besides the forces so far considered is necessary to explain the origin of domains.

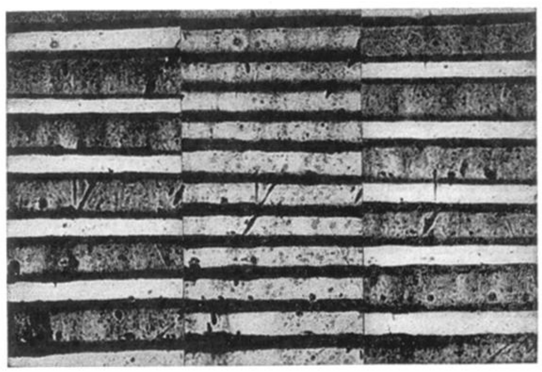
## CONCLUSIONS

The present domain picture is undoubtedly useful, but its usefulness is limited because it is not precise. Its lack of precision is a consequence of the lack of a precise theoretical basis for it. Until this defect is remedied, detailed calcula-

[14] Cf. W. F. Brown, Jr., Phys. Rev. 58, 736 (1940).

tions and analyses based on it are of doubtful value. I think theoretical and experimental effort should be directed, instead, toward improving our understanding of the factors that determine the microscopic distribution of magnetization.

One becomes particularly conscious of the limitations of the domain picture when one attempts, by means of it, to answer such questions as the following: in demagnetizing a specimen by reversals, how large an initial field must be used and how closely spaced must the steps be to insure that all effects of previous history are removed? The guidance afforded by the domain concept is negligible; to find an answer, one must resort to laborious experimentation on each individual material. A model capable of providing even an approximate answer would be of great practical value.



a b c

FIG. 2. Patterns of magnetic colloid on a cobalt surface approximately perpendicular to the basal plane with applied normal field (a) outward; (b) zero; (c) inward. The lines run parallel to the hexagonal axis. Magnification approximately 65×. (From W. C. Elmore, Phys. Rev. **53**, 757 (1938); his Fig. 3, p. 759.)