ELEMENTS OF MAGNETIC TAPE RECORDING

N. M. Haynes

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PREFACE

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PART ONE

INTRODUCTION

chapter 1

THEORY OF MAGNETISM

EVERY INVESTIGATOR IN ANY OF THE PHYSICAL SCIENCES ultimately finds himself on the frontiers of knowledge, facing into an unknown abyss as he tries to fathom the ultimate reality of nature. The nature of magnetism is no exception, for scientists delving into the very essence of its substance are faced with many enigmatic facets. In fact, the confirmation of what an elementary magnet really is still constitutes a fundamental problem in magnetic research.

THE BASIS OF MAGNETISM

For a fundamental understanding of the essence of magnetism in accordance with modern theories, concepts of spinning electrons in discrete orbits (resembling elements of our solar system) are necessary. In addition, contributory explanations involve group behavior of molecular masses, called "domains," and intercrystalline forces.

The idea of molecular magnets stems back to Ampère, who more than a hundred years ago indicated how circulating currents within molecules accounted for their magnetic behavior. Recently however, physicists probing the structure of the atom, have been able to conjecture about the mechanism which gives atoms their magnetic properties. These explanations involve the number of electrons in an atom, their relative orbital placement, and direction of spin.

In fact, further probing into the nucleus of the atom has opened a new field of "nuclear magnetism" which deals with the magnetic properties of a spinning nucleus whose size is about one-thousandth of an atom.[1]

Crystal Lattice Structure

Ferromagnetic materials are all crystalline substances and each elemental crystal has a unique and orderly arrangement of atoms. The precise pattern of arrangement repeats itself periodically in three dimensions. The structural arrangement of the elemental pattern is called the unit cell of the crystal lattice. Iron and ferrous alloys have a cubic unit cell with atoms in each of the corners and one in the center as diagrammed in Figures 1-1 and 1-2. This cubic structure has three principal axes: (1) along the cubic edge designated 100,* (2) along the cubic face diagonal 110, and (3) the axis in the direction of the diagonal through the body 111. As all of the atoms in the unit are miniature magnets it is to be expected that they will influence each other (just as a group of bar magnets would if they

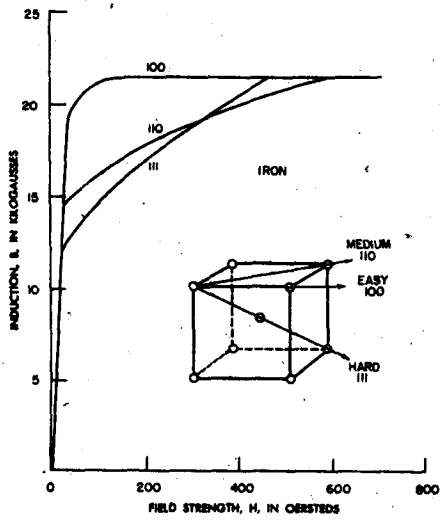

Fig. 1-1. Lattice structure of iron and its magnetic axes which vary in ease of magnetization.

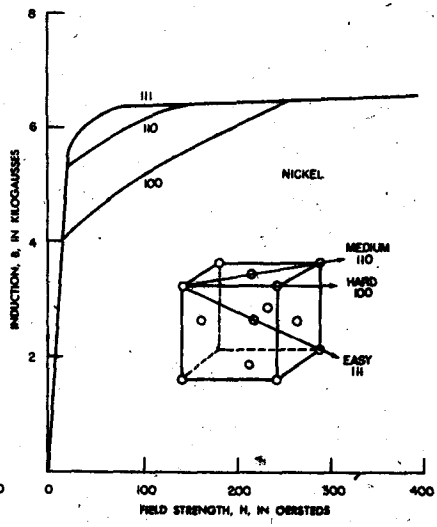

Fig. 1-2. Comparable lattice structure of nickel and its characteristic magnetic anisotropy.

* Axes of cube crystals are designated by the Miller index, which is extensively used in crystallography. Each index denotes coordinates in a Cartesian system formed by the three edges of the cube. The shorthand notation of 100 designates $X_1 = 1$, $Y_1 = 0$, $Z_1 = 0$. The direction 110 refers to $X_1 = 1$, $Y_1 = 1$, and $Z_1 = 0$.

were similarly arranged) and because of this intracellular interaction some of the atoms will be influenced more readily by one directional magnetic field than others. As a result, the crystalline structure will exhibit a directional non-uniformity of magnetic property. The behavior favoring one crystallographic direction over another is called *magnetic anisotropy*.

Grain Orientation

Single crystals of pure iron are most easily magnetized along the 100 axis, and are a little more difficult to magnetize along the 110 axis and most difficult to magnetize along the 111 axis as is illustrated in Figure 1-1.

Many of the magnetic materials used in the manufacture of tape coatings, as well as some used in the production of the core structure of record and playback heads, exhibit magnetic anisotropy. Full advantage of these properties is taken in the orientation of the magnetic particles in the tape coating by applying a longitudinal magnetic field to the suspension of magnetic particles after its application to the tape but before the binder dries. This gives the magnetic particles an opportunity to align themselves so that the most responsive crystallographic axis lies in the direction of subsequent magnetization during recording. Advantages of particle orientation in tape coating include: a marked increase in sensitivity, lowered random noise, and decreased distortion at low signal level.

The Domain Theory

A multiplicity of exchange forces between atoms serves to align the axes of adjacent spinning electrons. Although these alignments usually extend over appreciable atomic areas of the specimen, the actual volume of alignment is limited. Each of the relatively small aligned volumes is called a *domain*. All appreciably-sized ferromagnetic materials contain thousands of domains, each of which is spontaneously magnetized to saturation in some direction. As the random orientation of domains in an unmagnetized specimen neutralize each other, the overall magnetic effect is nullified.

Domain Shapes.[2] Four possible domain structures of a single crystal are illustrated in Figure 1-3. The single domain of A exhibits a strong magnetization because of its two unneutralized poles. The structure of B illustrates the arrangement assumed by four domains with eight poles and three separations (walls). As the pole arrange-

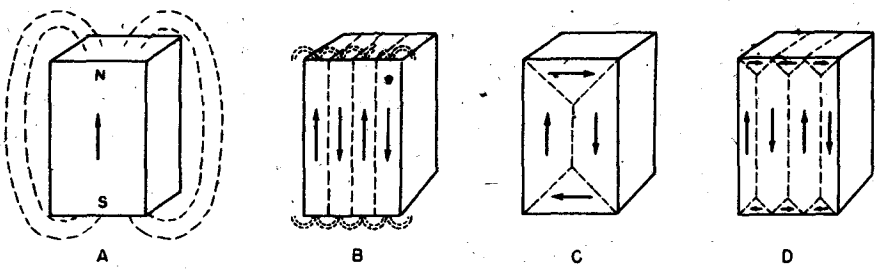

Fig. 1-3. Typical domain shapes showing characteristic internal magnetic structure. (*From Harvey, Hegi, and Leverenz.*)

ment of each domain virtually neutralizes the adjacent domains, the segment as a whole exhibits weak external magnetization. Another variation of the four-domain structure is shown in C wherein the domains are effectively rotationally disposed about an imaginary center. This structure does not exhibit external magnetism because of the complete neutralization of each domain. Still another variation of domain structure is shown in D wherein ten domains are abutted with fifteen walls to effectively internally neutralize all poles so that no net external magnetic phenomenon exists.

The Bloch Wall.[3] The separation or transition layer, between adjacent domains, is named after F. Bloch who first studied the nature of the change in spin direction between magnetized domains as illustrated in Figure 1-4. Of particular importance to magnetic recording is that the change of spin direction in iron is spread over the space occupied by approximately one thousand atoms or about 1/10,000 of an inch. If a continuous series of such transitions occurs a complete cycle or reversal would occupy 2/10,000 of an inch, permitting five thousand reversals in one inch which would be indicative of the highest frequency that can be recorded on tape at a given tape speed.*

Changes in Domain Shape

Domain shapes may be studied by visible powder patterns produced when their external fields act on a coating of colloidal magnetite in a liquid suspension. As the colloidal particles concentrate at or near domain boundaries the lines of concentration indicate the terminal outlines of adjacent domains.

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* For the data given, 5,000 cycles per second can be recorded at a tape speed of one inch per second.

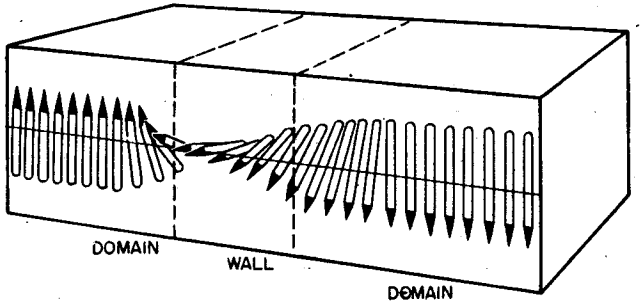
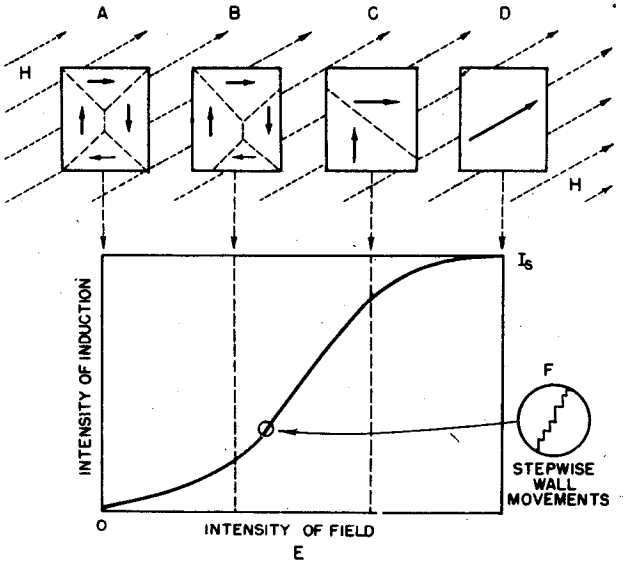


Fig. 1-4. The wall structure between domains does not occur in one discontinuous jump but takes place in a gradual manner. (*From Kittel.*)

When a multidomain crystal structure of Figure 1-5A is placed under the influence of an external magnetic field H of controllable intensity, some domains will grow at the expense of the adjacent domains which oppose the applied field as diagrammed in Figure 1-5B. Any form of mild agitation, thermal* or magnetic at an ultra-

Fig. 1-5. Successive stages in the magnetization of a four-domain crystal. (*From Harvey, Hegi, and Leverenz*).



* When the thermal agitation energy equals or exceeds the exchange energy, the alignment of atomic magnets is destroyed and the material ceases to exhibit ferromagnetism. This phenomenon usually occurs at a discrete temperature (Curie point) for each type of magnetic material and ranges from 318° C for nickel through 770° C for iron to 1,130° C for cobalt. Oxides of iron used in tape coatings have Curie points ranging between 500° to 700° C. Therefore, usual climatic temperatures have little or no effect on the permanency of magnetic recording.

sonic* rate, will favor wall displacement instead of disorientation within domains.

Weak external fields produce small interdomain wall displacements which are reversible spontaneously.[2] (Initial domain shape returns when the weak field is removed.) As the field strength is increased, larger and larger wall displacements occur with increased difficulty. These wall movements are not easily reversible and are discontinuously produced in small steps. Domains of this type are shown in Figure 1-5C. The stepwise wall movements produce an irregularity in the intensity of induced magnetization while the material is being magnetized under the influence of a gradually increasing external magnetic field as plotted in Figure 1-5E. The magnified magnetization curve shown in the enlargement of Figure 1-5F discloses the erratic magnetic realignment of domain volumes and is called the *Barkhausen effect.*† The application of a still stronger external magnetic field rotates the spin orientation away from the preferred crystallographic directions until all domain spins are parallel to the applied field. This condition represents saturation, as shown in Figure 1-5D.

CLASSIFICATION OF MAGNETIC BEHAVIOR

In order to classify materials as magnetic or non-magnetic, the behavior of a vacuum is used as the dividing line. The influence of a magnetic field upon any material in relation to the same field in a vacuum determines its broad grouping. Thus, if a bar suspended in a field tends to align its longest dimension along the direction of the field it is said to be *paramagnetic;* whereas, if it tends to align its shortest dimension in the direction of the field it is called *diamagnetic.* A qualitative measurement for differentiating paramagnetic and diamagnetic materials involves the use of terms like "permeability" and "susceptibility" which are described in detail in the following chapter.

Permeability may be thought of as the ability of a substance to concentrate, contribute to, or conduct a magnetic field. If the permeability of a vacuum is assumed to be unity, materials having per-

* This phenomenon explains the basic reason for the use of ultrasonic bias and erase currents in magnetic recording which are described in detail in Chapters 7 and 9.

† The stepwise motion is attributed to scattered impurity atoms and other localized structural imperfections which increase the activation energy required to move the wall.

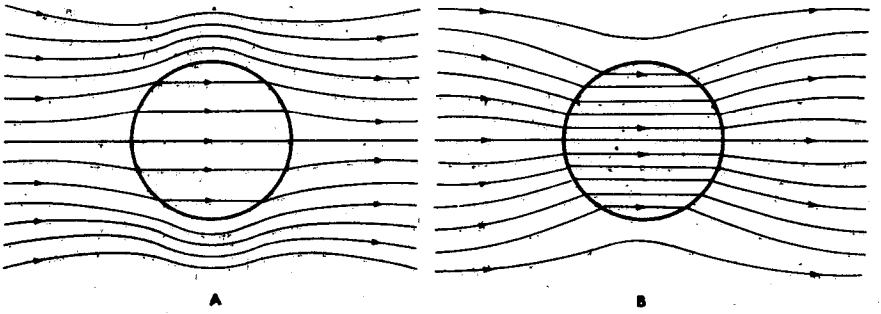


Fig. 1-6. Effect of placing a diamagnetic (A), and a paramagnetic (B), solid in a uniform magnetic field. (*From Williams.*)

meabilities less than unity are classified as diamagnetic; and conversely, materials with permeabilities above unity are classified as paramagnetic. Because of the wide range of permeabilities and behavior of paramagnetic materials, this class is further subdivided into three subclasses: (1) ferromagnetic, (2) antiferromagnetic, and (3) ferrite-ferromagnetic.

Diamagnetism

As indicated, the permeability of diamagnetic substances is less than unity and—strangely—the most diamagnetic material known (bismuth) is imperceptibly less than unity (0.99983). Water is similarly diamagnetic with a permeability of 0.99999. Basically, diamagnetism reduces the intensity of the field within which it is placed.[4] For example, if a diamagnetic rod of bismuth is placed in a uniform field, the field redistributes itself as illustrated in Figure 1-6A. If a diamagnetic liquid, in a container, is placed at the pole pieces of a strong magnet the liquid would tend to flow away from the field as shown in Figure 1-7A.

Fig. 1-7. Effect of placing a diamagnetic (A), and a paramagnetic (B), liquid into an intense magnetic field. (*From Williams.*)