

CHAPTER I

INTRODUCTION

1.1. The domain hypothesis

The outstanding property of ferromagnetic materials is the ease with which their intensity of magnetization can be varied. There is abundant evidence that the source of their magnetism is the same as in paramagnetic substances, namely, the magnetic moment possessed by certain electrons of the material by virtue of their spin or orbital momentum. In paramagnetics, however, the directions of these moments are arranged at random, so that no magnetization can be detected on a macroscopic scale. In order to produce a measurable magnetization the elementary moments have to be aligned more or less in the same direction, despite the effects of thermal agitation. Theory and experiment agree in showing that very large magnetic fields ($\sim 10^6$ oersted) are needed if the state of perfect alignment, with the macroscopic magnetic moment equal to the sum of the elementary moments, is to be approached at room temperatures.

In ferromagnetics, on the other hand, a marked degree of alignment is somehow achieved in very much smaller fields (~ 100 oersted) and may even persist in the absence of any field at all. The fundamental problem of ferromagnetism is to explain why the elementary moments of a ferromagnetic can be aligned so much more easily than those of a paramagnetic. The first satisfactory explanation, which has been the basis of all later theories, was put forward by Weiss in 1907. He suggested that there were forces of interaction between the elementary magnetic moments, tending to make each one parallel to its neighbours. It is clear that such forces would cause all the moments to be aligned in the same direction at the absolute zero of temperature, and it can be shown that this ordering of the moments will continue when the temperature is raised, though with increasing deviations from perfect alignment, until a critical temperature is reached, above which the moments are arranged at random, as in a paramagnetic.

Weiss's theory can thus account for the fact that ferromagnetic materials may be spontaneously magnetized even in the absence of any external magnetic field; it does not, by itself, explain why the majority of ferromagnetics are not actually found in this spontaneously magnetized state, but are much more likely to have approximately zero magnetization. Weiss met this difficulty by introducing the secondary hypothesis of division into domains. He supposed that the forces of interaction only maintained the parallel alignment of the elementary moments over fairly small regions, while over longer distances it was relatively easy for the direction of alignment to change.

Weiss thus pictured a ferromagnetic material as containing a large number of 'domains' with the magnetization held constant in magnitude and direction by the interaction forces within each domain, but varying in direction from one domain to another. In this way a distinction can be made between the 'micromagnetization', or 'intrinsic magnetization', whose magnitude must everywhere be equal to the value given for the spontaneous magnetization by the interaction theory, and the 'macromagnetization', which is equal to the vector sum of the micromagnetization of all the domains and can therefore have any value from zero (when as many domains have their magnetization in one direction as in the opposite direction) to a saturation value equal to the spontaneous micromagnetization (when all domains are magnetized in the same direction). Changes in the ordinary macromagnetization are to be thought of as the result of changes in the directions of domain micromagnetizations, their magnitude remaining constant.

The domain hypothesis simplifies the problems of ferromagnetism by separating them into two almost independent parts. The first, and more fundamental, is concerned with the magnitude of the spontaneous micromagnetization; the second is concerned with its direction and the variation of this direction from place to place in a material.

This book is concerned with the second set of problems, and for the most part the magnitude of the spontaneous magnetization is accepted as a fixed quantity, without inquiry into its origin. A very brief summary of the main facts and theories will, however, be given here.

1.2. The spontaneous magnetization

The spontaneous magnetization, I_s , is the magnetization that would be observed in the absence of a magnetic field if none of the various secondary effects we shall be considering later intervened and caused the material to split up into domains with differing directions of magnetization. In practice these secondary effects always occur, and we can only observe and measure the spontaneous magnetization by applying a magnetic field strong enough to override them and cause all domain magnetizations to lie in the same direction. The spontaneous magnetization measured in this way differs slightly from the true value because the field required to align the domains will itself increase the magnetization of each domain to some extent. However, this effect is nearly always small and can be allowed for by suitable extrapolation.

The measured values of I_s are different for the different ferromagnetic metals and alloys and vary markedly with temperature for each material. The form of the temperature variation is, however, nearly the same for all materials and the results for nickel shown in fig. 1 are typical. Weiss showed that this was just the type of curve to be expected if the spontaneous magnetization was due to the interaction mechanism already indicated. He assumed that the interaction forces between the elementary magnetic moments could be represented by a field acting on each of the moments, the direction of this 'internal' or 'molecular' field being parallel to the mean magnetization and its strength proportional to the intensity of the magnetization. With this representation of the interaction forces the statistical equilibrium of an assembly of elementary moments at any given temperature can be calculated, and it is found that below a certain critical temperature (the 'Curie temperature') the assembly will be spontaneously magnetized, the intensity of magnetization varying with temperature as shown by the full curve in fig. 1. The agreement between the experimental points and the theoretical curve, calculated from such simple assumptions, is very striking. There are, moreover, various other phenomena, such as the variation of susceptibility with temperature above the Curie point and the anomaly of specific heat at the Curie point which fit into the molecular field treatment.

When the theory was first put forward, no satisfactory explanation could be given of the origin of the interaction forces producing the molecular field. There is, of course, a magnetic interaction between any two magnetic moments, but the internal field produced by this effect is only of the order of $\frac{4}{3}\pi I$, while the value required to give the curve of fig. 1 is nearly a thousand times larger. The mechanism of the interaction remained a mystery until 1928,

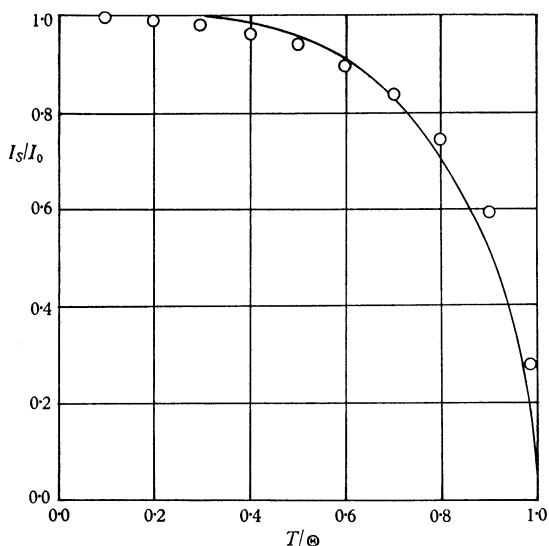


Fig. 1. Variation of spontaneous magnetization, I_s , with temperature, T . I_0 = value of I_s at absolute zero, Θ = Curie temperature. Circles show experimental values obtained by Weiss and Forrer (1926); curve obtained from Weiss's theory, modified by quantum-mechanical considerations. (See Stoner, 1948, eq. (2.11).)

when Heisenberg showed that according to the quantum theory there should be 'exchange interaction' between the different atoms that could give effects of the required type and magnitude. The Weiss molecular field theory, with quantum exchange forces as the source of the interactions, thus provides an explanation of ferromagnetism which is satisfactory in broad outline, but a more detailed examination reveals many serious discrepancies between theory and experiment, discrepancies which are often increased rather than diminished by elaboration of the theory or increased accuracy in experiment. The problem of the spontaneous magneti-

zation is therefore by no means completely solved; the state of the theory has been reviewed recently by Stoner (1948) and by van Vleck (1945).

It has recently been shown (Néel, 1948*c*) that spontaneous magnetization may arise not only through positive interactions, i.e. ones tending to make neighbouring elementary moments parallel to each other, but also through negative interactions, tending to make neighbouring moments antiparallel. In a simple cubic lattice such interactions would, of course, lead to exact compensation between neighbouring antiparallel moments and so to zero spontaneous magnetization, but in more complicated lattices the attempt to make each moment antiparallel to as many as possible of its neighbours can sometimes lead to an uncompensated residue of moments all pointing in the same direction and so producing a spontaneous magnetization. It appears that the magnetism of many oxides and, in particular, of the ferrites ($\text{Fe}_2\text{O}_3 \cdot \text{MO}$, where M is a bivalent metallic ion) is of this type, to which Néel gives the name 'ferrimagnetism'. Although the source of the spontaneous magnetization may be different, the considerations affecting the occurrence and behaviour of domains in these materials must be the same as those in ordinary ferromagnetic metals and alloys.

1.3. The directions of domain magnetizations

In most ferromagnetics the molecular field at temperatures well below their Curie temperatures is so large ($\sim 10^7$ oersteds for iron) compared with experimentally available magnetic fields that the magnitude of the spontaneous magnetization can be treated as independent of applied fields and dependent only on the temperature and composition of the material. All ordinary changes of magnetization and their related effects must therefore be explained in terms of changes of the direction of the spontaneous magnetization. According to the domain hypothesis this direction is not constant within the material, but varies from one domain to another. If the changes of direction were slow and gradual, then there would be no clear distinction between one domain and another and the idea of domains would not be a useful basis on which to discuss the properties of ferromagnetics. It turns out, however, that in most

substances there is a strong tendency for the intrinsic magnetization to lie in one of a small number of directions (called 'easy' or 'preferred' directions), so that each domain is magnetized in one or other of these directions and separated from domains magnetized in different easy directions by relatively small transition zones where the magnetization is changing from one easy direction to the other. The width of these transition zones, the 'domain walls', will be calculated in Chapter V. It is often of the order of 1000 atom diameters (10^{-5} cm.), whereas the width of the domains themselves may be 100,000 or more atom diameters (10^{-3} cm.). The idea of domains as well-defined regions with an almost constant direction of magnetization is thus a valid one for many materials. Exceptions, where the domain walls are very broad, may occur, but they can best be dealt with after considering the simpler cases with narrow walls.

The concept of domains was originally a somewhat vague hypothesis, introduced to account for the difference between the theoretical intrinsic magnetization and the macromagnetization that was actually observed. The only property of domains was that they should be large enough to contain many atoms each, and small enough for all magnetic measurements to represent mean values over many domains. As knowledge of ferromagnetics has increased, more and more facts have been interpreted in terms of domains, so that the idea of domains has gradually become more definite. Recent theoretical work by Néel (1944*a*) and experiments by Williams, Bozorth and Shockley (1949) make it possible to say exactly what the size and shape of the domains are in certain materials, and even to follow in detail the changes in domain arrangements when the magnetization is changed. It is therefore possible to use the hypothesis of domains with confidence and to assume that in the laws governing their behaviour lie the clues to most of the phenomena of magnetization in low and moderate fields.

In an ordinary ferromagnetic material the domains are arranged in a complicated three-dimensional pattern, an equilibrium state determined by the action and interaction of many different forces. It is confusing to study the nature and mode of action of these forces in the common complicated cases, and we shall therefore, as

far as possible, try to deal with simple cases where as few variables as possible have to be considered. Such cases can only be chosen if we have some knowledge of the types of forces that have to be taken into account, and we shall therefore give a brief, general survey of the factors determining domain arrangements, before considering the separate factors in more detail in later chapters. For some purposes it is convenient to discuss the equilibrium conditions in terms of the forces acting on the magnetizations of the domains, but more often it is simpler to discuss the contribution these forces make to the energy of the system and to find the equilibrium state by finding the conditions to make the energy a minimum. Our aim is therefore to find expressions for all those terms in the energy of a ferromagnetic which depend on the directions of magnetization of its domains. Such direction-dependent terms must arise from anisotropy either in the material itself or in the external influences acting on it. Internal anisotropies can be divided into natural anisotropy, which is due to the crystalline nature of the material, and imposed anisotropy, which is due to stresses of one sort or another which deform the crystal lattice. The chief external directional influence is that of magnetic fields, though in many cases the actual shape of the magnetic specimen also plays an important role, through the demagnetizing field it creates.

1.4. Magnetic field

The action of a magnetic field, H , on a domain magnetized to an intensity I_s in a direction making an angle θ with the field is simply to exert a couple $I_s H \sin \theta$ per unit volume on it, tending to turn the magnetization into the field direction. The corresponding contribution to the energy of the system is $-I_s H \cos \theta$. The field H in these expressions is, of course, the field actually acting on the domain; it may differ considerably from the applied external field, H_e , first because of the demagnetizing field of the specimen as a whole, secondly because of the local demagnetizing field depending on conditions at the domain boundary. We shall see later that these differences are often very important, but for the present they need not be considered.

1.5. Magnetocrystalline anisotropy

If magnetization curves (I against H) are measured for single crystals of a ferromagnetic it is found that much smaller fields are needed to magnetize the crystal in some directions (the easy directions) than in others; magnetization curves measured along the three principal crystallographic axes of an iron crystal are shown in fig. 2. On the domain hypothesis this is to be inter-

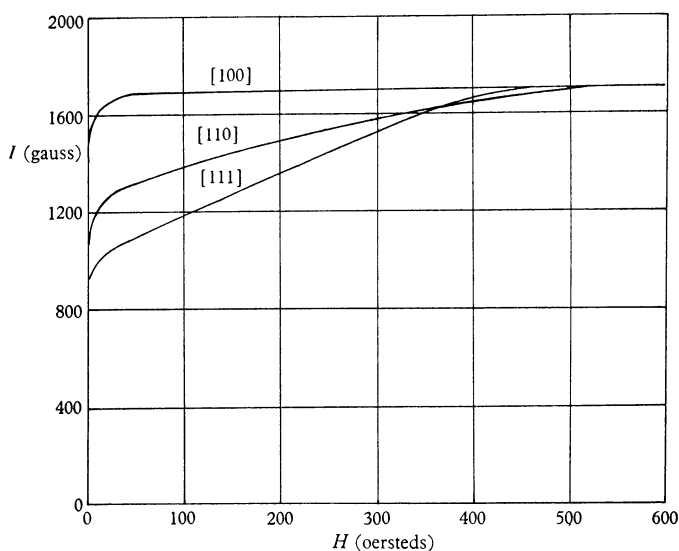


Fig. 2. Magnetization curves for the three principal axes of iron single crystals. Data from Honda and Kaya (1926).

preted as showing that there are forces tending to turn the domain magnetizations into these easy directions; or, using the energy concept, we can say that the energy of the system depends on the direction of magnetization relative to the crystal axes and that this 'magnetocrystalline' component of energy is a minimum when the magnetization lies along an easy direction. In iron there are six easy directions (counting positive and negative ones separately), those parallel to the edges of the cubic lattice. The Miller indices of these directions are $[\pm 100]$, $[0 \pm 10]$ and $[00 \pm 1]$; it is often convenient to refer to them collectively as 'the $[100]$ directions'. In nickel, which also has a cubic lattice, the $[100]$ directions are

directions of maximum magnetocrystalline energy, and the easy directions are the eight body-diagonals, the $[111]$ directions. Cobalt is hexagonal in structure and has two easy directions, along its principal axis ($[0001]$ axis). The magnitude of the magnetocrystalline energy also varies from one material to another. In nickel it is of the order of 5×10^4 ergs/c.c., in iron 4×10^5 ergs/c.c. and in cobalt 5×10^6 ergs/c.c. More exact definitions and values of the magnetocrystalline energy will be given in the next chapter, where its effects are considered in detail.

1.6. Stress anisotropy

There are many materials which are approximately magnetically isotropic, either because their magnetocrystalline anisotropy is small or because they consist of many small crystals oriented at random. If, however, a stress is applied to such a material, it usually becomes anisotropic and harder to magnetize in some directions than in others. This shows that stress can produce forces affecting the directions of domain magnetization or, in other words, add to the expression for the energy of the domains terms depending on the direction of their magnetization relative to the stress directions. If, for example, a nickel wire magnetized nearly to saturation (fig. 3*a*) is subjected to tension, the magnetization is found to decrease considerably, showing that the domains have turned away from the axis of the wire (fig. 3*b*). In nickel under tension there is therefore a couple tending to turn the magnetization away from the axis of tension and consequently a stress-energy term depending on the direction of magnetization relative to that of tension and having its maximum value when the magnetization is parallel to the tension.

These effects are clearly connected with magnetostriction, the changes in dimensions accompanying changes in magnetization. Since the magnetization of nickel is diminished by tension, we can infer that an increase in magnetization will reduce the length, as is actually observed. The stress-energy term in the expression for domain energy, in fact, represents the work done against the stress by the magnetostrictive change in dimensions accompanying rotation of the domain magnetization. It is of order $\lambda\sigma$ per unit volume, where λ is the magnetostrictive coefficient (the fractional

change in length on magnetization to saturation) and σ is the stress. λ may be negative, as in nickel, or positive, as in iron, and is not necessarily the same for all directions in a crystal.

1.7. Reasons for the occurrence of domains

In a homogeneous material subject to a uniform stress and a uniform magnetic field the three effects just considered would determine the direction of its magnetization; this direction would, however, be the same at all points in the material, so that no division into distinct domains would occur. It was originally thought that the existence of domains depended on microscopic irregulari-

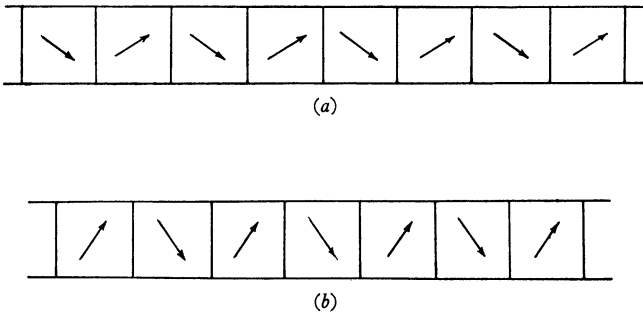


Fig. 3. Arrangement of domains in a nickel wire (schematic). (a) Moderate magnetic field acting from left to right; no stress. (b) Same magnetic field; tension applied longitudinally to wire.

ties in the crystal structure, causing the equilibrium direction of magnetization to vary from place to place, but it gradually became clear that in most cases such irregularities could play only a secondary part in the creation of domains. A more fundamental reason for their existence, even in ideally regular crystals, was pointed out by Landau and Lifshitz (1935). Any finite specimen magnetized in the same direction throughout is subject to a demagnetizing field, which can attain considerable values. A sphere of iron, for example, uniformly magnetized (fig. 4a) to its spontaneous magnetization value, I_s ($= 1720$ gauss), produces a uniform demagnetizing field of $\frac{4}{3}\pi I_s$ (about 7000 oersteds), tending to turn the magnetization into the opposite direction. This field is far larger than that required to overcome any magnetocrystalline or magnetostrictive effects which might be holding the magnetization