# Chapter 3
# Ferromagnetic Materials

**Abstract** Ferromagnetic properties of materials exert a profound influence upon EC NDE. Successful interpretation of EC measurements on many steels or other types of ferromagnetic conductor requires an understanding of the magnetization (and demagnetization) processes that occur in ferromagnetic materials. This chapter builds upon the role of electric current as the fundamental source of the magnetic field to explain the phenomenon of magnetization, to describe hysteresis, and to show the nonlinear character of permeability. Energy arguments are invoked to explain the existence of ferromagnetic domains and domain processes are described. Methods of demagnetizing test-pieces to regularize them for EC inspection are suggested. Description of the role of low-conductivity ferromagnetic ceramics (ferrite cores) in EC coil construction is described in Chap. 6, Signals and Coils.

## 3.1 Introduction

Ferromagnets are materials that become strongly magnetized in response to an applied magnetic field, even retaining some magnetization when the applied magnetic field is removed. A naturally occurring ferromagnetic material is magnetite or lodestone, $Fe_3O_4$. Early records speak of a spoon-shaped compass formed from magnetite being used in Chinese ceremonies of the second century BCE. By the time of the seventh and eighth centuries CE, magnetized iron needles were being used by Chinese navigators; either floating in water in the form of a "wet" compass, placed on a pointed shaft as a "dry" compass, or suspended from a silk thread.

Elements of the periodic table that are ferromagnetic at room temperature are iron (Fe), nickel (Ni), and cobalt (Co). Their alloys and compounds are also often ferromagnetic. Some compounds, known as ferrites, are low-conductivity ferromagnetic materials. MnZn ferrite and its practical role in the construction of EC probe cores is discussed in Sect. 6.3.5 of this text.

In the context of EC NDE, ferromagnetic materials constitute a distinct material class because the EC probe impedance signal due to a ferromagnetic test-piece may be very different from that due to a non-ferromagnetic test-piece with the same conductivity. Recalling the normalized impedance-plane plot of Fig. 6.3, the reactance

N. Bowler, *Eddy-Current Nondestructive Evaluation*,
Springer Series in Measurement Science and Technology,
https://doi.org/10.1007/978-1-4939-9629-2_3

of the coil is reduced as it is brought near to the surface of a non-ferromagnetic test-piece (dashed lines). If the test-piece is ferromagnetic, however, the coil reactance may increase, as shown by the dotted lines. Most commonly, the ferromagnetic test-pieces encountered in EC NDE are *steels*, which are alloys of iron.

This chapter expands greatly on the brief introduction to permeability and magnetic induction given in Sect. 2.8 of this text. Nonetheless, even here I shall skim lightly over the deep and complicated topic of ferromagnetism. For a more detailed treatment, the interested reader is referred to Jiles' comprehensive yet accessible text [1] or to Cullity's classical work [2].

## 3.2 Fundamental Source of the Magnetic Field

Consider the schematic diagram of a bar magnet shown in Fig. 3.1. Such a magnet could be made from any ferromagnetic material. It is common knowledge that two such magnets, if their ends are brought together, will either repel or attract each other. Whether or not the force between the magnets is repulsive or attractive depends on the *polarity* of the magnets or the relative orientation of their *magnetic dipole moments*.

The magnetic dipole moment $\mathbf{m}$ of a bar magnet like the one depicted in Fig. 3.1 can be expressed

$$\mathbf{m} = P\,\mathbf{d} \tag{3.1}$$

where $P$ is the pole strength and $\mathbf{d}$ is the vector length between the poles. $\mathbf{m}$ is directed from S toward N. This definition is analogous to that of the electrostatic dipole given in (2.30). By analogy with electrostatics, the definition in (3.1) suggests the existence of a magnetic monopole as the fundamental source of the magnetic field and leads to speculation that the magnetic monopole might play a role in magnetostatics that is similar to that of the electric charge in electrostatics. In fact, expression (3.1) is of limited use. The notion of magnetic poles remains popular in everyday thinking, and may be used to describe the interactions of long, thin bar magnets whose poles

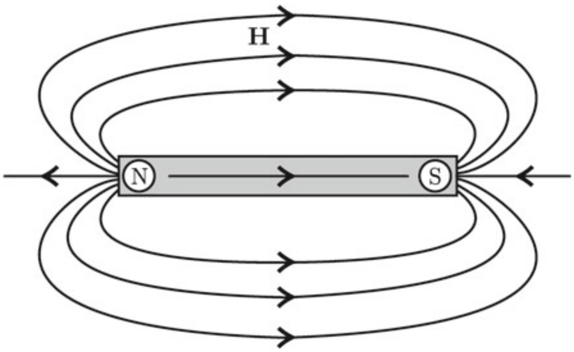


**Fig. 3.1** By convention, the lines of magnetic field **H** originate at the north pole (N) and terminate at the south pole (S) of a simple bar magnet

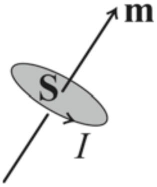


**Fig. 3.2** Magnetic dipole moment **m** of a loop formed by current *I*

are well separated, but scientifically it is held that magnetic monopoles do not exist. One simple experiment that immediately shows a difficulty with the notion of the magnetic monopole is the following. If you try to isolate one pole of a bar magnet by, say, dividing the magnet in half, then immediately new poles are formed at the surface of division. Each half of the original magnet forms a new magnetic dipole with its own N and S poles.

What, then, is the fundamental source of the magnetic field? During the course of Ampère's experiments on electricity and magnetism, he discovered that the magnetic field of a small current loop is identical to that of a small bar magnet. This observation led Ampère to hypothesize that *all* magnetic effects are due to current loops, and that the magnetic effects in ferromagnetic materials such as iron are due to so-called *molecular currents*. These currents are now known to be quantum mechanical in origin, due to the orbital and spin angular momenta of atomic electrons. Ampère's insight was especially remarkable because it predated the discovery of the electron by about 100 years!

We are led to deduce, therefore, that the fundamental source of the magnetic field is not a magnetic monopole, but the motion of electrical charge or, equivalently, electric current. The magnetic dipole moment of a current loop, **m**, is defined to be the product of the current flowing in the loop, $I$, and the vector area of the loop, **S**;

$$\mathbf{m} = I\mathbf{S}. \tag{3.2}$$

This is shown schematically in Fig. 3.2. The units of **m** are Ampère-meter-squared (Am$^2$).

## 3.3 Magnetization

The application of a magnetic field **H** to a ferromagnetic material results in magnetization **M** (with SI unit A/m) of that material. Magnetization was introduced in Sect. 2.8 of this text. In fact, the application of a magnetic field to any material gives rise to a magnetization

$$\mathbf{M} = \chi\mathbf{H}, \tag{3.3}$$

where $\chi$ is the magnetic susceptibility of the material (dimensionless). There are several classes of magnetic material, but in ferromagnets (e.g., iron, cobalt, nickel,

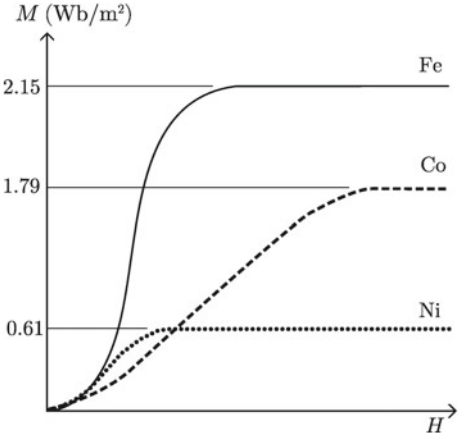


**Fig. 3.3** Initial magnetization curves for several ferromagnetic metals. Note that the units of M differ between Fig. 3.3 and Table 3.1 by the factor $\mu_0$

and their alloys) $\chi$ is positive, relatively large, and nonlinear, so that

$$\mathbf{M}(H) = \chi(H)\mathbf{H}. \tag{3.4}$$

One of the puzzles of ferromagnetism, eventually explained by domain theory (Sect. 3.6), was the very large magnetization that can occur on the application of a relatively small magnetic field. In fact, the resulting **M** can be of the order of a thousand times larger than the field of **H** applied to produce it!

The *initial magnetization curve* is the nonlinear response of a ferromagnetic material, initially in the demagnetized state, to an applied magnetic field. The demagnetized state is one in which the ferromagnet exhibits zero magnetization in the absence of an applied **H**, corresponding to the origin of Fig. 3.3. The demagnetized state, and methods for achieving it, will be discussed in more detail in Sects. 3.6 and 3.7 of this text. Initial magnetization curves for the ferromagnetic elements Fe, Co, and Ni are shown in Fig. 3.3. It can be seen that each element has a different value of saturation magnetization, $M_0$. The saturation magnetization is the maximum achievable value of $M$ for a specific material, and is an intrinsic property of the material. Values of saturation magnetization for various ferromagnets are listed in Table 3.1. Note that the units of $M$ differ between Fig. 3.3 and Table 3.1 by the factor $\mu_0$. From the tabulated values of $M_0$ it can be seen that an alloy of two ferromagnetic elements often, but not always (as in the case of Permendur), yields a value of $M_0$ that lies between those of the individual elements.

Another feature of the magnetization curves shown in Fig. 3.3 is that the slope of the curve is different for each element. In consequence, Co requires significantly higher applied $H$ to reach saturation than Fe and Ni. This feature is a consequence of the crystal structure of the material and, indeed, varies according to magnetization direction in the case of a single crystal material.

**Table 3.1** Saturation magnetization ($M_0$) values for various ferromagnets [1]

| Material | $M_0$ ($\times 10^6$ A/m) |
|---|---|
| Iron | 1.71 |
| Cobalt | 1.42 |
| Nickel | 0.48 |
| 78 Permalloy (78% Ni, 22% Fe) | 0.86 |
| Supermalloy (80% Ni, 15% Fe, 5% Mo) | 0.63 |
| Permendur (50% Co, 50% Fe) | 1.91 |

### *3.3.1 Rayleigh Law*

In the region of the initial magnetization curve in which $H$ is *low*, $\mu$ can be expressed

$$\mu(H) = \mu(0) + \nu H, \tag{3.5}$$

where $\nu$ is a nonzero constant. This leads to dependence of $B$ on $H$ given by

$$B(H) = \mu(0)H + \nu H^2. \tag{3.6}$$

These relationships were first noted by Lord Rayleigh. They permit construction of hysteresis loops and expressions for hysteresis loss and remanence in terms of $\nu$ and $H$ [1]. The low-field region of the magnetization curve, for which these relationships hold, is highlighted in Fig. 3.4.

In EC NDE theory, often a linear relation between $B$ and $H$ in terms of the initial permeability is assumed. This relationship may be expressed as

$$B = \mu(0)H. \tag{3.7}$$

Comparison of (3.6) and (3.7) quickly reveals that the assumed relation (3.7) is only true in the asymptotic limit as $H \to 0$! On the other hand, incorporation of

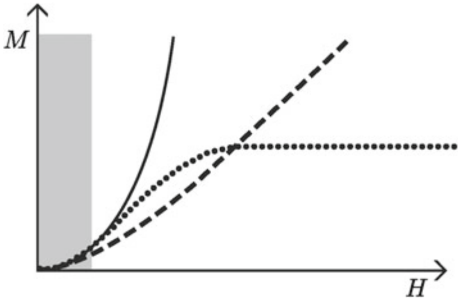


**Fig. 3.4** Rayleigh region of the initial magnetization curve, indicated by the shaded region

full, nonlinear, ferromagnetic behavior into eddy current theory quickly leads to great complexity. The relationship (3.7) is straightforward to incorporate and gives reasonable results for many purposes. One consequence of neglecting the nonlinear magnetic behavior in EC modeling is some loss of accuracy in computing $Z$ and $\Delta Z$ for ferromagnetic test-pieces. For example, results shown in [3] comparing computed and measured $\Delta Z$ for artificial rectangular defects in a flat test-piece show very good agreement for aluminum (within $\approx$5%), but poorer agreement for steel (within $\approx$20%).

## 3.4 Hysteresis

A magnetic hysteresis loop is the path traced by $B$ as $H$ is first reduced from its value at saturation, through zero, to a saturating value in the opposite direction, and then increased again through zero to saturation. A sketch of a typical hysteresis loop is shown in Fig. 3.5. The fact that the loop is not closed indicates that there is an energetically irreversible process occurring. The area of the loop is the work done by the magnetic field in magnetizing the material. The hysteresis loop is a common means of representing the bulk magnetic properties of a ferromagnetic material. It has certain characteristics that vary from material to material. One of these is the *coercivity*, $H_c$ (A/m). Coercivity, or coercive field, is the reverse magnetic field needed to reduce the magnetization of a ferromagnetic sample to zero, once it has been magnetized to saturation. Remanence, $B_r$ (T or Wb/m$^2$), is the field of magnetic

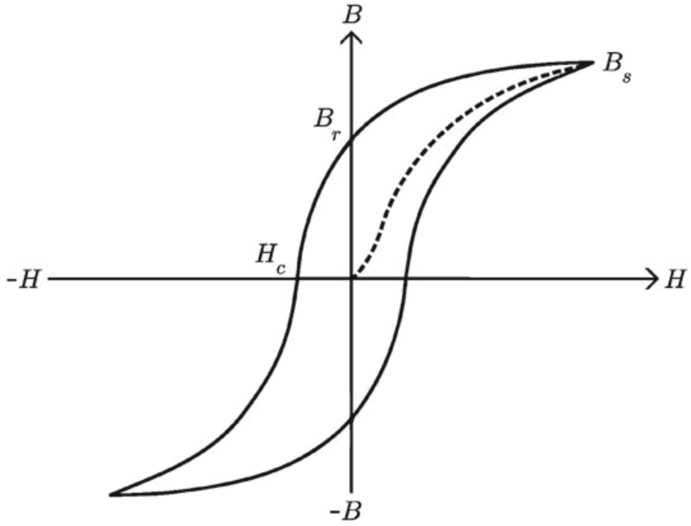


**Fig. 3.5** Typical major hysteresis loop of a ferromagnetic material. The dashed line indicates the initial magnetization curve

induction exhibited by a ferromagnet on removal of the applied magnetizing field $H$, after the ferromagnet has been magnetized to saturation. It is important to note that the definitions of $H_c$ and $B_r$ involve the *major* hysteresis loop of a material, in which the material is magnetized to saturation. Smaller (minor) hysteresis loops may be obtained by cycling the applied magnetic field $H$ to lower strengths, but the definitions of $H_c$ and $B_r$ relate only to the major hysteresis loop.

Various applications in which ferromagnets are used require different characteristics of the material, that may be deduced from the hysteresis loop. For example, the core of an electromagnet should exhibit low $H_c$ and $B_r$ so that the strength of the magnetization can be easily controlled. Materials for permanent magnets should have high $B_r$, so that they exhibit strong magnetization, and high $H_c$ so that they are not easily demagnetized by stray fields. Ferromagnets for transformer cores must exhibit minimal losses in order to convert energy efficiently. Low loss in a ferromagnet is observable as a narrow hysteresis loop with relatively small area. Explanation of the processes that underly the hysteresis loop are given in Sect. 3.6 of this text.

## 3.5 Permeability

Magnetic permeability, $\mu$ measured in Henrys per meter (H/m), provides a measure of the ability of a material to augment the applied magnetizing field by its own magnetization. It relates the field of magnetic induction to $\mathbf{H}$ and $\mathbf{M}$ as follows

$$\begin{aligned} \mathbf{B}(H) &= \mu(H)\mathbf{H} && (3.8)\\ &= \mu_0[\mathbf{H} + \mathbf{M}(H)] && (3.9)\\ &= \mu_0[1 + \chi(H)]\mathbf{H}, && (3.10) \end{aligned}$$

from which it is evident that

$$\mu = \mu_0(1 + \chi). \tag{3.11}$$

This leads to the definition of relative permeability, $\mu_\mathrm{r}$ (dimensionless), which is the ratio of the permeability of a specific material to that of free space,

$$\mu_\mathrm{r} = \frac{\mu}{\mu_0} = 1 + \chi. \tag{3.12}$$

Consider the initial magnetization curve of $B$ versus $H$ shown in Fig. 3.6, solid line. The permeability as a function of $H$, dashed line, can be obtained from the initial magnetization curve using the relation $\mu = B/H$. Other quantities that are in common usage are the differential permeability, defined

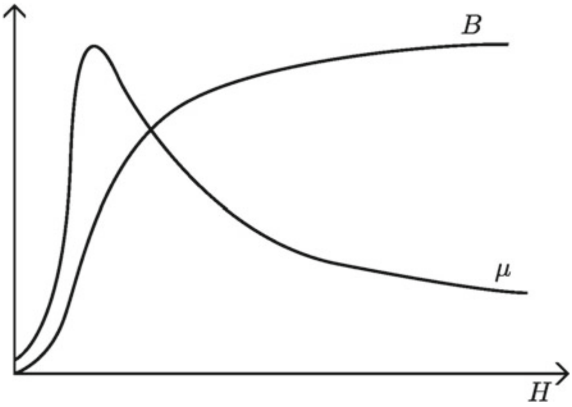


**Fig. 3.6** Initial magnetization curve for $B$ and associated permeability $\mu$ for a representative soft ferromagnetic material, e.g., annealed iron

**Table 3.2** Relative initial permeability $\mu_{\mathrm{r,in}}$, relative permeability at 2 T magnetic induction $\mu_{\mathrm{r,2T}}$, and maximum relative permeability $\mu_{\mathrm{r,max}}$ for various ferromagnets [1, 4]. Relative permeability is dimensionless

| Material | $\mu_{r,\mathrm{in}}$ | $\mu_{\mathrm{r,2T}}$ | $\mu_{\mathrm{r,max}}$ |
|---|---|---|---|
| Iron (purified) | | 5,000 | 180,000 |
| Armco iron | 250 | | 7,000 |
| Nickel (wrought) | 250 | | 2,000 |
| 78 Permalloy (78% Ni, 22% Fe) | | 8,000 | 100,000 |
| Supermalloy (80% Ni, 15% Fe, 5% Mo) | | 100,000 | 800,000 |
| Permendur (50% Co, 50% Fe) | | 800 | 5,000 |

$$\mu' = \frac{dB}{dH} \tag{3.13}$$

and the initial permeability, defined as the slope $B/H$ of the tangent to the initial magnetization curve as $H \to 0$

$$\mu_{\mathrm{in}} = \left.\frac{dB}{dH}\right|_{B=0,H=0} = \left.\frac{B}{H}\right|_{B\to 0,H\to 0}. \tag{3.14}$$

Some typical values of $\mu_{\mathrm{r,in}}$ are given in Table 3.2, together with values of maximum relative permeability $\mu_{\mathrm{r,max}}$ and relative permeability at 2 T magnetic induction field $\mu_{\mathrm{r,2T}}$. Note that $\mu$ varies as a function of $H$ whereas $\mu_{\mathrm{in}}$ and $\mu_{\mathrm{max}}$ do not.

Comparing (3.8) and (3.4) it is clear that $\mu$ is to $\mathbf{B}$ what $\chi$ is to $\mathbf{M}$. Correspondingly, the following definitions of differential and initial susceptibility mirror those for $\mu$:

$$\chi' = \frac{dM}{dH}, \tag{3.15}$$

$$\chi_{\text{in}} = \left.\frac{dM}{dH}\right|_{M=0,H=0} = \left.\frac{M}{H}\right|_{M\to 0,H\to 0}. \tag{3.16}$$

## 3.6 Ferromagnetic Domains

In ferromagnets, permanent magnetic moments exist on the atomic scale. They do not rely on the presence of an external magnetic field for their existence, but rather their existence is explained by quantum-mechanical descriptions of spin and orbit of atomic electrons. Another definition of magnetization relates $\mathbf{M}$ to the magnetic dipole moment per unit volume in the material:

$$\mathbf{M} = \frac{\mathbf{m}}{V}. \tag{3.17}$$

The macroscopic properties of ferromagnets can be explained if long-range magnetic order (over many atoms) exists within the material. Such a region of long-range order is known as a *domain*. The dimensions of a typical domain are on the order of tens of microns. A domain in a ferromagnetic material is a region in which the individual atomic magnetic dipole moments are aligned parallel with one another. This means that the magnetization within a particular domain is essentially saturated, with $\mathbf{M} = \mathbf{M}_0$. The direction of magnetization generally varies from one domain to another, accounting for the fact that a ferromagnet may exhibit no remanent magnetization despite the fact that each domain is magnetized to saturation. In the demagnetized state, the vector sum of the magnetization over all domains is zero. Magnetization is then the process of rearranging the domains so that their magnetic moments are in alignment with each other and, ultimately, with the direction of applied $\mathbf{H}$. The existence of domains within a bulk ferromagnetic sample explains the fact that a large magnetization $M$ may be achieved by application of a relatively small $H$ to a sample. The applied $H$ does not create order throughout the sample but, rather, overcomes energy barriers to align domain magnetization vectors that already exist.

### *3.6.1 Why do Domains Form?*

Materials in equilibrium occupy a state in which their free energy is minimized. If not, a change of some kind will occur until a local energy minimum is reached. A phase transition, such as from the solid to the liquid state, requires input of energy to effect the transformation. In a solid ferromagnet, minimization of quantum mechanical *exchange energy* occurs when neighboring atomic magnetic moments are aligned parallel with one another. So, minimization of exchange energy drives the magnetic ordering that occurs in ferromagnets. A ferromagnet does not just spontaneously magnetize throughout its entire volume, however, because although exchange energy is reduced, a fully ordered sample has large magnetostatic energy associated with it. In other words, there is a large external magnetic field associated with a fully ordered sample. We know this because the purpose of a simple bar magnet, which is normally magnetized to saturation and therefore fully ordered, is to have a large external magnetic field associated with it in order to interact strongly with other bodies. A schematic diagram of the external magnetic field due to a bar magnet is shown in Fig. 3.1. Domains, then, form in order to reduce the magnetostatic energy of the sample. Simply speaking, the magnetic state of the ferromagnet is determined by a balance between the exchange energy, the magnetostatic energy, and the energy cost associated with creating domain walls.

### 3.6.2 Domain Walls

The boundary between two domains consists of a region in which neighboring atomic magnetic moments cannot be perfectly aligned with one another but rotate, over many atoms, from the magnetization direction of one domain to that of its neighbor. An example of one type of domain wall is shown schematically in Fig. 3.7. Domain wall thickness varies according to material type, but is typically of the order of 100 nm, occurring on the scale of many atomic moments. In iron, **M** in neighboring domains switches direction by either 90° or 180°, due to the cubic crystal structure of iron. The walls that separate these domains are hence known as 90° (Néel) or 180° (Bloch) walls, respectively. Other ferromagnetic materials exhibit different characteristic arrangements of their domain structure, that are related to their crystal structure.

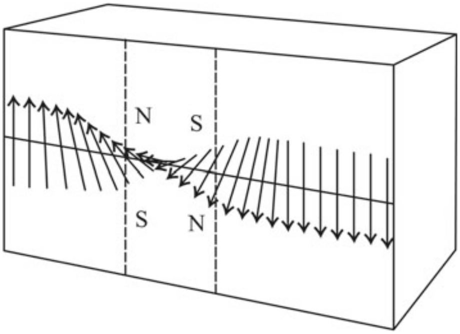


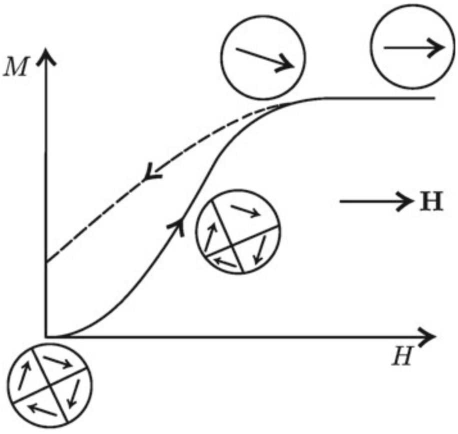
**Fig. 3.7** Rotation of magnetic moments across a 180° Bloch wall

### *3.6.3 Domain Processes During Magnetization*

When a magnetic field is applied to a ferromagnetic material, work is done by the magnetic field to reorient the domain magnetization directions to a direction more closely aligned with that of the applied field. There are several processes by which this occurs.

At low applied $H$-field strengths magnetic domains whose magnetization vector is directed in a direction similar to that of the applied field grow at the expense of domains whose magnetization direction is not similar to that of the applied field. The growth of one domain at the expense of another takes place by movement of the domain wall between them. Strictly, the atomic magnetic moments that are at the edge of a domain whose $\mathbf{M}$ vector is directed similarly to $\mathbf{H}$ rotate into alignment with $\mathbf{M}$. This process gives the appearance of domain wall movement. The process of domain wall movement is shown schematically in the first two insets of Fig. 3.8. At higher strengths of applied $H$, the restructuring of the domains continues until only a single domain exists, with magnetization direction similar to that of the applied field. This situation is shown in the third inset of Fig. 3.8. The magnetization of the single domain does not at first lie parallel to the direction of applied $\mathbf{H}$, because all ferromagnetic materials have one or more *easy axes* along which the magnetization vector will preferentially align and the directions of the easy axes are determined by the crystal structure of the particular material. For example, iron has body-centered cubic crystal structure and the six equivalent easy axes are in the directions of the cube edges $\langle 100 \rangle$ and similar. Cobalt, on the other hand, has a hexagonal close-packed crystal structure and there is only one easy axis, in the $\langle 0001 \rangle$ direction. For very high applied $H$, the magnetization direction rotates away from the easy axis to align fully with the direction of $\mathbf{H}$, as shown in the fourth inset in Fig. 3.8. This latter magnetization stage, in which $\mathbf{M}$ rotates, is reversible (anhysteretic), which means that when $H$ is reduced from its saturating value the reorientation of $\mathbf{M}$ to realign with the easy axis

**Fig. 3.8** Schematic showing domain rearrangement during magnetization



follows the same $M$-$H$ curve as it did when $H$ was increasing. On the other hand, motion of the domain walls is a hysteretic process because, simply speaking, domain walls are "pinned" at positions in which their local energy is minimized. Pinning sites are associated with inhomogeneities in the material such as impurities (small quantities of other elements dispersed in the crystal structure) and discontinuities in the crystal lattice (such as might occur at a grain boundary). Hysteresis loops such as the one shown in Fig. 3.5 are observed because it is necessary to supply energy to overcome domain wall pinning regardless of their direction of motion.

### 3.6.4 Hard and Soft Ferromagnets

Hard ferromagnetic materials, such as the permanent magnet material samarium-cobalt, are those with a high density of pinning sites. These materials require relatively high applied $H$ to become magnetized; to provide sufficient energy to move the domain walls across multiple pinning sites. Hard ferromagnetic materials have relatively high $H_c$. Soft ferromagnetic materials such as iron, on the other hand, contain relatively few impurities and exhibit correspondingly low $H_c$. The motion of the domain walls is not smooth but occurs as a series of jumps from one pinning site to the next. In other words, as $H$ is increased smoothly, $B$ or $M$ respond in a step-like manner because the increase in $H$ produces no change in $B$ or $M$ while the domain wall is pinned, but then a sudden change is observed when the domain wall snaps away from one pinning site and moves to the next. This discontinuous motion is evidenced by looking closely at the hysteresis curve, which turns out to be made up of a sequence of steps rather than being a smooth curve, Fig. 3.9.

### 3.6.5 Evidence for the Existence of Domains

The existence of domains was first observed indirectly by Heinrich Barkhausen in 1919 in the form of audible clicks produced by a loudspeaker attached to a voltage

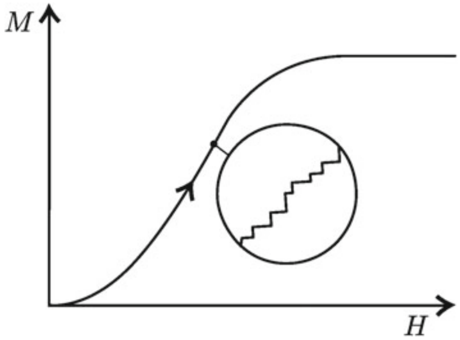


**Fig. 3.9** Discontinuous changes in $B$ as a function of $H$

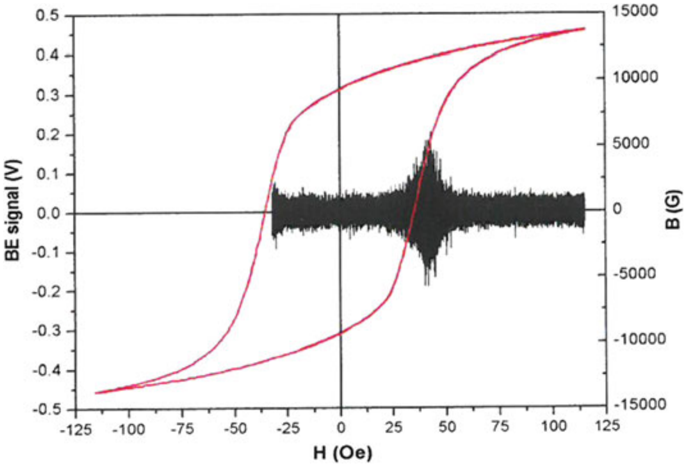


**Fig. 3.10** One hysteresis cycle shown in terms of magnetic induction $B$. The Barkhausen effect (BE) signal overlays part of the hysteresis cycle [5, Fig. 8, used with permission]. Note, 1 Oersted (Oe) $=1000/(4\pi) \approx 79.58$ A/m and 1 Gauss (G) $=10^{-4}$ T

pick up loop wrapped around a ferromagnetic sample, as the sample was being magnetized. The discrete movements of the domain walls as they jump from one pinning site to another cause small, rapid changes in $B$ that induce voltage pulses in the pick up coil, by Faraday's Law of induction. The loudspeaker in Barkhausen's experiment made it possible to observe these discrete changes in $B$. Today, Barkhausen "noise" can be recorded and analyzed digitally and is useful in some near-surface magnetic NDE applications. Figure 3.10 shows the increase in Barkhausen noise in a region of steepest slope of the hysteresis loop, which corresponds to a maximum in $\mu'$.

Today, magnetic force microscopy (an adaptation of atomic force microscopy) permits direct imaging of ferromagnetic domains, with lateral resolution around 40 nm, but is limited to surface observations.

### *3.6.6 The Curie Temperature, $T_C$*

Ferromagnetic ordering disappears at temperatures higher than the so-called *Curie temperature* $T_C$, at which a phase transition occurs. This is a temperature above which thermal agitation of the crystal lattice overcomes ferromagnetic ordering. Curie temperatures for some ferromagnetic materials are listed in Table 3.3. The fourth ferromagnetic element, Gadolinium, has not been mentioned until now because $T_C$ for Ga is below room temperature and consequently, its applications are not widespread in the context of EC NDE.

**Table 3.3** Curie temperatures for various ferromagnets [1]

| Material | $T_C$ (°C) |
|---|---|
| Iron | 770 |
| Cobalt | 1130 |
| Nickel | 358 |
| Gadolinium | 20 |
| Hard ferrites | 400–700 |

## 3.7 Demagnetization

In the context of EC NDE, the process of demagnetization is important for controlled EC experiments on ferromagnetic samples. As mentioned in Sect. 3.3 of this text, the theory of EC NDE commonly assumes a linear relationship between $B$ and $H$ with the form of (3.7), which is most closely true in the asymptotic limit as $H \rightarrow 0$. For this reason, better agreement between EC theory and experimental data can be obtained by demagnetizing any magnetic sample that is to be the subject of an EC benchmark experiment. Or, if comparative electromagnetic measurements are to be made on ferromagnetic samples, it is better to remove the influence of magnetic history by demagnetizing them first.

In many cases, magnetization and demagnetization are performed by inserting the test-piece into a solenoid and appropriately adjusting the magnetic field that the solenoid produces. A solenoid is a long, air-cored coil whose axial magnetic field is given by $H_z = nI$ where $n$ is the number of turns per unit length and $I$ is the current flowing in the coil. $H_z$ is approximately uniform over the cross section of the solenoid, when its length is much greater than its diameter. (A solenoid is the subject of Exercise 3 at the end of Chap. 6) For samples that are too large to fit inside a solenoid, a C-core magnetic can be moved over the surface of the sample, demagnetizing it at each location. To demagnetize a sample, the current flowing in the solenoid or other electromagnets is gradually reduced in amplitude while being cycled at a frequency sufficiently low to permit domain reordering to occur under the influence of the magnetic field that the electromagnet produces. As the applied $H$ is reduced in amplitude, $B$ also reduces as shown in Fig. 3.11 until, ultimately, the material reaches the demagnetized state characterized by $B = 0$.

Figure 3.12 shows the emergence of multiple domains as a sample of iron, initially saturated, is demagnetized. Notice how the magnetostatic field external to the iron is reduced as domains form during demagnetization. The triangular domains formed with 90° domain walls are known as *closure domains*. They act to eliminate the external magnetostatic field by "closing the loop" of $\mathbf{M}$ within the material.

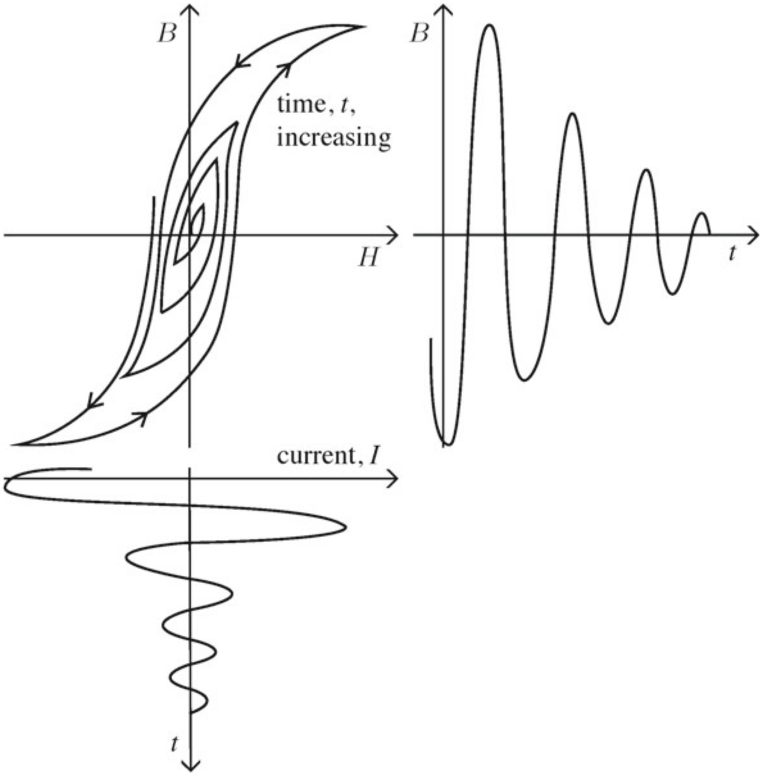


**Fig. 3.11** The variation in applied current $I$ in a solenoid enclosing a ferromagnetic sample as the sample is demagnetized. $B$ cycles to zero as $I$ and $H$ (produced by $I$) cycle to zero

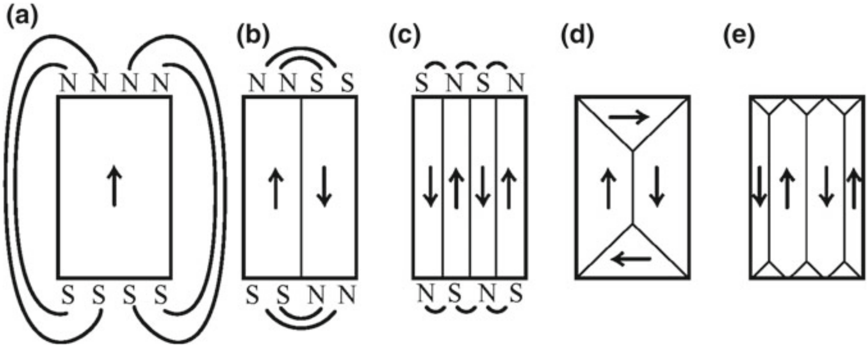


**Fig. 3.12** Schematic diagram showing the emergence of domains as a saturated sample (a) is demagnetized (e). Iron forms domains of this kind since the cubic crystal structure support 90° and 180° domain walls

## 3.8 Summary

In this chapter, an introduction to ferromagnetic materials and their properties has been given. Ferromagnetic materials are important in EC NDE for both enhancing probe performance (Sect. 6.3.5) and because some test-pieces exhibit ferromagnetic behavior that influences the EC signal (Chaps. 6 and 9). A basic understanding of this topic is one of the building blocks that contributes to a complete understanding of EC NDE, that we are working toward. Similarly, the topic of the next chapter—electrical circuits—gives us a building block that helps us to understand the function of an EC coil and probe.

## 3.9 Exercises

1. Several devices exist for making quantitative measurements of magnetic field strength. These are known as magnetometers. Conduct a little research to find four examples of magnetometer and, in two sentences for each one, describe how they work.
2. Explain what is meant by the initial magnetization curve, mentioning the domain processes that occur along with it.
3. Discuss the reasons why magnetic ordering occurs in ferromagnets, explaining why a material does not usually spontaneously magnetize uniformly throughout its volume.
4. Give two pieces of evidence for the existence of ferromagnetic domains.
5. Explain the meaning of coercivity and remanence, and give their SI units.
6. For a typical hysteresis loop of $B$ versus $H$, sketch the form of $\mu$ as a function of $H$. Where is $\mu$ maximum?

## References

1. Jiles, D.C.: Introduction to Magnetism and Magnetic Materials, 2nd edn. CRC Press/Wiley, Boca Raton (1998)
2. Cullity, B.D., Graham, C.D.: Introduction to Magnetic Materials, 2nd edn. IEEE Press, Hoboken (2009)
3. Bowler, J.R., Harfield, N.: Evaluation of probe impedance due to thin-skin eddy-current interaction with surface cracks. IEEE T. Magn. **34**, 515–523 (1998)
4. Kaye, G.W.C., Laby, T.H.: Tables of Physical and Chemical Constants, 15th edn. Longman, London (1986)
5. Kinser, E.R.: Magnetic nondestructive characterization of case depth in surface-hardened steel. M.S. thesis, Iowa State University (2005)