## 4.6 SUPERCONDUCTING MAGNETS

When a superconductor in its normal (i.e., nonsuperconducting) state is placed in a magnetic field and then cooled below its critical temperature the induced magnetization, *M*, exactly opposes *H* and so from Eq. 4.3, we can write

$$B = 0 \tag{4.8}$$

The net effect is that the whole of the magnetic flux appears to have been suddenly ejected from the material and it behaves as a perfect diamagnet. This phenomenon is known as the Meissner effect and is usually demonstrated by suspending a magnet above a cooled pellet of the superconductor. There is an upper limit to the strength of the magnetic field that can be applied to a superconductor without changing its diamagnetic behavior. At a critical field $H_{cr}$ the magnetization goes toward zero and the material reverts to its normal state. For most elemental superconductors *M* rises in magnitude up to $H_{cr}$ and then abruptly drops to zero; this is Type I behavior.

A few elemental and most compound superconductors, including all HTSCs, exhibit Type II behavior. Above a certain field, $H_{c1}$, magnetic flux can penetrate the material without destroying superconductivity. Then at a (usually much) higher field, $H_{c2}$, the material reverts to the normal state. These two behaviors are compared in Figure 4.3. When a Type II superconductor is in the "mixed" state, it consists of both normal and superconducting regions.

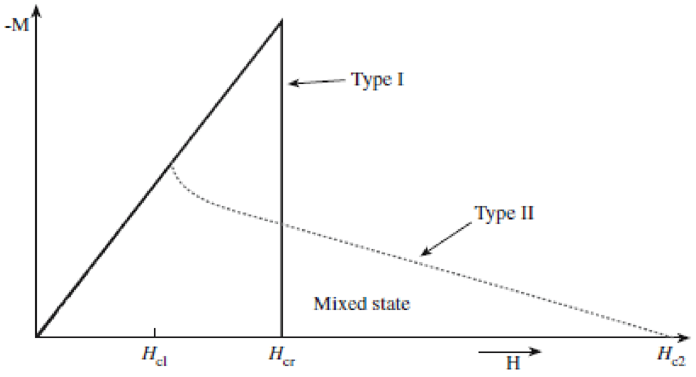


*FIGURE 4.3 Magnetization behavior of Type I and Type II superconductors as a function of the applied field.*

The normal regions are called vortices, which are arranged parallel to the direction of the applied field. At low temperature, the vortices are in a close-packed arrangement and vibrate about their equilibrium positions, in the same way that atoms in a solid vibrate. If the temperature is high, enough the vortex motion becomes so pronounced that the arrangement randomizes and the vortex lattice “melts.” Defects in the material can trap or pin vortices in place and higher temperatures are then needed to cause “melting.” Pinning is of considerable practical importance because it enables higher currents to flow through the material before superconductivity is lost.

Although ceramic superconductors have not been used for the generation of large magnetic fields, because it is difficult to form them into long wires, they have been made into superconducting quantum interference devices (SQUIDs). Uses for SQUIDs include the following:

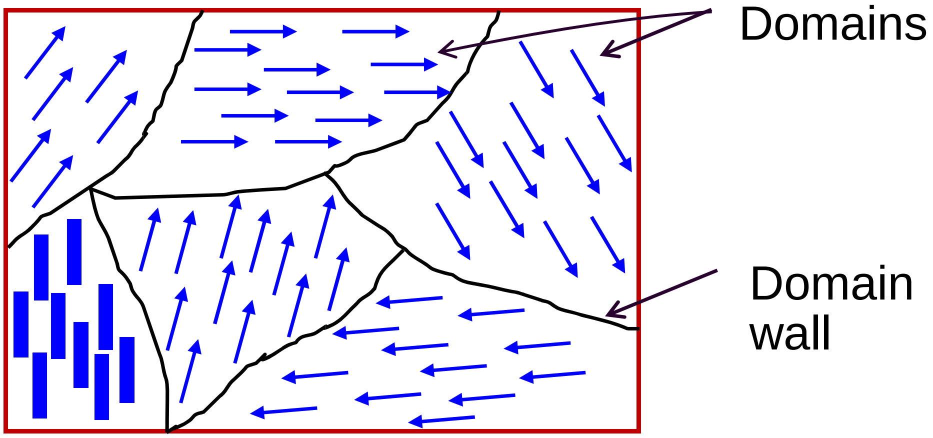
- They can detect small changes in magnetic field strength at the earth’s surface that can then be related to the underlying geological structure (e.g., thickness of the crust, movement of magnetic poles over time, etc.).
- Magnetic imaging using scanning SQUID microscopy. This allows local magnetic fields to be measured at the surface of a sample.
- Searching for submarines. When a submarine moves through the water, the metal hull slightly disturbs the earth’s magnetic field and this small distortion can be measured.
- The human brain can be imaged by detecting small magnetic fields produced because of the currents due to neural activity. This area of research is called magneto encephalography (MEG) and is being used to study epilepsy.

## 4-7 Domains

- Ferromagnetic materials exhibit small-volume regions in which magnetic moments are aligned in the same directions. These regions are called domains.

- Adjacent domains are separated by domain boundaries. The direction of magnetization changes across the boundaries.

- The magnitude of magnetization in the material is vector sum of magnetization of all the domains.



## 4. 8 MOTION OF DOMAIN WALLS AND HYSTERESIS LOOPS

When an external magnetic field is applied to a ferromagnetic or ferrimagnetic material the domain boundaries begin to move. They move in such a way that domains in which the magnetization direction is aligned with *H* grow at the expense of the unaligned domains. The change in *B* with *H* is shown in Figure 4.13. Initially the movement of the domain walls is reversible and *B* increases only slightly with increasing *H*. As the field increases the favorably oriented domains grow more easily and μ increases. At very large *H* the unaligned domains will rotate and saturation will be reached in which all the domains are aligned in the same direction.

When the field is removed, there is a resistance to domain wall motion preventing reorientation of the domains. As a result there is a residual magnetization, known as remanence (*B*r), and the material acts as a permanent magnet. If *H* is then applied in a direction opposite to what was originally used then domains grows with an alignment in the new direction. A certain field, called the coercive field, $H_c$, is needed to completely randomize the domains. Further increases in $H$ eventually align the domains to saturation in the new direction. The behavior of a ferromagnetic or a ferrimagnetic material in an alternating magnetic field is shown in Figure 4.14. The size of the hysteresis loop, i.e., the values of $B$r and $H_c$, vary from material to material.

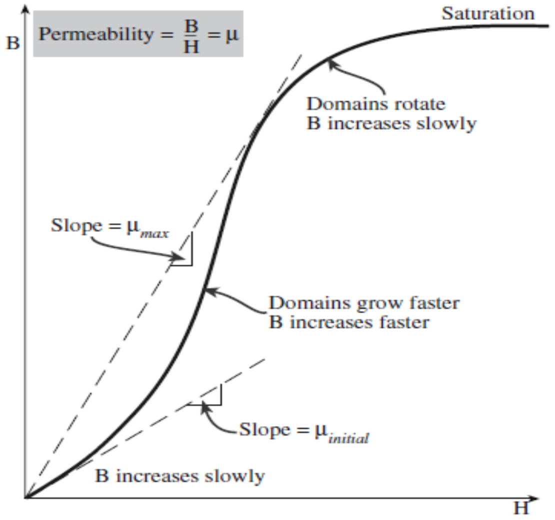


***FIGURE 4.13 the effect of H on B. The ratio is μ.***

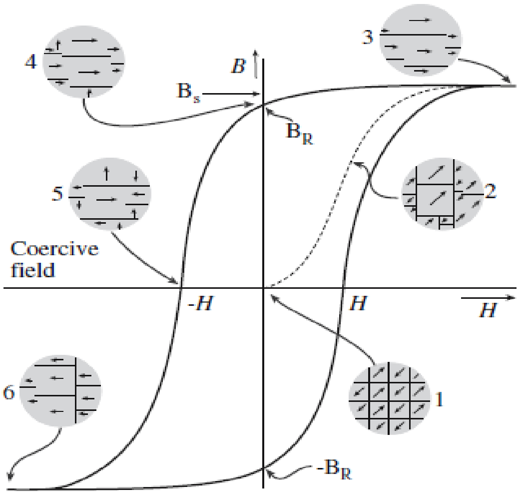


***FIGURE 4.14 the variation of B as H alternates. The insets illustrate the domain structure at various points along the hysteresis curve.***

## 4.8 <u>Ferrite:</u>

***Ferrite*** is one of magnetic oxide compounds, which comprise iron oxide as a major component. Ferrites consist lanthanides compounds and fast transition metals, in particular, iron, chromium, and manganese. The general formula is $M'M''_2O_4$, where M' is a rare-earth element (divalent metal ions such as $Fe^{2+}$, $Mg^{2+}$, $Ni^{2+}$, $Co^{2+}$, $Zn^{2+}$, $Cu^{2+}$) and M" is iron, chromium, manganese, etc. (trivalent metal ions); that is, $Fe^{3+}$, $Cr^{3+}$, $Al^{3+}$, $Mn^{3+}$. Most important marketable derivatives of these ferrites are $Zn^{2+}$ substituted Ni and Mn ferrite, denoted as $NiZnFe_2O_4$ and $MnZnFe_2O_4$, respectively.

Ferrites find potential applications for making many devices such as permanent magnets, memory storage devices, microwave devices, and for the telecommunication equipment purpose. The importance of ferrites lies in the fact that they possess a wide range of electrical and magnetic properties. That properties like high electrical resistivity, low eddy current and dielectric loss, high saturation magnetization, high permeability, high Curie temperature, low cost, large selection material, shape versatility, and economical assembly.

### 4.8-1 Classification Of Ferrites:

Ferrites are classified according to magnetic properties and their crystal structure. First, have two varieties of ferrites: soft ferrite and hard ferrite. Second, there are four different crystal structure types: Ferrites crystallize Spinel ferrite, Garnet, Ortho ferrite, and Hexagonal ferrite.

#### 1- Soft ferrites

The major requirements for a soft ferrite is a high Ms and small Hc. Therefore, Soft ferrites have narrow hysteresis loops as shown in Fig. (4.3).

During changes of the magnetic field direction, the domains are rapidly and easily realigned. Therefore, domain wall motion and/or magnetization rotation become easy. Domain wall motion is affected by the microstructure of the material and characteristics as grain size and grain-boundary, the presence of inclusions or pores within the grains, impurity levels, and stresses, which reduce the domain wall motion. Soft ferrites have high electrical resistivities because this limits eddy current losses.

Generally, soft ferrites are used in many applications, in which the direction of Hc is frequently changing such as high frequency inductors, transformers and magnetic elements in microwave components, electromagnetic cores of transformers, switching circuits in computers and radio frequency (RF) inductors. Many examples of Spinel ferrites like manganese–zinc ferrite $(Mn,Zn,Fe)O_4$ system are commercially important soft magnets. In addition, lithium ferrite, nickel ferrite, and garnets are other examples of soft ferrites.

## 2- Hard ferrites

Hard ferrites, which are used to make permanent magnets, must have large Hc, as shown in Fig. (4.3). It is necessary to use materials with crystal structures that exhibit a large magnetic anisotropy and to prevent the growth and rotation of magnetic domains (by, for example, controlling the grain size so that each grain becomes a single domain). Barium ferrite and oxides with a magnetoplumbite structure are the preferred choices. Both $BaO{\cdot}6Fe_2O_3$ and $SrO{\cdot}6Fe_2O_3$ have a hexagonal ferrite structure, but Sr-M hexaferrite has slightly superior magnetic characterizations hard ferrite magnets are used in the following: starter motors in automobiles, loudspeakers, rotors for cycle dynamos, windscreen wiper motors, mixed with a flexible polymer in door-catches and decorative magnets for refrigerators, DC motors in fuel pumps, and household appliances.

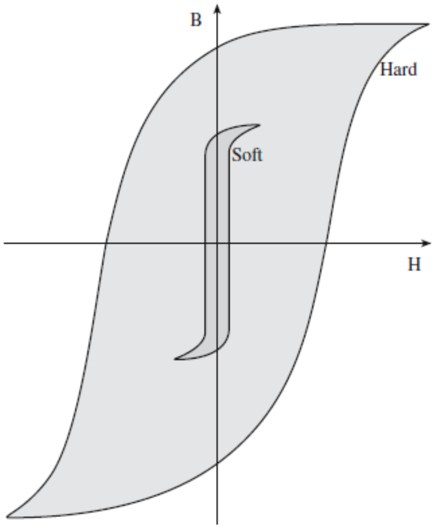


*Figure (4.3) Comparison of the size and shape of Hysteresis loops for hard and soft magnets*