10 - Magnetism

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Learning objectives:

1. Calculate the magnetic field strength in an ideal solenoid
2. Define magnetic dipole moments, and the basic unit of the Bohr magneton
3. Describe magnetization and magnetic susceptibiliy
4. Describe the four types of magnetic materials
5. Calculate the saturation magnetization for a ferromagnetic material
6. Describe magnetic domains
7. Relate process of magnetizing a material to magnetic domain structure: the M-H curve
8. Explain Curie temperature

Creating a magnetic field: the ideal solenoid

If you imagine a wire wrapped around an invisible cylinder and you pass a current through that wire, then this is a solenoid, and inside the solenoid, the current will generate a magnetic field defined by:

$$H = \frac{NI}{L} \qquad (1)$$

where H is the magnetic field, N is the number of turns of the wire, I is the current, and L is the length of the solenoid.

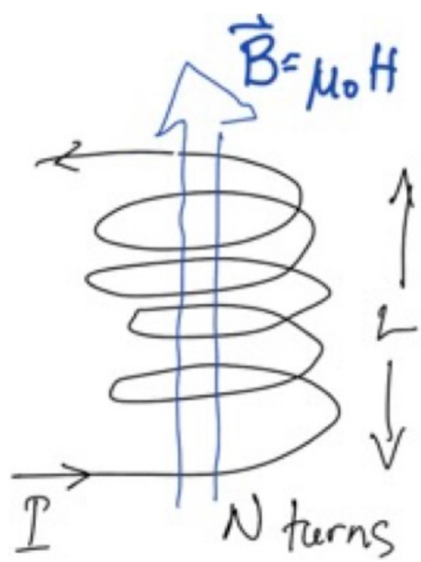


Figure 1. A schematic sketch of a solenoid.

We define an additional quantity called the magnetic flux density B. In a vacuum, we denote this as Bo

$$B_0 = \mu_0 H \qquad (2)$$

If we now insert a material inside the solenoid, then there is an induced magnetization inside the material that is proportional to the applied magnetic field, and the proportionality constant is called the magnetic susceptibility

$$M = \chi_m H \qquad (3)$$

The magnetization adds to the original flux density so the total flux density in the material is

$$B = \mu_0 H + \mu_0 M = (1 + \chi_m)\mu_0 H \qquad (4)$$

χ_m is a measure of the materials response to the applied magnetic field H

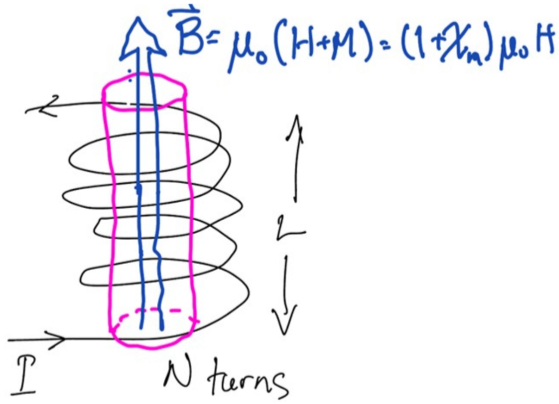


Figure 2. A schematic sketch of a solenoid, with total flux expanded.

Magnetic dipole moments

If we imagine a single loop of wire with a circulating current, it produces a magnetic dipole moment in units of area times current, and is oriented perpendicular to the plane of the current circulation. Picture each magnetic dipole as a small bar magnet with its own magnetic field. If will also like to align itself with an applied field, just like a compass needle.

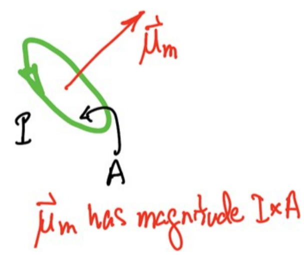


Figure 3. A single loop magnetic dipole.

In reality, every atom can have a magnetic moment associated with the angular momenta of its electrons (both orbital and spin), but only partially filled subshells have a net magnetic moment. Filled shells have angular momenta and spin arranged so that all contributions cancel out.

Bohr Magneton

The basic unit of atomic magnetic dipole moment is the Bohr magneton. The spin of a single electron has a magnetic moment of one Bohr magneton along the Z axis.

$$\mu_B = \frac{e\hbar}{2m_e} = \beta \qquad (5)$$

$$\mu_B = \beta = 9.27 \times 10^{-24} Am^2 \qquad (6)$$

Types of magnetic materials

There are four basic types of magnetic materials. We will describe them in terms of weakest to strongest magnetic properties

Diamagnetism

In these materials, the magnetic susceptibility is small and negative, meaning that the induced magnetization opposes the applied field. This arises when each atom has no permanent magnetic moments. Covalent materials and many ionic materials are diamagnetic.

Example: graphite $\chi_m = -6 \times 10^{-6}$

Paramagnetism

In these materials, each atom or molecular unit as a dipole moment, but they tend to be randomly aligned due to thermal fluctuations. In these materials the magnetic susceptibility is small and positive meaning that the diples will have a tendency to align with an applied field. Many metals are paramagnetic

For example: Magnesium $\chi_m = +1.2 \times 10^{-5}$

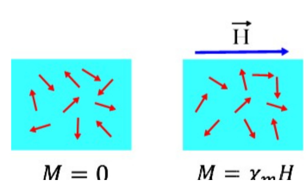


Figure 4. Paramagnetism

Ferromagnetism

In ferromagnetic materials, each atom has a dipole moment, and they tend to align parallel to each other (within a single magnetic domain) Ferromagnetic materials such as iron can have permanent magnetization, even in the absence of an applied field. The relationship between M and H (and hence H and B) is not linear (as we will see in the discussion of M-H curves) At saturation magnetization, all atomic magnetic dipole moments are aligned in the same direction.

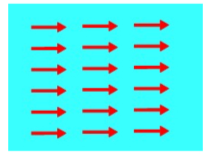


Figure 5. Ferromagnetism

Above the Curie temperature, a ferromagnet becomes paramagnetic (i.e. the temperature fluctuations are strong enough that the dipoles no longer align with each other. Examples of ferromagnetic elements are Fe, Ni, Co, Gd, and Dy. Some alloys are also ferromagnetic.

Antiferromagnetism

In antiferromagnetic materials, each atom has a dipole moment, but they tend to align anti parallel to each other, so that the net magnetization is zero. The susceptibility is small and positive. An example of an antiferromagnetic material is Chromium.

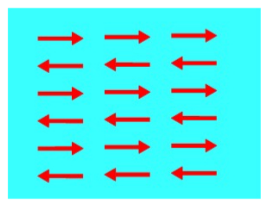


Figure 6. Antiferromagnetism

Ferrimagnetism

Some transition metal oxides (such as iron oxides) are ferrimagnetic. The moments on adjacent atoms are antiparallel but unequal in strength, resulting in a net magnetization. Therefore they can have permanent magnetization, like ferromagnetic materials. Ferrimagnetic materials are important for magnetic storage applications.

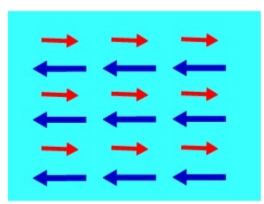
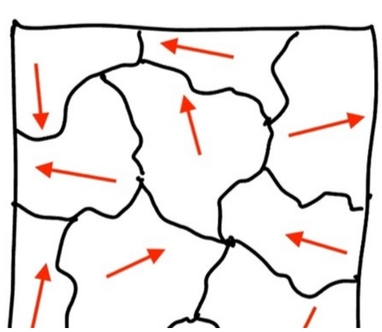


Figure 7. Ferrimagnetism

Polycrystalline ferromagnetic metals

So the question is why ferromagnetic materials do not automatically show an external magnetic field. One factor is that metals are usually polycrystalline, and the orientation of the magnetic moments is random. Within each grain, the magnetic moments tend to be along a particular crystallographic directions. For iron, the easy axis of magnetization is along <001> type directions. Usually the orientation of the grains themselves is random.



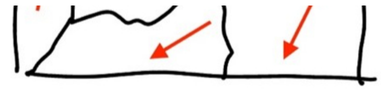


Figure 8. Polycrystalline ferromagnetic metals.

Magnetic domains

In a perfect single crystal of a ferromagnet like iron, the magnetization likes to align in a specific direction aligned with <001> type directions. However, if all dipoles are aligned, then there is an external magnetic field, and there is an energy associated with this. In this case, the iron is **magnetized**. The energy of the system can be lowered if the magnetization splits itself into magnetic domains, i.e. separate areas where the magnetization is in different <001> directions so that on average over the entire crystal there is no net magnetization.

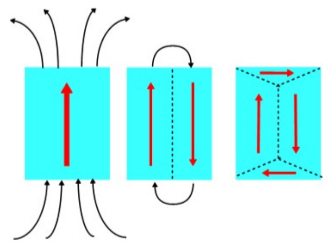


Figure 9. Magnetic domains.

There is an energy associated with the domain wall creation, but overall the energy is reduced if the domain structure minimizes the external magnetic field. In this case, the iron is no longer **magnetized**.

Under the influence of an externally applied magnetic field, the relative sizes of the domains can shift due to movement of the domain walls, resulting in a net magnetization that is parallel to the applied field.

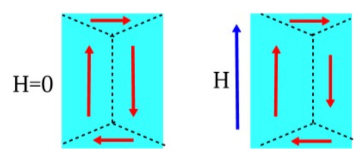


Figure 10. Polycrystal in magnetic field.

In addition to domain wall formation within a crystal, a regular piece of iron would be polycrystalline, with the individual grains in random orientations. Therefore there is no net magnetization, i.e. the iron is not normally magnetized.

The magnetization of a ferromagnetic material.

Let's now look at how to magnetize a piece of iron. The upper squares show a schematic of the domain wall behavior in a single grain that is randomly oriented with respect to the applied magnetic field $\vec{H}$

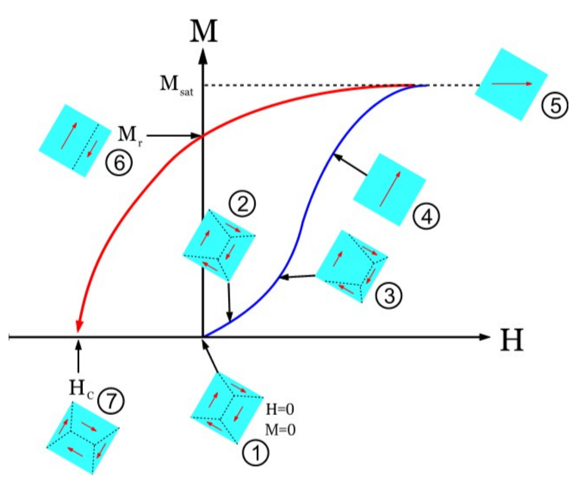


Figure 11. Domains

The lower part of Figure 11 shows the net magnetization of the whole piece of material as a function of the applied field, starting at zero field and zero magnetization M.

1. At H=0, the grain has initial state M=0
2. As H increases, domains that are more aligned with the field grow. Initially the domain movement is reversible and the increase in M is linear in H
3. As H increases further, the domain wall movement becomes irreversible

4. Eventually the entire grain is a single domain (c)
5. At still higher fields, M is forced to rotate from an easy axis of magnetization to the direction of H. At this point, the magnetization is saturated and M = Msat
6. As the field is decreased, M within each domain rotates back to an easy axis, and at the same time, some domains in other directions may grow. At H=0, there is a **remanent magnetization** (Mr), This is due to the fact that there was irreversible domain wall motion during the magnetization process. The material is now magnetized, i.e. M≠0 even with H=0.
7. In order for M to be reduced to zero, a field in the reverse direction must be applied. The magnitude of this field, Hc, is called the coercivity or the **coercive** field. The size of the coercivity is a measure of how difficult it is to demagnetize the material.

It is possible to completely reverse the direction of the magnetization by applying more and more field in the reverse direction. One can then repeat the cycle, forming what is called an M-H loop, where the magnetization is cycled between $\pm M_{sat}$

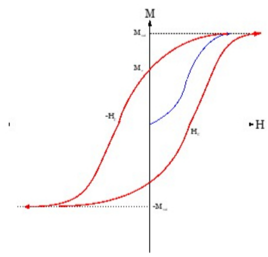


Figure 12. M-H loop.

Materials with high values of H_c are difficult to demagnetize, and they are called hard magnetic materials.

Materials with low values of H_c are easy to magnetize or demagnetize, and they are called soft magnetic materials.

Magnetic recording requires a combination of hard and soft magnetic materials. The read/write heads are soft since they have to switch their directions quickly to read or write data. The magnetic storage material is hard since we don't want the written data to be easily erased.

Material	H_c (kA/m)	B_r (T)	BH_{Max} (kJ/m^3)	Tc (°C)	Applications
Permalloy	< 0.08				Read/write heads
Iron	0.16	0.9			
Ferrite	1.2 - 16	0.35	10 - 40	450	Magnetic recording
NdFeB	800 - 950	1.3	200 - 440	310 - 400	
Alnico	30 - 150	0.6 - 1.4	10 - 88	700 - 860	