

Summary Magnetic materials 2015.

The magnetic susceptibility, i.e. χ_m , is the relation between the magnetization and the magnetic H-field, i.e.

$$M = \chi_m H \quad [1]$$

Note that this definition is slightly different from the definition of electric susceptibility which was the relation between P and E, i.e.

$$P = \chi_e E \quad [2]$$

We considered three different type of materials:

1. Diamagnetic materials: Magnetic moment is anti-parallel to the applied magnetic field. For small fields, M is linear with H (χ_m is constant and negative of the order of -10^{-6} to -10^{-7}). This type of effect was discussed in the beginning of chapter 5. An external magnetic field will speed up the spinning of the electrons anti-parallel to the magnetic field and will slow down the spinning of the electrons that are oriented parallel to the magnetic field. Diamagnetism is the smallest magnetic effect and is often only visible when the material has no paramagnetism and ferromagnetism.
2. Paramagnetic materials: Magnetic moment is parallel to the applied magnetic field. For small fields, M is linear with H (for small fields χ_m is constant and positive of the order of 10^{-5} to 10^{-6} , M saturates for large fields, i.e. when all magnetic dipoles are lined up to the magnetic field). An external magnetic field will orient the magnetic dipoles parallel to the field. Note that the alignment caused by a higher magnetic field can be destroyed by increasing the temperature of the system. So best alignment is obtained at low temperatures in high fields.
3. Ferromagnetic materials: The magnetic moment of two neighboring atoms like to be parallel to each other. Ferromagnetic materials are not linear. The relation between the magnetization and the applied magnetic field is not linear and the susceptibility is of the order of 100 to 10,000, so a much stronger effect than diamagnetism or paramagnetism. Ferromagnetic materials also show hysteresis, which means that the magnetization of the material depends not only on the current applied magnetic field but also depends on the magnetic field that was applied to the material in the past. Because of the hysteresis, it is possible to apply magnetic materials in recording devices, such as hard disk and magnetic RAM. A typical ferromagnetic material shows an M-H relation as shown in figure 6.28 (The I-axis is basically proportional to H). The M-H relation can be considered as the finger print of a magnetic material. The graph shows three curves. The curve starting at the origin is the relation between the magnetic field and the magnetization assuming the material is demagnetized to start of with. It is often referred to as the virgin curve. The top curve is the relation between the magnetic field and the magnetization assuming you start off in high magnetic fields when all dipoles are lined up to a positive applied magnetic field. The lower curve, shows the relation between the magnetization of the material

and the applied magnetic field for the case that one starts off in saturation at negative applied magnetic fields.

Strictly speaking there are two contributions to the magnetic moment of ferromagnetic and paramagnetic materials:

1. The spin of the electrons implies moving charge and a current, resulting in a magnetic moment of each electron. If the atom contains unpaired electrons this can result in the atom having a net magnetic dipole moment.
2. The electrons orbiting the nucleus also implies a moving charge and current. This can result in the atom having a net magnetic dipole moment. In most atoms however, the contributions of the electrons angular momentum to the magnetic moment is very small.

There are only three elements that are ferromagnetic at room temperature, i.e. Fe, Co, and Nickel. Some of the rare earth ferromagnetic materials are ferromagnetic at low temperatures, for example Gd (290 Kelvin), Terbium (220 Kelvin), Dysprosium (85 Kelvin), Ho (15 K), Er (15 K), Tm (15 K).

Although ferromagnetism can only be really understood from quantum mechanics, Weiss showed that one can understand the temperature dependence of the magnetic properties of ferromagnetic materials by assuming the existence of a molecular field. This field is the result of the interaction of all magnetic moments in the material with each other. The molecular field is parallel to the magnetization of the material, i.e.

$$H_m = \gamma M \quad [3]$$

H_m keeps the magnetic dipole moments lined up in the same direction even in the absence of an externally applied magnetic field. Note that the origin of the molecular field can only be understood from quantum mechanics.

From quantum mechanical point of view we can understand ferromagnetism by realizing that two neighboring atoms whose magnetic dipole moments make an angle with each other, have a higher total energy than two neighboring magnetic dipoles that are parallel to each other. We say that the wave-functions of two neighboring atoms interact with each other and that this interaction leads to an extra energy term the exchange energy:

$$E_{exchange} = -\sum 2J_{ij} \vec{s}_i \cdot \vec{s}_j \quad [4]$$

Where the summation is across the next neighbors and J_{ij} is the exchange constant which magnitude and sign depends on the distance between the atoms. So if the magnetic dipole of two neighboring atoms have a slightly different orientation, the total energy of the system will increase. The minimum energy will be realized if all spins have the same orientation. You will learn more about this in graduate quantum and graduate EMT.

Although iron is a ferromagnetic material, and all spins are lined up in the same directions on an atomistic scale, it is possible that on a mesoscopic or microscopic scale this order is not maintained. An iron object can consist of grains, and although all the atoms in a particular grain are lined up with each other, resulting in the grain having a permanent magnetic dipole moment, the magnetic dipole moment of each grain can have a different direction. So the magnetic dipole moment of the different grains will cancel each other out, resulting in the object having a very small or zero total magnetic dipole moment. So an iron scissors or screwdriver does not have to be magnetic. One can make the iron object magnetic though by exposing it to a large magnetic field. The large field will pull the magnetization in each grain parallel to its direction. When removing the magnetic field of the object, the magnetization of the grains remains in the same direction (hysteresis) resulting in the object having a non-zero net magnetic dipole being turned into a permanent magnet. The areas in the object that have all their spins parallel are called magnetic domains. Initially the object consists of a lot of different magnetic domains. After the object is exposed to a magnetic field which creates a homogeneous magnetization all through the object, the object contains only a single magnetic domain.

In addition to exchange energy, ferromagnets will also contain magnetostatic energy. Notice that a magnetic dipole \vec{m} in a magnetic \vec{B} field has an energy given by:

$$E = -\vec{m} \cdot \vec{B} \quad [5]$$

Assuming that the magnetic dipole is placed in free space we can replace \vec{B} by $\mu_0 \vec{H}$:

$$E = -\mu_0 \vec{m} \cdot \vec{H} \quad [6]$$

So if we now add up over all dipoles we get for the energy:

$$E_{\text{magnetostatic}} = -\mu_0 \int \vec{M} \cdot \vec{H} d\tau \quad [7]$$

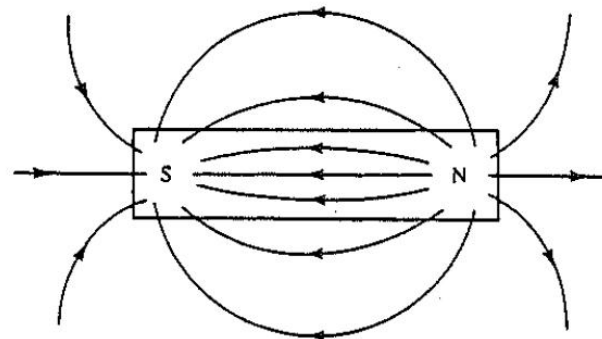
Note that $\vec{m} = \vec{M} d\tau$. The magnetostatic energy of a collection of magnetic dipoles can be calculated from this expression once \vec{H} is known. To determine the \vec{H} -field we have to go back to Maxwell's equations. If we assume that there are no free currents the equations are:

$$\begin{aligned} \nabla \cdot \vec{H} &= -\nabla \cdot \vec{M} \\ \nabla \times \vec{H} &= 0 \end{aligned} \quad [8]$$

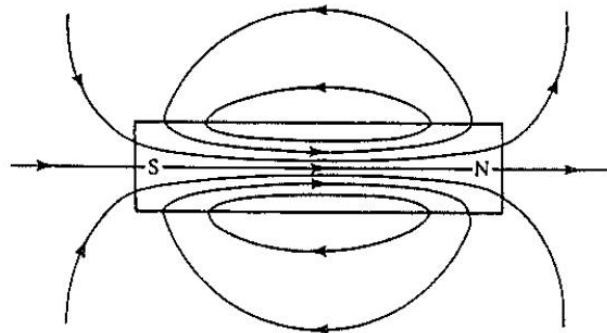
Note that the first expression looks similar to Gauss' law with ρ/ϵ_0 replaced by $-\nabla \cdot \vec{M}$. So in other words the sources of the \vec{H} -fields are the areas that have a non-zero divergence. Note that the divergence in Cartesian coordinates is given by:

$$\nabla \cdot \vec{M} = \frac{\partial M_x}{\partial x} + \frac{\partial M_y}{\partial y} + \frac{\partial M_z}{\partial z} \quad [9]$$

For a homogeneously magnetized cube, the divergence of M is unequal to zero at the north and south poles of the cube. Or in other words the north and south poles are the sources of the H -field in the case no free currents are around. This is also illustrated in the graphics below. The lower graph shows the B -field. Notice that the B -field lines close upon themselves. The top graphics show the H -field. The north pole are the sources of the H -field lines and the south poles the sinks.



(a)

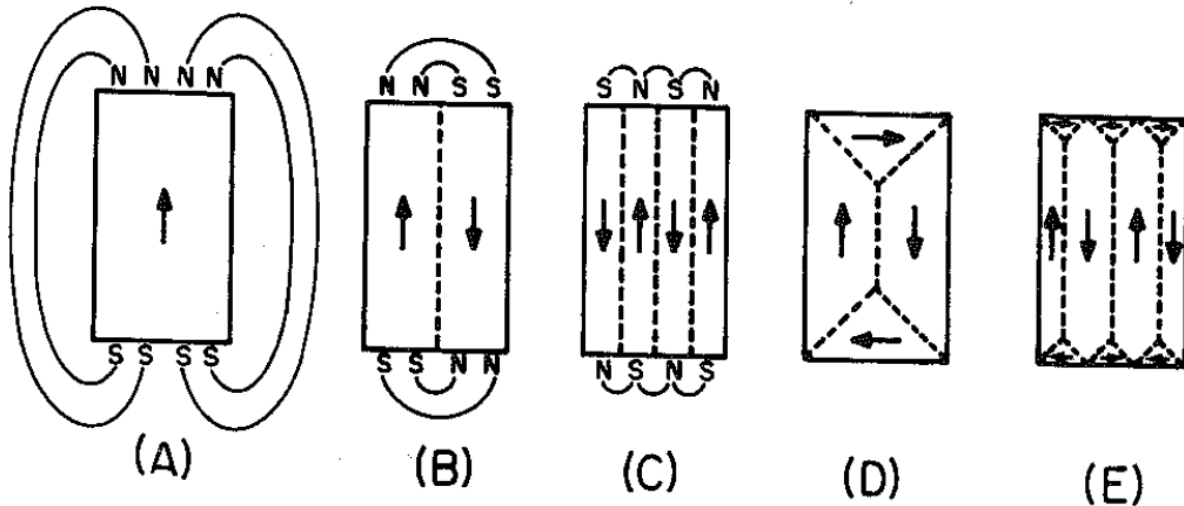


(b)

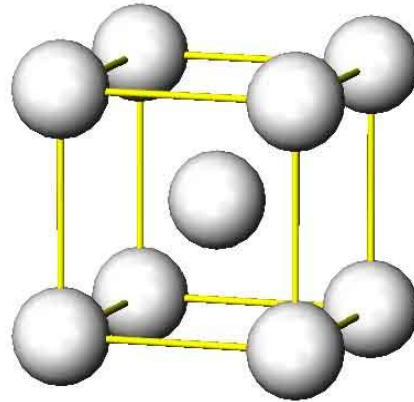
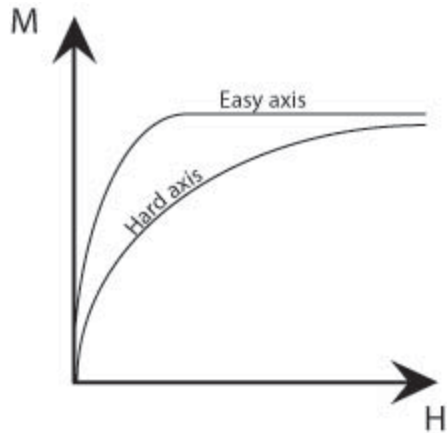
Fig. 2.4 (a) Magnetic field H both inside and outside a bar magnet, (b) magnetic induction B both inside and outside a bar magnet. Notice in particular that the magnetic field and induction lines are identical outside the material, but inside they are quite different (they even point in opposite directions).

So the H -field can be calculated from an integration over all sources and sinks, similarly as the E -field in electrostatics can be calculated from an integration over all charge contributions. Having that said, it should be clear which of the domain patterns of the figure below has the lowest magnetostatic energy.

Just consider the H-field in the center of the object. The H-field is larger for (a) than for (b). The H-field in the center of the object is even smaller for configuration (c). Configuration (d) has a zero H-field. Note that there are no north and south poles. Even in the material between the domain, the divergence of M is zero. As there are no sources and no sinks of the H-field, the H-field is everywhere zero in the material. The same is true for configuration (e). So both (d) and (e) have a zero magnetostatic energy.



Note that above discussion does not mean that configuration (d) and (e) have a lower total energy than configuration (a). Note that for configurations (b) through (e) the spins are not everywhere parallel to each other. At the boundaries between two domains neighboring spins make an angle of 180 or 90 degrees. According to equation [4] this results in an extra exchange energy term. So although the magnetostatic energy of (e) is definitely smaller than the magnetostatic energy of configuration (a), the exchange energy of (a) is smaller than the exchange energy of (e). So the total energy of the various configurations depends on M_s and J . In fact another effect that we have not considered here is important, i.e. the magnetic crystal anisotropy. The magnetic crystal anisotropy describes how the system's energy varies as a function of the orientation of the magnetization within the crystal structure. A ferromagnetic material has 'easy' crystallographic directions along which it is preferred that the magnetisation vector points and 'hard' directions along which a higher field is required to achieve the same magnetisation. Therefore, it is easiest to magnetise a ferromagnetic material along these easy axes, as shown by the schematic below. There is an energy difference associated with magnetisation along the hard and easy axes which is given by the difference in the areas under (M,H) curves. This is called the magnetocrystalline energy. For bcc iron the easy axis is along the $\langle 100 \rangle$ directions. If the magnetization is along the $\langle 111 \rangle$ direction the crystal anisotropy energy is large. Both the crystal anisotropy and the exchange energy contribute to the energy of a domain wall.



The domain configuration with the lowest energy is the domain configuration that one can expect in the magnet.

In addition to the text above we discussed two types of magnetic domain walls, a Bloch wall and a Neel wall. We also discussed the two most common magnetic reversal mechanisms, i.e. domain wall motion, and magnetic rotation.

For further reading please check out:

[1] David Jiles, Introduction to Magnetism and Magnetic Materials, Whapman & Hall, ISBN 0 412 79850, ISBN 0 412 79860 3, 1998.

[2] B. D. Cullity, Introduction to magnetic materials, ISBN-10: 0471477419, 2008.