5: Magnetic Materials

5.1 The Magnetisation Curve

We have already shown that for an air-cored solenoid:

$$B = \frac{\Phi}{A} \quad H = \frac{IN}{l} \quad \text{and} \quad \frac{B}{H} = \mu_0$$

A graph of the magnetic flux density (B) against the magnetising force (H) is called the *magnetising curve*. Such a graph for air-cored and nonmagnetic-cored solenoids is shown in figure 5.1. This graph is a straight line with a gradient equal to μ_0, therefore no matter how great the magnetising force is, it will always be directly proportional to the magnet flux density produced.

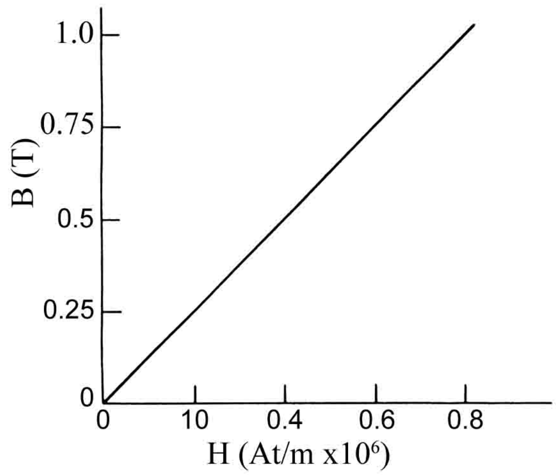

Figure 5.1: The magnetising curve for an air-cored solenoid or a solenoid cored with a nonmagnetic material.

For ferromagnetic materials:

$$\frac{B}{H} = \mu_0 \mu_r$$

Since μ_0 is a constant μ_r changes depending on the value of H and there is no fixed relationship between B and H for ferromagnetic materials.

Ferromagnetic materials, such as iron, cobalt, nickel and steel, can be considered to be made up from small permanent magnets called 'domains'. When the material is not magnetised, the poles of these domains point in all directions (figure 5.2a) and their individual magnetic fields cancel out so that there is no detectable overall magnetism. As the material is subjected to an increasing external magnetising force, the poles of the domains begin to swing into line, so that when the material is fully magnetised all the north poles point in one direction (figure 5.2b).

If we consider a solenoid consisting of a wire coiled around a ferromagnetic core we can plot a graph of the magnetic flux density (B) of the solenoid verses the magnetising force (H) produced by the coil (remembering that H = IN/*l,* so that as the current in the coil increases so does H). Such a graph is shown in figure 5.3. We can see that while the tiny magnets are rearranging the graph is a straight line after a small, initial curve. Once all of the magnets have become aligned with the solenoid's field the graph levels out until B can not increase any more; at this point the material is said to have reached *saturation*.

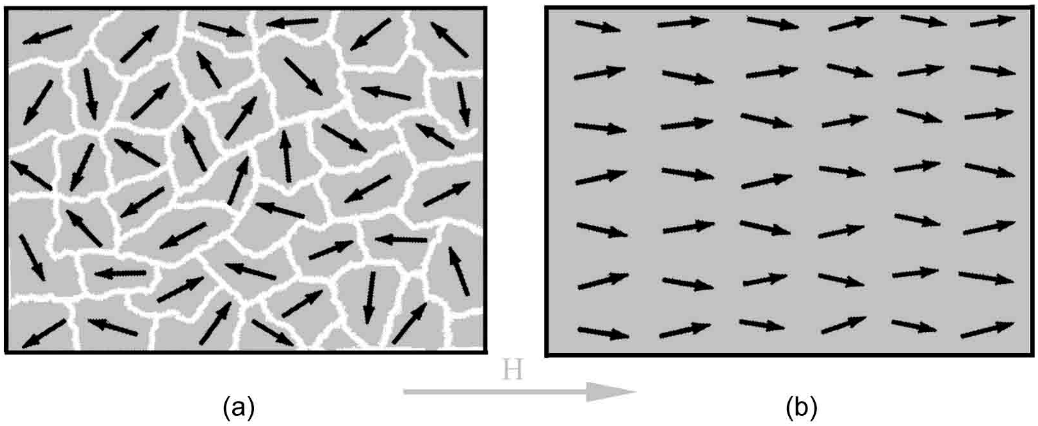

Figure 5.2: (a) a piece of ferromagnetic material which is not magnetised, where the domain poles are not aligned; (b) the domain poles aligned with an external magnetising force (H).

Figure 5.3 also shows the variation of μ_r with H and shows that μ_r falls of rapidly after saturation.

Note that to produce as much flux as possible for a given value of H the material should not be saturated. If you increase the current flowing through a solenoid that has reached saturation very little or no extra flux will be obtained. Note also the much larger flux density produced using a ferromagnetic core; the H axis in figure 5.1 is At/m $\times 10^{-6}$ whereas in figure 5.3 it is just At/m.

The magnetisation curves for different ferromagnetic materials are shown in figure 5.4.

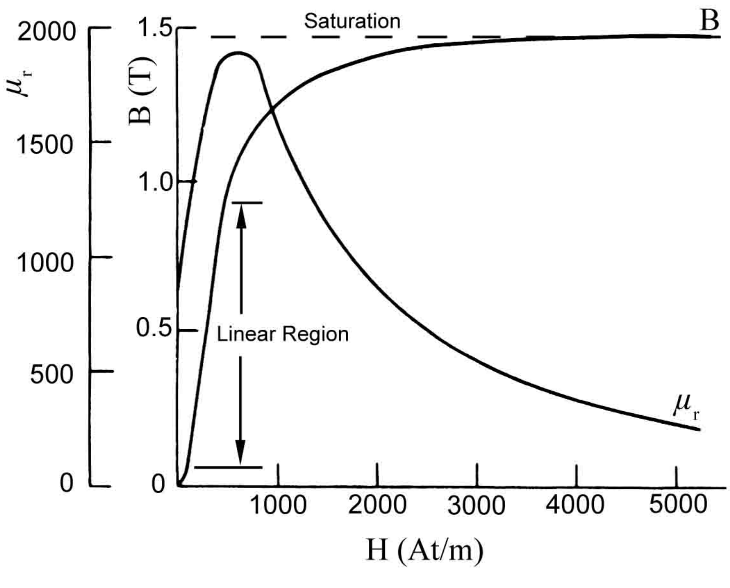

Figure 5.3: The magnetising curve of a ferromagnetic core.

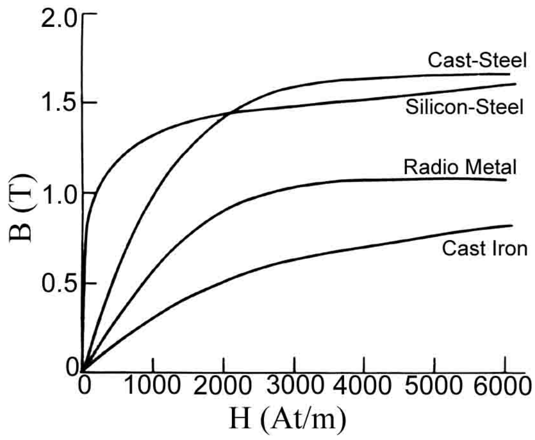

Figure 5.4: The magnetisation curve for various ferromagnetic materials.

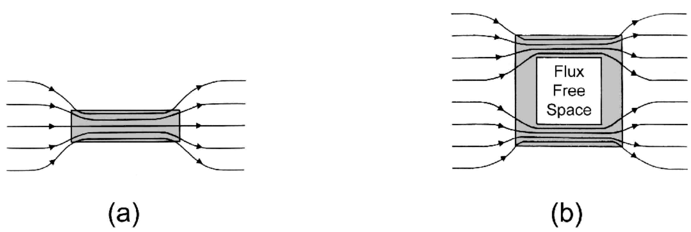

Figure 5.5: (a) a ferromagnetic material in a magnetic filed; (b) a ferromagnetic material being used as a magnetic shield.

A piece of ferromagnetic materials placed in a magnetic field will carry more of the flux than the surroundings (figure 5.5a) and the field will be distorted. Thus such materials can be used to create a magnetic shield (figure 5.5b).

5.3 Hysteresis Losses

For ferromagnetic materials the magnetising curve shown in figure 5.3 is not reversible; that is if H is increased until the material is saturated, when H is reduced again the value of B does not reduce to zero along the same line. Figure 5.6 shows a *hysteresis loop* that illustrates the complete story.

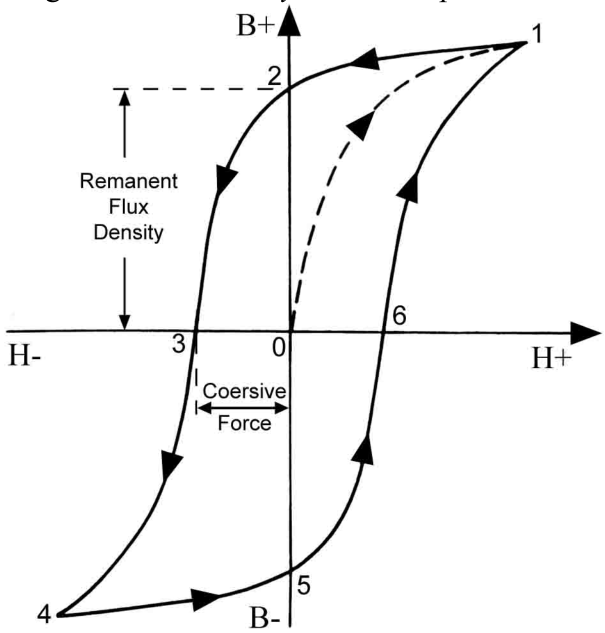

Figure 5.6: a hysteresis loop for a solenoid's ferromagnetic core.

In figure 5.6 the point 0, where the axes cross, represents a ferromagnetic material that is not magnetised. As the current in the coil is increases, H also increases and between points 0 and 1 B increases following the magnetisation curve. At point 1 the material has reached saturation and B will no longer increase. Now we start to reduce the current in the coil so that we can demagnetise the material, as stated before the graph will not following the same path it did when the current increased but instead goes from point 1, through point 2 then down to point 3.

At point 2 H=0, therefore the current has reached zero but there is still some *remnant flux density* so that the material is still partially magnetised. The current is now reversed so that H is in the opposite direction than before and H has a negative value, therefore when the current is increased, the value of H reduces. At point 3 the material is finally demagnetised and the value of H at this point is called the *coercive force*.

If the reversed current increases furtherer we reach point 4, where the material saturates so that the magnetic poles of the domains face in the opposite direction to those at point 1. The reversed current is now reduced and reaches zero at the point 5 however, once again, some flux remains. If the current is now increased in the original direction all the flux has gone at point 6 and saturation is reached once more at point 1.

Note that the distances between points 0 and 2, and, 0 and 5 are equal. Also the distances between points 0 and 6, and, 0 and 3 are equal.

Since the coercive force must be applied to overcome the remanent magnetism, work is done in completing the hysteresis loop and the energy concerned appears as heat in the magnetic material. This heat is known as hysteresis loss, the amount of loss depends on the material's value of coercive force. By adding silicon to iron a material with a very small coercive force can be made, such materials typically contain 5% silicon and have very narrow hysteresis loop (figure 5.7b). Materials with narrow hysteresis loops are easily magnetised and demagnetised and known as *soft magnetic materials*.

Hysteresis loses will always be a problem in AC transformers where the current is constantly changing direction and thus the magnetic poles in the core will cause losses because they constantly reverse direction. Rotating coils in DC machines will also incur hysteresis losses as they are alternately passing north the south magnetic poles.

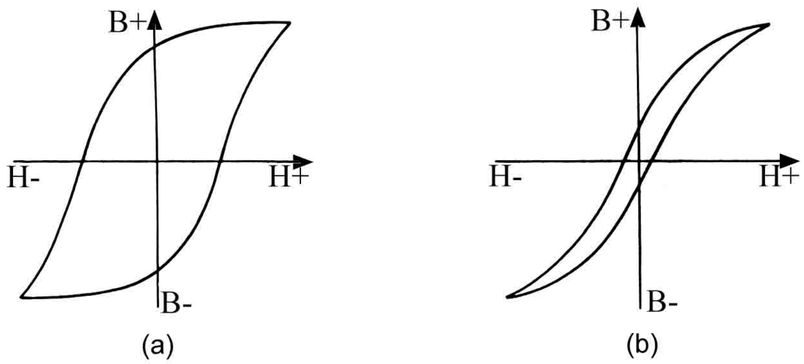

Figure 5.7: (a) the hysteresis loop for hard magnetic material suitable for permanent magnet; (b) the hysteresis loop for soft magnetic material suitable for a transformer core.

If you wish to create a permanent magnet you should use a material with a very fat hysteresis loop (figure 5.7a). Such materials, once magnetised, are very difficult to demagnetise and when the magnetising force is removed a substantial magnetic flux density remains. These materials are known as *hard magnetic materials*.

5.4 Eddy-Current Losses

We will see in the next section that any conductor subjected to a changing magnetic flux will have an EMF induced in it. An alternating flux, such as that in the core of a transformer or rotor in a DC motor, will be continuously changing and will thus induce and EMF in any conductor it cuts. These induced EMF's will drive alternating current within the core or windings, these are known as *eddy-currents*. Eddy-currents can be quite large, since although the induced EMFs are small, the resistance of core or winding will be small. Thus they can lead to substantial heating losses. Eddy currents can never be completely removed but they can be reduced considerably by laminating the transformer cores.

5.5 Iron Losses

Hysteresis losses and eddy-current losses taken together are called *iron loses*. The power loss due to eddy-currents (P_E) is proportional to the frequency (f) of the supply squared and the maximum value of flux density (B_{max}) squared. Thus:

$$PE \propto f^2 B_{max}^2$$

The relationship between the power loss due to hysteresis loss (P_H), f and B_{max} is similar:

$$PE \, \alpha \, f \; B_{max}^{1.6}$$

Exact equations for these losses are very complex.

5.6 Properties And Uses Of Some Ferromagnetic Materials

Material	***Composition***	***B_r* (T)***	***B_{sat}* (T)***	***H_c* (A/m)***	**μ_r***	***Uses***
Silicon iron	Fe – 3%Si	0.8	1.95	24	500 to 1500	Bell and telephone electromagnets. Relay cores. DC choke cores. Magnetic circuits for rotating machinery (up to 3%si), transformer cores (up to 5%Si).
Mumetal	5% Cu, 2%Cr, 77% Ni, 16 %Fe	0.6	0.65	4	2×10^4	Magnetic shields, instrument magnetic circuits, current transformers.
Carbon Steel	0.9% C, 1% Mn, 98% Fe	1.0	1.98	4×10^3	14	Permanent magnets.
Alnico V	24% Co, 14% Ni, 8% Al, 3% Cu, 51% Fe	1.31	1.41	5.3×10^4	20 to 250	Permanent magnets.

Table 5.1: The properties and uses of some magnetic materials.

* B_r = the remanent flux density, B_{sat} = the saturation flux density, H_c = the corsive force, μ_r = the relative permeability at H=0.