

Magnetic Materials: Hysteresis

Ferromagnetic and ferrimagnetic materials have non-linear initial magnetisation curves (i.e. the dotted lines in figure 7), as the changing magnetisation with applied field is due to a change in the magnetic domain structure. These materials also show hysteresis and the magnetisation does not return to zero after the application of a magnetic field. Figure 7 shows a typical hysteresis loop; the two loops represent the same data, however, the blue loop is the polarisation ($J = \mu_0 M = B - \mu_0 H$) and the red loop is the induction, both plotted against the applied field.

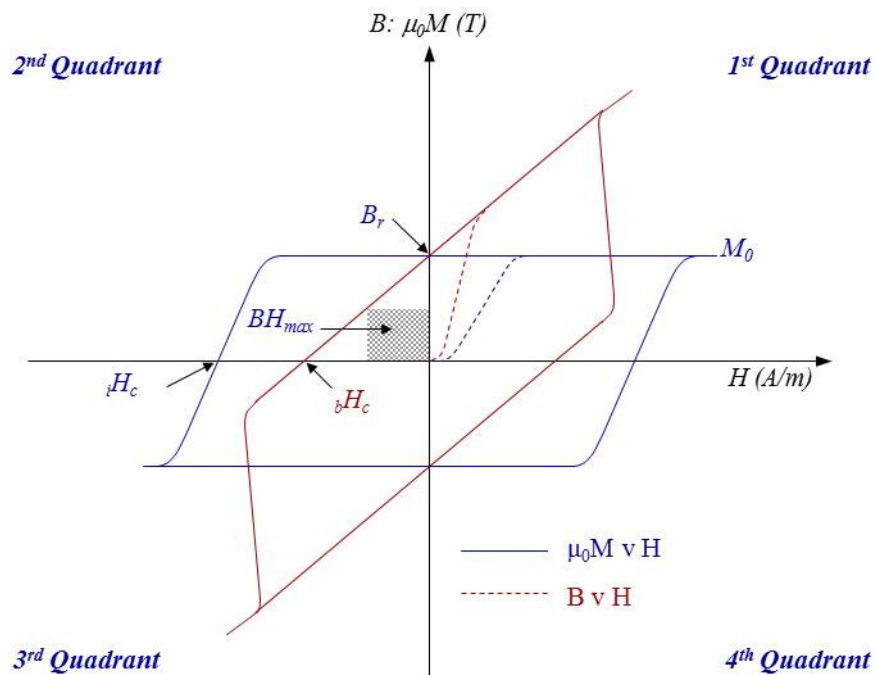


Figure 7: A typical hysteresis loop for a ferro- or ferri- magnetic material.

Illustrated in the first quadrant of the loop is the initial magnetisation curve (dotted line), which shows the increase in polarisation (and induction) on the application of a field to an unmagnetised sample. In the first quadrant the polarisation and applied field are both positive, i.e. they are in the same direction. The polarisation increases initially by the growth of favourably oriented domains, which will be magnetised in the easy direction of the crystal. When the polarisation can increase no further by the growth of domains, the direction of magnetisation of the domains then rotates away from the easy axis to align with the field. When all of the domains have fully aligned with the applied field saturation is reached and the polarisation can increase no further.

If the field is removed the polarisation returns along the solid red line to the y-axis (i.e. $H=0$), and the domains will return to their easy direction of magnetisation, resulting in a decrease in polarisation. In figure 7, the line from the saturation point to the y-axis is horizontal, which is representative of a well aligned material, where the domains are magnetised in the easy direction of the crystal at the saturation point.

If the direction of applied field is reversed (i.e. to the negative direction) then the polarisation will follow the red line into the second quadrant. The hysteresis means that the polarisation lags behind the applied field and will not immediately switch direction into the third quadrant (i.e. negative polarisation). The polarisation will only decrease after a sufficiently high field is applied to:

1. nucleate and grow domains favourably oriented with respect to the applied field or
2. rotate the direction of magnetisation of the domains towards the applied field

After applying a high enough field saturation polarisation will be achieved in the negative direction. If the applied field is then decreased and again applied in the positive direction then the full hysteresis loop is plotted.

If the field is repeatedly switched from positive to negative directions and is of sufficient magnitude then the polarisation and induction will cycle around the hysteresis loop in an anti-clockwise direction. The area contained within the loop indicates the amount of energy absorbed by the material during each cycle of the hysteresis loop.

Magnetic parameters

The hysteresis loop is a means of characterising magnetic materials, and various parameters can be determined from it. From the first quadrant the saturation polarisation, J_s and hence the saturation magnetisation, M_s can be measured. Most of the useful information, however, can be derived from the second quadrant of the loop, and indeed it is conventional only to show this quadrant. The field that is produced by the magnet after the magnetising field has been removed is called the remanence, B_r or J_r . The reverse field required to bring the induction to zero is called the inductive coercivity, ${}_bH_c$, whereas the reverse field required to bring the magnetisation to zero is called the intrinsic coercivity, ${}_iH_c$. The maximum value of the product of B and H is called the maximum energy product, $(BH)_{max}$ and is a measure of the maximum amount of useful work that can be performed by the magnet. $(BH)_{max}$ is used as a figure of merit for permanent magnet materials.

In addition, the shape of the initial magnetisation curve and the hysteresis loop can provide information about the magnetic domain behaviour within the material. The squareness factor is a measure of how square the loop is and is a dimensionless quantity between 0 and 1, defined by the ratio of the reverse field required to reduce J by 10% from the remanence to H_{cj} . A squareness factor of one therefore corresponds to a perfectly square loop. There are several other methods to quantify the squareness of the loop, such as the ratio of J_r to J_s .

Coercivity Mechanisms

There are various methods of increasing or decreasing the coercivity of magnetic materials, all of which involve the controlling the magnetic domains within the material. For a hard magnetic material it is desirable that the domains cannot easily rotate its direction of magnetisation and that the domain walls do not move easily and/or nucleation of domains is difficult.

To prevent easy rotation of domains the material could have a strong uniaxial magnetocrystalline anisotropy. Alternatively, shape anisotropy can occur in needle-like particles/grains, where the magnetostatic energy is less when the magnetisation is in the long axis of the needle compared to the short axis.

If the size of a magnetic particle/grain decreases then there is a critical size below which the decrease in magnetostatic energy by splitting into two domains is less than the increase in energy due to the introduction of the domain wall. Particles that are below this critical size are known as “single domain particles”, and if they have sufficiently high anisotropy to prevent the easy rotation of the direction of magnetisation then the particles will be permanently magnetic and difficult to demagnetise. This type of coercivity mechanism can be observed in melt-spun NdFeB magnets where the crystal size is ~50nm, compared to the critical size for single domain particles of ~300nm.

Permanent magnets can also achieve their resistance to demagnetisation by pinning of the domain walls. In $\text{Sm}_2(\text{Co,Fe,Cu,Zr})_{17}$ type magnets this is achieved by the presence of a SmCo_5 based phase in which the domain wall energy is significantly lower than that of the majority $\text{Sm}_2\text{Co}_{17}$ based phase. The domain walls are therefore pinned within the SmCo_5 phase and both magnetisation and demagnetisation processes are difficult.

Permanent magnets can also achieve coercivity by making the nucleation of new domains difficult. This mechanism can be found in sintered NdFeB permanent magnets where a non-magnetic grain boundary phase acts to smooth the grain boundaries, removing domain nucleation sites. Nucleation controlled permanent magnets are easily magnetised as the initial state has several domains in each crystal, but are difficult to demagnetise because this would require the nucleation of new reverse domains.