The magnetic properties of the material can be investigated by hysteresis curves. It is found that the magnetic properties depend on the previous history of the particular sample. Nevertheless, one can get a sample into a state where it possesses a certain regularity of behaviour. This is accomplished by the frequent reversal of an applied field of decreasing amplitude.

Usually one applies an **H** field, produced by external free currents, and then measure **B** as a function of **H**. The diagram received, **B** versus **H** is called the *magnetization curve*. This name is also given to **M** versus **H**.

As mentioned above, the relative permeability, and the magnetic susceptibility, are constants, characteristic of the material. The permeability changes with temperature, magnetic field strength and pressure. The (absolute) permeability is given by the equation Vs/Am or H (Henry).

A magnetic material can be classified into three main groups:

- Diamagnetic, = 1 (is a very small negative number)
- Paramagnetic, = 1 (is a very small positive number)
- Ferromagnetic, >> 1 (is a large positive number)

For diamagnetic and paramagnetic substances the simple linear relation **B**=μ**H** holds. For the ferromagnetic substances, this equation must be replaced by a nonlinear functional relationship **B** = μ **F**(**H**). (The permeability for ferromagnetic materials is very rare in handbook's).

Most untreated ferromagnetic materials have a linear relationship between **B** and **H** for very small fields.

Ferromagnetic materials

For many thousands of years iron was the only known ferromagnetic substance. Today iron, nickel and cobalt and all their alloys are known to be ferromagnetic. The magnetization of ferromagnetic materials can be many orders of magnitude larger than that of paramagnetic substances. Ferromagnetism can be explained in terms of ferromagnetic domains. According to this model that has been experimentally confirmed, a ferromagnetic material is composed of many small domains, their dimensions ranging from a few microns to about 1 mm. These domains, are fully magnetized in the sense that they contain aligned magnetic dipoles resulting from spinning electrons even in the absence of an applied magnetic field. Quantum theory asserts that strong coupling forces exist between the magnetic dipole moments of the atoms in the domain, holding the dipole moments in parallel. Between adjacent domains there is a transition region about 100 atoms thick called a domain wall. In an unmagnitized state the magnetic moments of the adjacent domains in a ferromagnetic material have different direction, see figure 1 below.

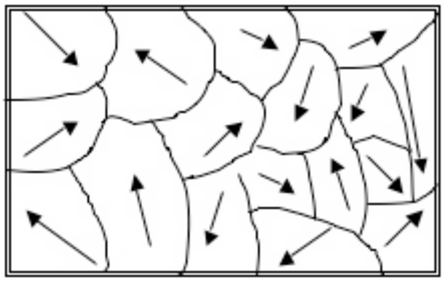

Figure 1 Domain structure.

Viewed as a whole, the random nature of the orientations in the various domains results in no net magnetization. When an external magnetic field is applied to a ferromagnetic material, the walls of those domains having magnetic moments aligning with the applied field move in such a way as to make the volumes of those domains grow at the expense of other domains. As a result magnetic flux density is increased. (The core inside the coils of the Magnetic Field Heater are of ferromagnetic material to increase the magnetic flux density). To start with the magnetic field is zero, we apply a magnetic field, when the magnetic field is weak, say up to a point between O and P1 in figure 2 below, the domain-wall moments are reversible . But when the magnetic field becomes stronger , past that point, domain wall moments are no longer reversible, and domain rotation toward the direction of the applied field will occur.

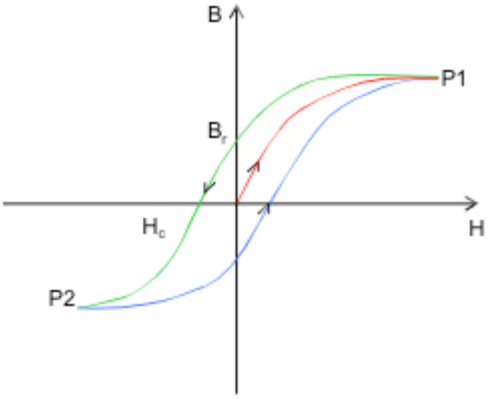

Figure 2 Hysteresis loop.

As the applied field becomes even much stronger, domain wall motion and domain rotation will cause essentially a total alignment of the microscopic magnetic moments with the applied field, at which point the magnetic material is said to have reached saturation (P1). It should be noted that beyond the saturation value, further increase in H will not produce greater magnetization of the part. Therefore for heating some materials in the Magnetic Field Heater, the H field does not have to be very high. Other materials may need a very large value of H. It should also be noted that if the core has reached saturation, further increase in H will give unnecessary energy loss. Today the core material is a limiting factor in the values of the magnetic field density that can be achieved.

The curve OP1 is called the normal magnetization curve. For example, if an applied field is reduced to zero at a point P1, the B-H relationship will not follow the solid curve P1O, but will go down from P1 to P2. This phenomenon of magnetization lagging behind the field producing it is called hysteresis. If the magnetic field is reduced to zero from the point P1 the magnetic flux density doesn’t go to zero but to the value . This value is called residual or remanent flux density. The existence of a remanent flux density in a ferromagnetic material makes permanent magnets possible. To make the magnetic flux density zero, it is necessary to apply a magnetic field intensity H in the opposite direction. This required Hc is called coercive force, but a more appropriate name would be coercive field intensity. H also depends on the maximum magnetic field intensity. As mentioned before, the permeability also depends on the history of the material's magnetization, since even for the same H we must know the location of the operating point on a particular branch of a particular hysteresis loop in order to determine exactly the value of the permeability.

Ferromagnetic materials for use in electric generators, motors, and transformers should have a large magnetization for a very small applied field; they should have tall, narrow hysteresis loops. As the applied magnetic field intensity varies periodically between +**H**max and - **H**max, the hysteresis loop is traced once per cycle. The area of the hysteresis loop traced corresponds to energy loss (hysteresis loss) per unit volume per cycle. Hysteresis loss is the energy lost in the form of heat in overcoming the friction encountered during domain wall motion and domain rotation. Ferromagnetic materials, which have tall, narrow hysteresis loops with small loop areas, are referred to as soft materials; they are usually well annealed materials with very few dislocations and impurities so that the domain walls can move easily. Good permanent magnets have a fat hysteresis curve and are referred to as *hard materials.*

Ferromagnetism is the result of strong coupling effects between the magnetic dipole moments of the atoms in the domain. When the temperature of a ferromagnetic material is raised so that the thermal energy exceeds the coupling energy, the magnetized domains becomes disorganized. Above this temperature, known as the curie temperature, a ferromagnetic substance behave like paramagnetic substance. Hence, when a permanent magnet is heated above its curie temperature it loses its magnetization.

For example, the Curie temperature of iron is 770 °C and that of nickel being 360 °C. Some elements such as chromium and manganese, which are close to ferromagnetic elements in atomic number and are neighbours of iron in the periodic table, also have strong coupling forces between the magnetic dipole moments; but their coupling forces produce antiparallel alignments of electron spins. The spins alternate in direction from atom to atom and result in no net magnetic moment. A material possessing this property is said to be antiferromagnetic, see figure 3. Antiferromagnetism is also temperature dependent. When an antiferromagnetic material reaches it's curie temperature, the spin directions suddenly become random, and the material becomes paramagnetic. There is another class of magnetic materials that exhibit a behavior between ferromagnetism and antiferromagnetism. Here quantum mechanical effects make the directions of the magnetic moments in the ordered spin structure alternate and the magnitudes unequal, resulting in a net nonzero magnetic moment. These materials are said to be ferrimagnetic. Because of the partial cancellation, the maximum magnetic flux density attained in a errimagnetic substance is substantially lower than that in a ferromagnetic specimen. Ferrites are a subgroup of ferrimagnetic materials, which we will not discuss further in this ocument.

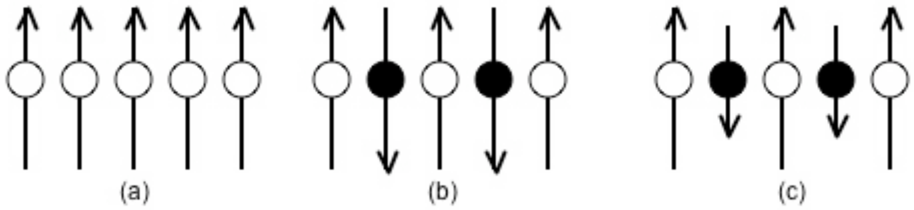

Figure 3 Orientation of magnetic dipole moments in various substances.

(a) Ferromagnetism, (b) Antiferromagnetism, (c) Ferrimagnetism.

It has been observed that the movement of domain boundaries is impeded by imperfections and proceeds in jumps. These jumps can be made audible by surrounding the crystal with an induction coil connected to an amplifier. This is called the *Barkhausen effect*, and is even more noticeable if the domains change their magnetization directions by rotation. The latter effect becomes even more prominent when the strength of the field is increased rapidly.

Paramagnetic materials

In some materials the magnetic moments due to the orbiting and spinning electrons do not cancel completely, and the atoms and molecules have a net average magnetic moment. An externally applied magnetic field, in addition to causing a very weak diamagnetic effect, tends to align the molecular magnetic moments in the direction of the applied magnetic field, thus increasing the magnetic flux density. There is little coherent interaction and the increase in magnetic flux density is quite small. Paramagnetic materials generally have very small positive values of magnetic susceptibility. Example of paramagnetic materials are aluminium, magnesium, titanium and tungsten. Unlike diamagnetism, which is essentially independent of temperature, the paramagnetic effect is temperature dependent, being stronger at lower temperatures where there is less thermal collision. Paramagnetic materials has crystalline form.

Diamagnetic materials

Example of diamagnetic materials are bismuth, copper, lead, mercury, germanium, silver, gold and diamond. Diamagnetism arises mainly from the orbital motion of the electrons within an atom and is present in all materials. Diamagnetic materials exhibit no permanent magnetism i.e. the molecules has no individual dipole moment when the **B** field is zero.

When an **B** field is applied, a small dipole moment is induced, the induced magnetic moment disappears when the applied field is withdrawn.

Magnetic dipole moment

Let us see how an atom comes to possess a magnetic moment. Take for example a hydrogen atom which just have one electron. In the Bohr model of a hydrogen atom, an electron occupies a circular orbit.

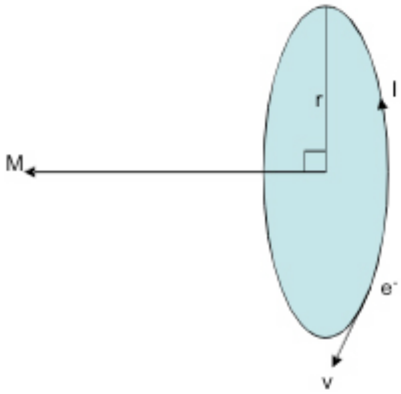

Figure 4

The magnetic dipole moment due to a current loop. An electron of charge -e is moving around a nucleus.

A moving charge is equivalent to an electric current, so that an electron moving in anclosed orbit forms a current loop, and this in turn creates a magnetic dipole. A circulating current of magnitude I enclosing a small plane area dA gives rise to a magnetic dipole moment, M = I dA. It is possible to measure the magnetic dipole moments of atoms but we won’t go further into that here. It should be noted that an external magnetic field produces in an atom a magnetic dipole moment in a direction opposite to the applied field and that the substance as a whole will acquire a magnetization opposed to the applied magnetic field.