

Magnetostatic Testing Methods

Overview and General Principles

Electrical, Magnetic and Penetrant Methods

Overall Module Assessment:

Examination 60%

Assignments 40%

Magnetostatic Methods Assignments/Coursework: Contribute 20% of above

5 Task based Assignments 5%

1 Major Analytical Report 15%

Magnetic Testing - Introduction

Generally two specific methods:

- **Magnetic Particle**

uses magnetic fields and small magnetic particles (e.g. iron filings) or magnetic ink, to detect flaws in components. The only requirement from an inspection standpoint is that the component being inspected must be made of a ferromagnetic material such as iron, nickel, cobalt, or some of their alloys.

- **Magnetic Flux Leakage**

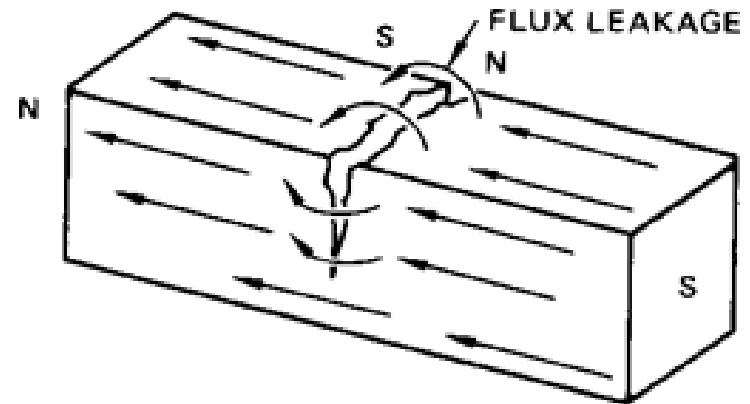
MFL technology is similar to Magnetic Particle Inspection (MPI) but without the ink or magnetic particle. With MFL, suitable sensors are used to give an electrical signal at the leakage site. This signal may operate an audible or visual alarm to alert the inspector, or may store the event for computer mapping of the area.

Magnetic Testing - General Principles

MFL requires two basic things:

- a method of magnetisation, and
- a method of detecting the leakage field.

The component is magnetised to a level at which the presence of a significant local reduction in material thickness or volume causes sufficient distortion of the internal magnetic field to allow flux lines to break the test surface at the site of the discontinuity.



Magnetic Testing - General Principles

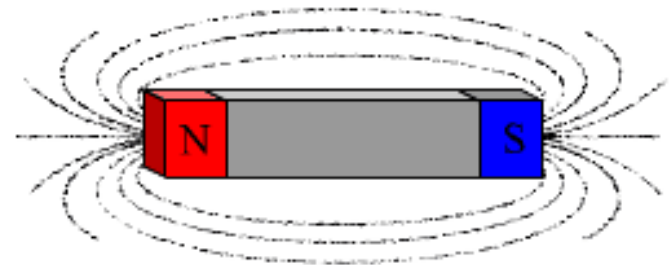
Magnetic Particle Inspection

Combination of two methods:

- Magnetic Flux Leakage
- Visual Testing

A bar magnet has both an internal and external magnetic field. Any place that a magnetic line of force exits or enters the magnet is called a pole.

- A pole where a magnetic line of force exits the magnet is called a north pole and,
- a pole where a line of force enters the magnet is called a south pole.

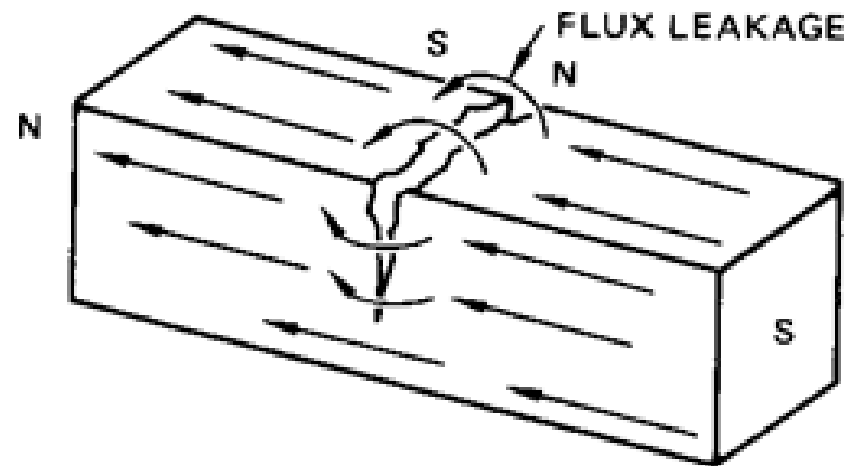
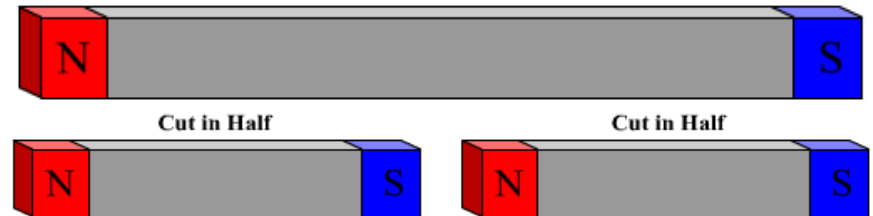


Magnetic Testing - General Principles

When a bar magnet is broken in the centre of its length, two complete bar magnets with magnetic poles on each end of each piece will result.

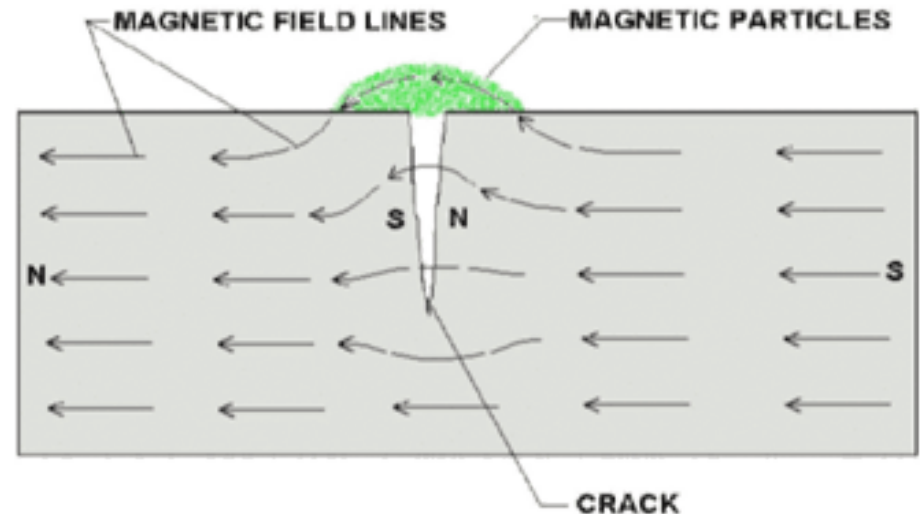
If the magnet is just cracked but not broken completely in two, a north and south pole will form at each edge of the crack. The magnetic field exits the north pole and re-enters at the south pole.

The magnetic field spreads out when it encounters the small air gap created by the crack because the air cannot support as much magnetic field per unit volume as the magnet can. When the field spreads out, it appears to leak out of the material and, thus is called a **flux leakage field**.



Magnetic Testing - General Principles

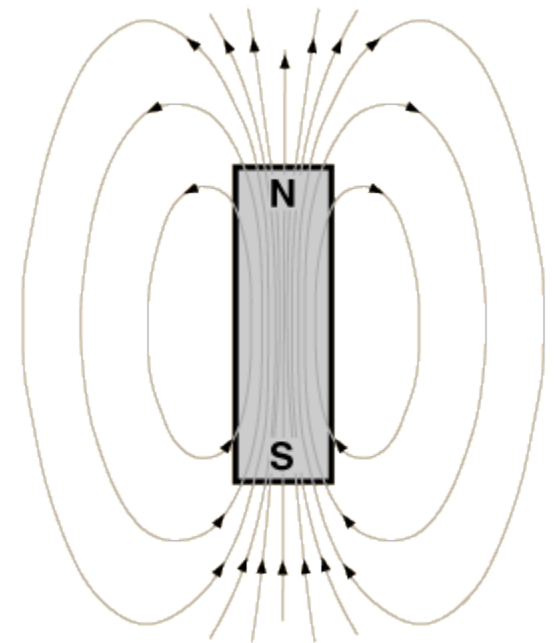
- If iron particles are sprinkled on a cracked magnet, the particles will be attracted to and cluster not only at the poles at the ends of the magnet, but also at the poles at the edges of the crack.
- This cluster of particles is much easier to see than the actual crack and this is the basis for magnetic particle inspection.



Magnetism

Magnetic Dipole

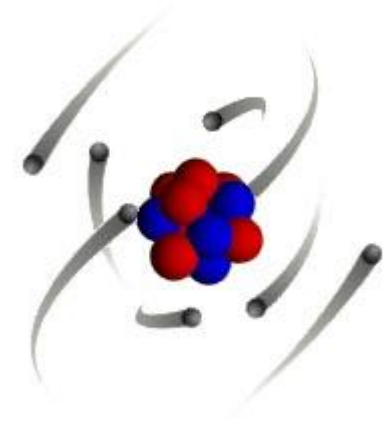
- Most people are familiar with the general properties of magnets but are less familiar with the source of magnetism.
- The traditional concept of magnetism centres around the magnetic field and what is known as a dipole.
- The term "**magnetic field**" simply describes a volume of space where there is a change in energy within that volume. This change in energy can be detected and measured.
- The location where a magnetic field can be detected exiting or entering a material is called a magnetic pole.
- Magnetic poles have never been detected in isolation but always occur in pairs, hence the name dipole. Therefore, a **dipole** is an object that has a magnetic pole on one end and a second, equal but opposite, magnetic pole on the other.



Magnetism

Source of Magnetism

- All matter is composed of atoms
- Atoms in turn are composed of protons, neutrons and electrons.
- The protons and neutrons are located in the atom's nucleus and the electrons are in constant motion around the nucleus.
- Electrons carry a negative electrical charge and produce a magnetic field as they move through space.
- A magnetic field is produced whenever an electrical charge is in motion.
- The strength of this field is called the **magnetic moment**.

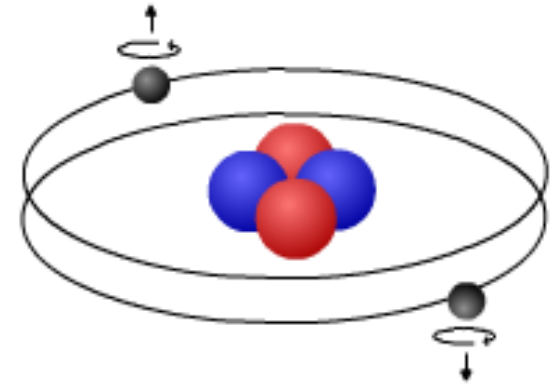


Magnetic Material Characteristics

- When a material is placed within a magnetic field, the magnetic forces of the material's electrons will be affected. This effect is known as Faraday's Law of Magnetic Induction.
- Materials can react quite differently to the presence of an external magnetic field and is dependent on a number of factors, such as the atomic and molecular structure of the material, and the net magnetic field associated with the atoms.
- The magnetic moments associated with atoms have three origins:
 - the electron orbital motion,
 - the change in orbital motion caused by an external magnetic field, and
 - the spin of the electrons.

Magnetic Material Characteristics

- In most atoms, electrons occur in pairs that spin in opposite directions.
- When electrons are paired together, their opposite spins cause their magnetic fields to cancel each other, and therefore, no net magnetic field exists.
- Alternately, materials with some unpaired electrons will have a net magnetic field and will react more to an external field.



Most materials can be classified by their response to externally applied magnetic fields as diamagnetic, paramagnetic or ferromagnetic.

Magnetic Material Characteristics

These magnetic responses differ greatly in strength.

- Diamagnetism is a property of all materials and opposes applied magnetic fields, but is very weak.
- Para-magnetism, when present, is stronger than diamagnetism and produces magnetization in the direction of the applied field, and proportional to the applied field.
- Ferromagnetic effects are very large, producing magnetizations sometimes orders of magnitude greater than the applied field and as such are much larger than either diamagnetic or paramagnetic effects.

Magnetic Material Characteristics

Diamagnetic materials – Main Points

- Very weak and negative susceptibility to magnetic fields.
- Slightly repelled by a magnetic field and the material does not retain the magnetic properties when the external field is removed.
- Materials are solids with all paired electrons resulting in no permanent net magnetic moment per atom.
- Diamagnetic properties arise from the realignment of the electron orbits under the influence of an external magnetic field.
- Most elements in the periodic table, including copper, silver, and gold, are diamagnetic.

Magnetic Material Characteristics

Paramagnetic Materials - Main Points

- have a small and positive susceptibility to magnetic fields.
- Slightly attracted by a magnetic field and the material does not retain the magnetic properties when the external field is removed.
- Paramagnetic properties are due to the presence of some unpaired electrons, and from the realignment of the electron orbits caused by the external magnetic field.
- Paramagnetic materials include magnesium, molybdenum, lithium, and tantalum.

Magnetic Material Characteristics

Ferromagnetic Materials – Main Points

- have a large and positive susceptibility to an external magnetic field.
- They exhibit a strong attraction to magnetic fields and are able to retain their magnetic properties after the external field has been removed.
- Ferromagnetic materials have some unpaired electrons so their atoms have a net magnetic moment.
- ***They get their strong magnetic properties due to the presence of magnetic domains. In these domains, large numbers of atom's moments (10^{12} to 10^{15}) are aligned parallel so that the magnetic force within the domain is strong.***
- When a ferromagnetic material is in the unmagnetized state, the domains are nearly randomly organized and the net magnetic field for the part as a whole is zero. When a magnetizing force is applied, the domains become aligned to produce a strong magnetic field within the part.

Note:

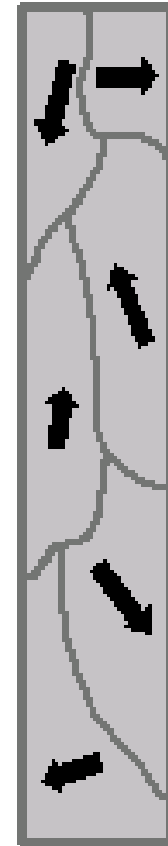
Components comprising of these materials are commonly inspected using the magnetic particle or magnetic flux leakage methods.

Ferromagnetism

- Iron, nickel, cobalt and some of the rare earths (gadolinium, dysprosium) exhibit this behaviour.
- Iron is the most common and most dramatic example.
- Samarium and neodymium in alloys with cobalt have been used to fabricate very strong rare-earth magnets.

Ferromagnetism and Magnetic Domains

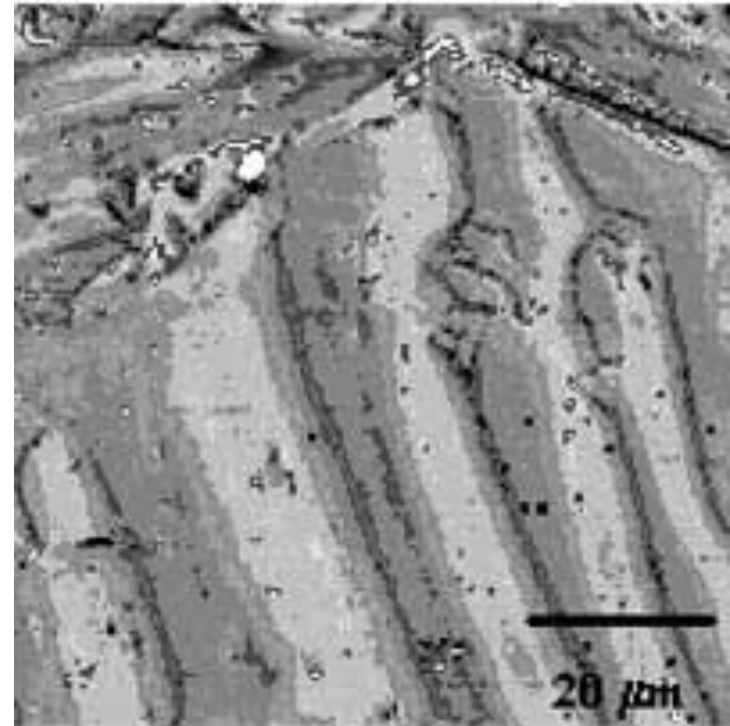
- Ferromagnetic materials get their magnetic properties not only because their atoms carry a magnetic moment but also because the material is made up of small regions known as magnetic domains.
- In each domain, all of the atomic dipoles are coupled together in a preferential direction. This alignment develops as the material develops its crystalline structure during solidification from the molten state.
- Within any one domain, the magnetic field is intense, but in a bulk sample the material will usually be unmagnetized because the many domains will themselves be randomly oriented with respect to one another.



Unmagnetized Material

Ferromagnetism and Magnetic Domains

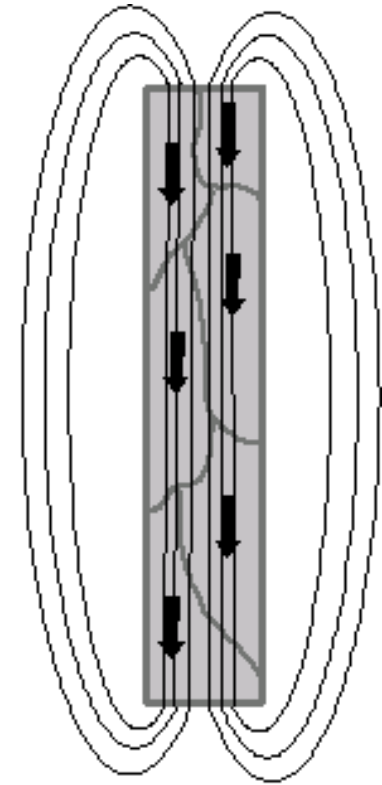
- During solidification, a trillion or more atom moments are aligned parallel so that the magnetic force within the domain is strong in one direction.
- Ferromagnetic materials are said to be characterized by "spontaneous magnetization" since they obtain saturation magnetization in each of the domains without an external magnetic field being applied.
- Even though the domains are magnetically saturated, the bulk material may not show any signs of magnetism because the domains develop themselves and are randomly oriented relative to each other.



Magnetic Force Microscopy (MFM) image showing the magnetic domains in a piece of heat treated carbon steel.

Ferromagnetism and Magnetic Domains

- Ferromagnetism manifests itself in the fact that a small externally imposed magnetic field can cause the magnetic domains to line up with each other and the material is said to be magnetized.
- The driving magnetic field will then be increased by a large factor which is usually expressed as a relative permeability for the material.
- Ferromagnets will tend to stay magnetized to some extent after being subjected to an external magnetic field. This tendency to "remember their magnetic history" is called hysteresis.
- The fraction of the saturation magnetization which is retained when the driving field is removed is called the remanence of the material, and is an important factor in permanent magnets.
- All ferromagnets have a maximum temperature where the ferromagnetic property disappears as a result of thermal agitation. This temperature is called the Curie temperature.
- Ferromagnetic materials will respond mechanically to an impressed magnetic field, changing length slightly in the direction of the applied field. This property, called magnetostriction, leads to the familiar hum of transformers as they respond mechanically to 60 Hz AC voltages.

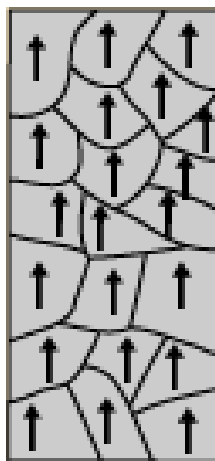


Magnetized Material

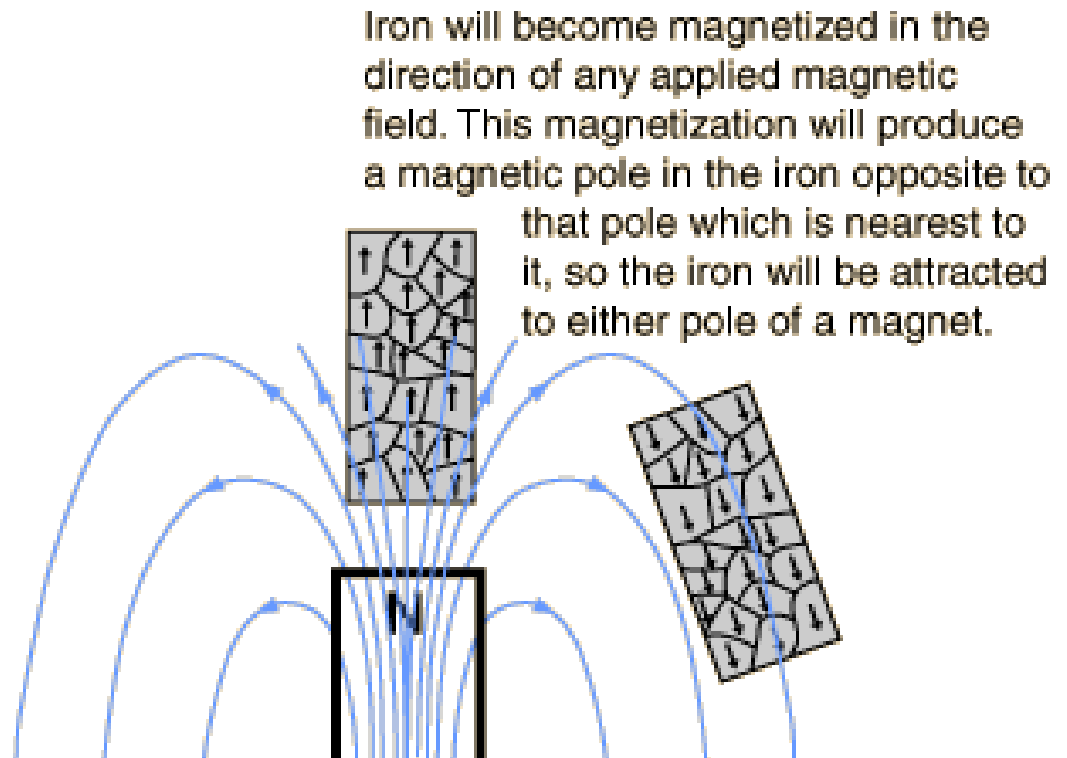
Ferromagnetism and Magnetic Domains



In bulk material the domains usually cancel, leaving the material unmagnetized.



Externally applied magnetic field.

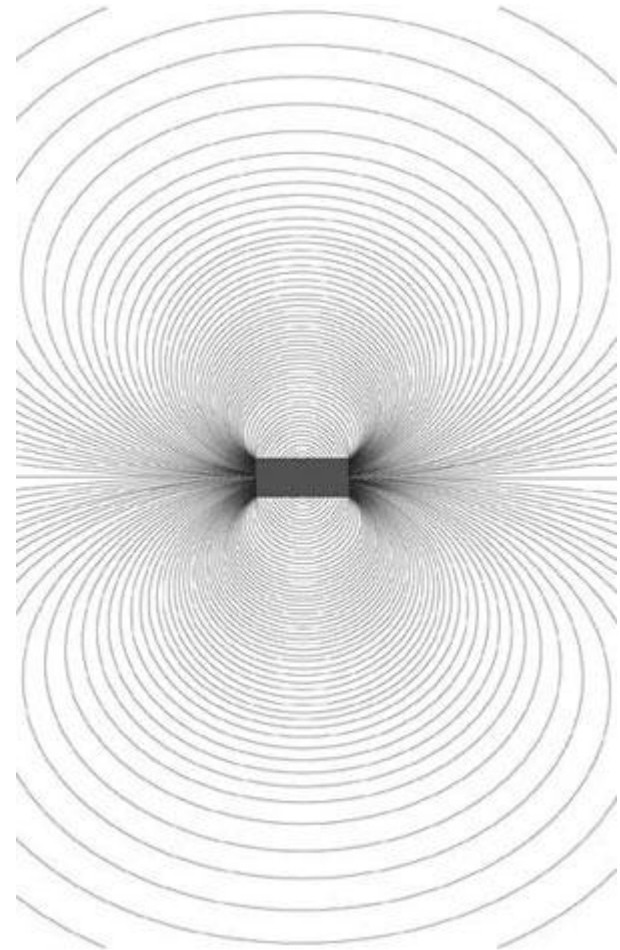


Iron will become magnetized in the direction of any applied magnetic field. This magnetization will produce a magnetic pole in the iron opposite to that pole which is nearest to it, so the iron will be attracted to either pole of a magnet.

General Properties of Magnetic Lines of Force

Magnetic lines of force have a number of important properties, which include:

- They seek the path of least resistance between opposite magnetic poles. In a single bar magnet as shown to the right, they attempt to form closed loops from pole to pole.
- They never cross one another.
- They all have the same strength.
- Their density decreases (they spread out) when they move from an area of higher permeability to an area of lower permeability.
- Their density decreases with increasing distance from the poles.
- They are considered to have direction as if flowing, though no actual movement occurs.
- They flow from the south pole to the north pole within a material and north pole to south pole in air.



Quantifying Magnetic Properties

(Magnetic Field Strength, Flux Density, Total Flux and Magnetization)

- Only the qualitative features of the magnetic field have been discussed so far.
- It is necessary to be able to measure and express quantitatively the various characteristics of magnetism.
- Unfortunately, a number of unit conventions are used.
- Advantage of using SI units is that they are traceable back to an agreed set of four base units - meter, kilogram, second, and Ampere.

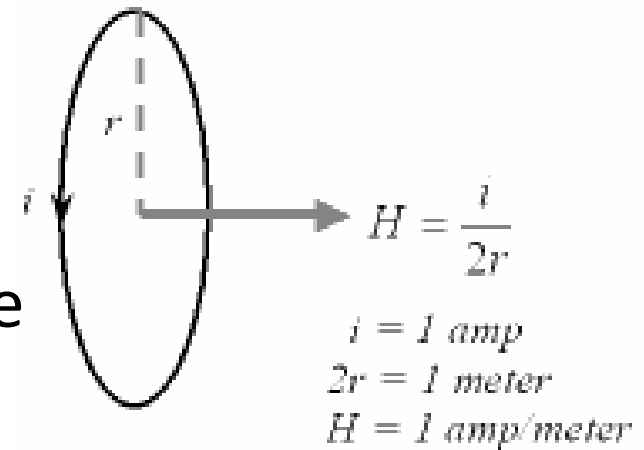
Quantity	Symbol	SI Units (Sommerfeld)	SI Units (Kennelly)	CGS Units (Gaussian)
Field Intensity/Strength	H	A/m	A/m	oersteds
Flux/Field Density (Magnetic Induction)	B	tesla	tesla	gauss
Flux	Φ	weber	weber	maxwell
Magnetization	M	A/m	-	erg/Oe-cm ³

Quantifying Magnetic Properties

(Magnetic Field Strength, Flux Density, Total Flux and Magnetization)

Magnetic Field Strength - H

- The units for magnetic field strength H are ampere/meter.
- A magnetic field strength of 1 ampere/meter is produced at the centre of a single circular conductor with a one meter diameter carrying a steady current of 1 ampere.



Quantifying Magnetic Properties

(Magnetic Field Strength, Flux Density, Total Flux and Magnetization)

Magnetic Flux Density - B

- The number of magnetic lines of force cutting through a plane of a given area at a right angle.
- The flux density or magnetic induction has the tesla as its unit.
- One tesla is equal to 1 Newton/(A/m).

Note: From these units, it can be seen that the flux density is a measure of the force applied to a particle by the magnetic field.

- The Gauss is the CGS unit for flux density and is commonly used by US industry with One gauss representing one line of flux passing through one square centimeter of air oriented 90 degrees to the flux flow.

Quantifying Magnetic Properties

(Magnetic Field Strength, Flux Density, Total Flux and Magnetization)

Magnetic Flux – ϕ

- The total number of lines of magnetic force in a material.
- The strength of the flux is determined by the number of magnetic domains that are aligned within a material.
- The total flux is simply the flux density applied over an area. Flux carries the unit of a weber, which is simply a tesla/meter².

Magnetization – M

- A measure of the extent to which an object is magnetized.
- It is a measure of the magnetic dipole moment per unit volume of the object.
- Magnetization carries the same units as a magnetic field: amperes/meter.

Quantifying Magnetic Properties

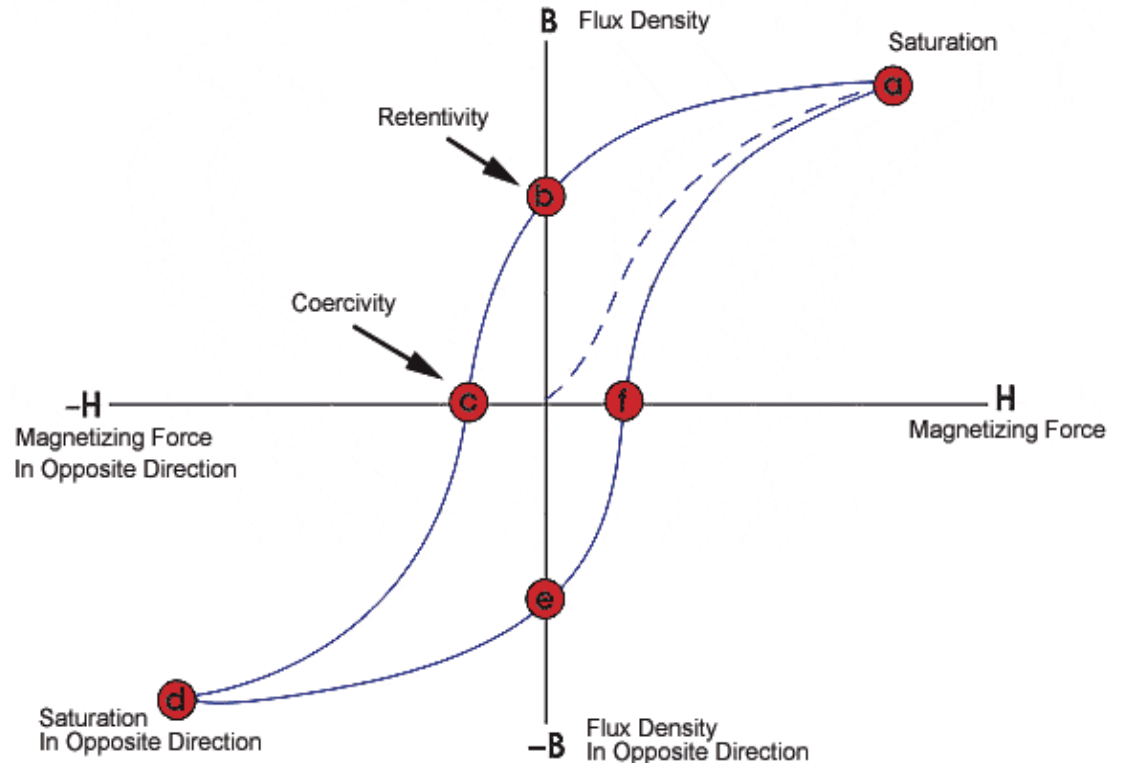
(Magnetic Field Strength, Flux Density, Total Flux and Magnetization)

Conversion between CGS and SI magnetic units

Quantity	CGS unit	SI Unit
Magnetic field	$H = 1 \text{ Oe}$	$H = 1000/4\pi \text{ A.m}^{-1}$
Magnetic induction	$B = 1 \text{ gauss}$	$B = 1 \times 10^{-4} \text{ Tesla}$
Magnetization	$M = 1 \text{ erg.Oe}^{-1}.\text{cm}^{-3}$	$M = 1 \times 10^3 \text{ A.m}^{-1}$

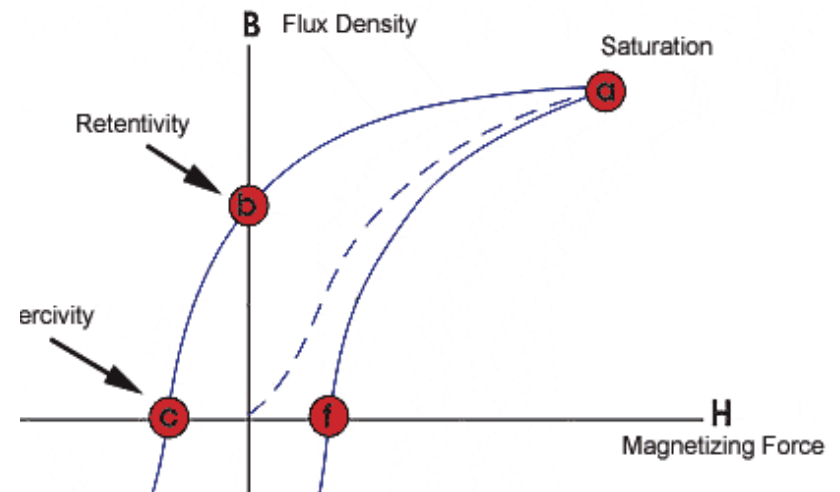
The Hysteresis Loop and Magnetic Properties

- A hysteresis loop shows the relationship between the induced magnetic flux density (**B**) or magnetization (**M**), and the magnetizing force (**H**) for a material.
- It is often referred to as the B-H loop.
- The loop is generated by measuring the magnetic flux of a ferromagnetic material while the magnetizing force is changed.



Hysteresis Loop

- A ferromagnetic material that has never been previously magnetized or has been thoroughly demagnetized will follow the dashed line as H is increased.
- The greater the amount of current applied (H), the stronger the magnetic field in the component (B).
- At point "a" almost all of the magnetic domains are aligned and an additional increase in the magnetizing force will produce very little increase in magnetic flux.
- The material has reached the point of magnetic saturation.



Hysteresis Loop

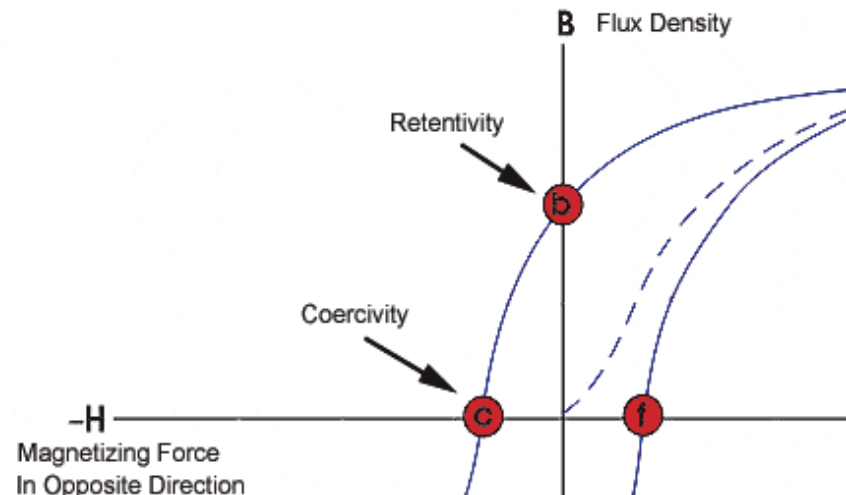
When H is reduced to zero, the curve will move from point "a" to point "b".

- At this point, it can be seen that some magnetic flux remains in the material even though the magnetizing force is zero.
- This is referred to as the point of retentivity on the graph and indicates the remanence or level of residual magnetism in the material.

(Some of the magnetic domains remain aligned but some have lost their alignment.)

As the magnetizing force is reversed, the curve moves to point "c".

- The flux has been reduced to zero.
- This is called the point of coercivity on the curve.
- The reversed magnetizing force has flipped enough of the domains so that the net flux within the material is zero.
- The force required to remove the residual magnetism from the material is called the coercive force or coercivity of the material.

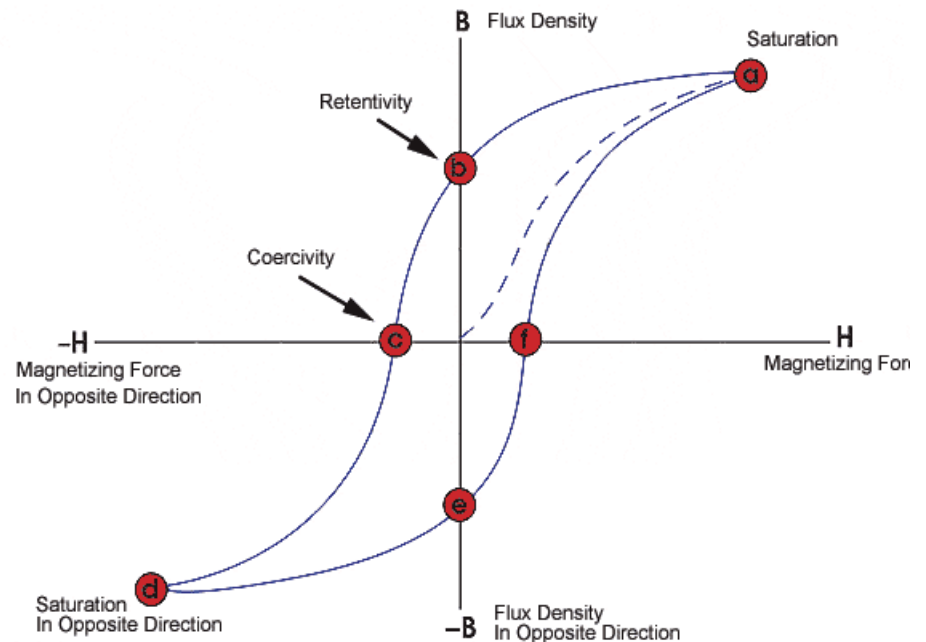


Hysteresis Loop

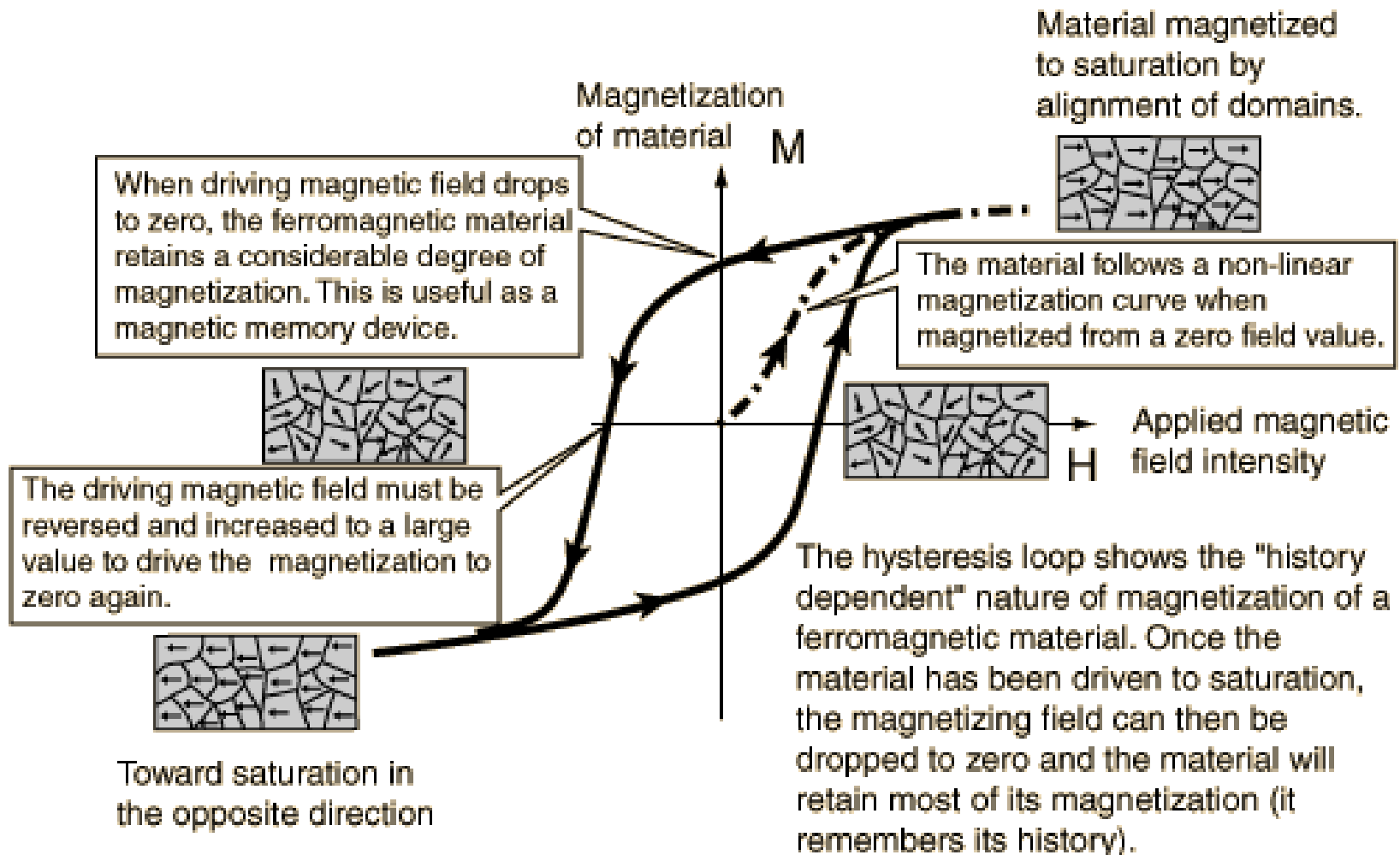
- As the magnetizing force is increased in the negative direction, the material will again become magnetically saturated but in the opposite direction (point "d").
- Reducing H to zero brings the curve to point "e." It will have a level of residual magnetism equal to that achieved in the other direction.
- Increasing H back in the positive direction will return B to zero.

Notice that the curve did not return to the origin of the graph because some force is required to remove the residual magnetism.

- The curve will take a different path from point "f" back to the saturation point where it will complete the loop.

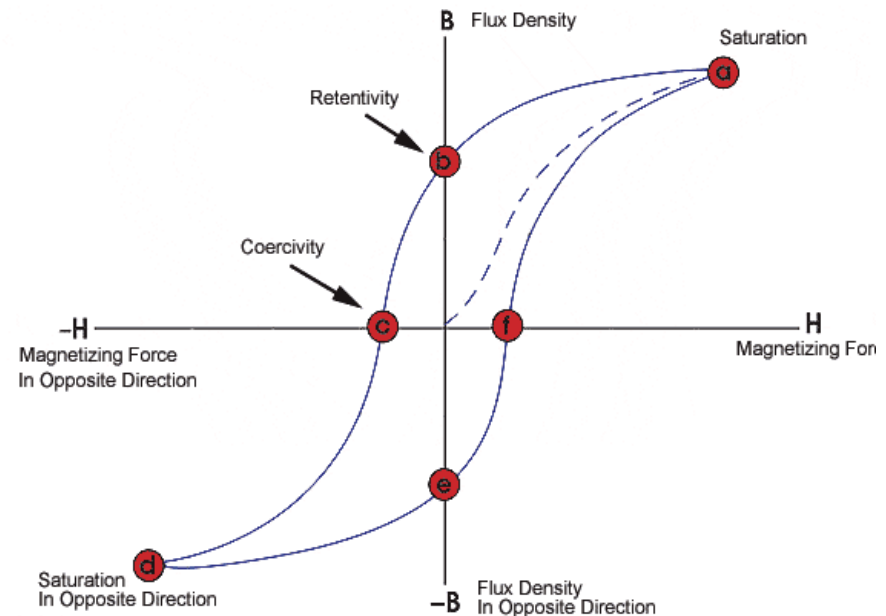


Hysteresis Loop



Hysteresis Loop – Primary Properties

- **Retentivity** - A measure of the residual flux density corresponding to the saturation induction of a magnetic material. In other words, it is a material's ability to retain a certain amount of residual magnetic field when the magnetizing force is removed after achieving saturation. (The value of **B** at point b on the hysteresis curve.)
- **Residual Magnetism** or **Residual Flux** - the magnetic flux density that remains in a material when the magnetizing force is zero. Note that residual magnetism and retentivity are the same when the material has been magnetized to the saturation point. However, the level of residual magnetism may be lower than the retentivity value when the magnetizing force did not reach the saturation level.
- **Coercive Force** - The amount of reverse magnetic field which must be applied to a magnetic material to make the magnetic flux return to zero. (The value of **H** at point c on the hysteresis curve)
- **Permeability, μ** - A property of a material that describes the ease with which a magnetic flux is established in the component.
- **Reluctance** - Is the opposition that a ferromagnetic material shows to the establishment of a magnetic field. Reluctance is analogous to the resistance in an electrical circuit.



Permeability

- Permeability is a material property that describes the ease with which a magnetic flux is established in a component.
- It is the ratio of the flux density to the magnetizing force

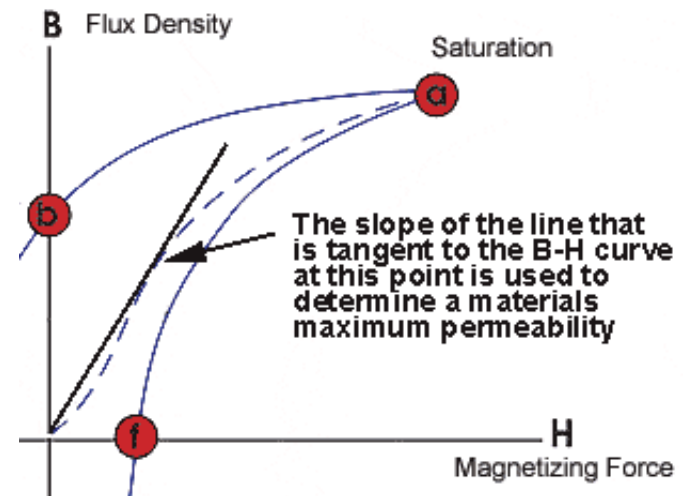
$$\mu = B/H$$

- The equation describes the slope of the curve at any point on the hysteresis loop (absolute permeability without suffix)
- The permeability value given in papers and reference materials is usually the maximum permeability or the maximum relative permeability.
- The maximum permeability is the point where the slope of the B/H curve for the unmagnetized material is the greatest and is often taken as the point where a straight line from the origin is tangent to the B/H curve.
- The relative permeability is arrived at by taking the ratio of the material's permeability to the permeability in free space (air).

$$\mu(\text{relative}) = \mu(\text{material}) / \mu(\text{air})$$

where:

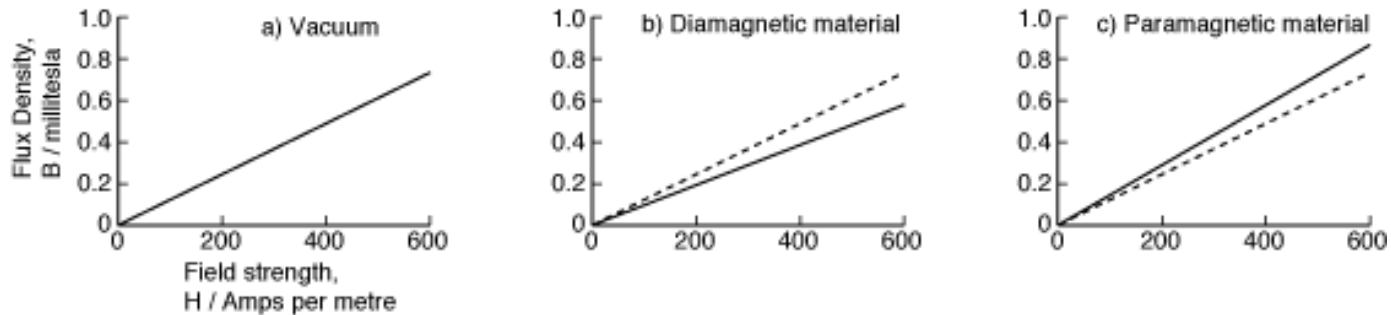
$$\mu(\text{air}) = 1.256 \times 10^{-6} \text{ H/m}$$



Try determining from actual magnetisation curves!

Magnetization Curves

Figure MPA: Magnetization in different materials



Negative values of H aren't shown but the graphs are symmetrical about the vertical axis.

Fig. MPA a) is the curve in the absence of any material: a vacuum. The gradient of the curve is $4\pi \cdot 10^{-7}$ which corresponds to the fundamental physical constant μ_0 .

Of greater interest is to see how placing a specimen of some material in the field affects this gradient. Manufacturers of a particular grade of ferrite material usually provide this curve because the shape reveals how the core material in any component made from it will respond to changes in applied field.

Magnetization Curves

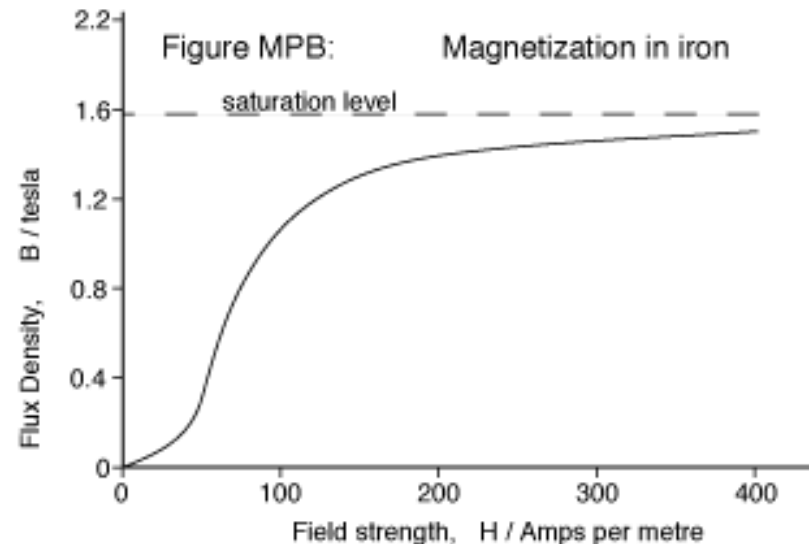
The figure shows a typical curve for iron.

The magnetization curves for ferromagnetic materials are all strongly dependant upon purity, heat treatment and other factors.

Two main features of this curve are immediately apparent:

- it is curved rather than straight (as with non-ferromagnets) and also,
- the vertical scale is now in teslas (rather than mT as with the previous figures).

This is a *normal magnetization curve* because it starts from an unmagnetized sample and shows how the flux density increases as the field strength is increased.



You can identify four distinct regions in most such curves. These can be explained in terms of changes to the material's magnetic 'domains':

- Close to the origin a slow rise due to 'reversible growth'.
- A longer, fairly straight, stretch representing 'irreversible growth'.
- A slower rise representing 'rotation'.
- An almost flat region corresponding to paramagnetic behaviour and then μ_0 - the core can't handle any more flux growth and has *saturated*.

Relative Permeability

- Relative permeability is a variation upon 'straight' or absolute permeability, μ , and provides a clearer view of how the presence of a particular material affects the relationship between flux density and field strength.
- The term 'relative' arises because this permeability is defined in relation to the permeability of a vacuum, μ_0 .

$$\mu_r = \mu / \mu_0$$

For example, If you use a material for which $\mu_r = 3$ then you know that the flux density will be three times as great as it would be if we just applied the same field strength to a vacuum. i.e. $\mu = 3.77 \times 10^{-6} \text{ H m}^{-1}$.

μ_r is a dimensionless ratio and therefore no units are associated with it.

Many texts simply say "permeability" and leave you to infer that they mean relative permeability.

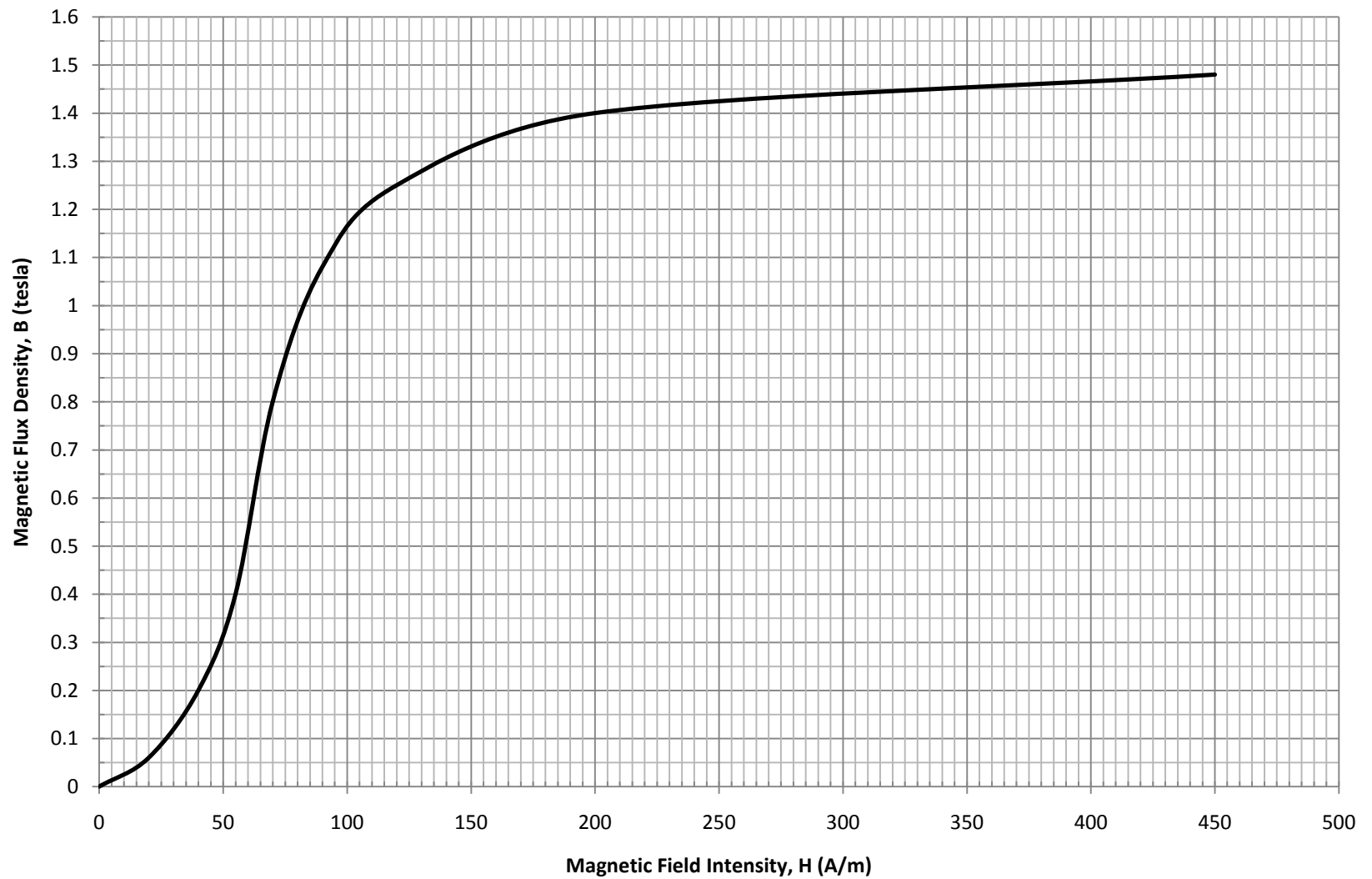
In the CGS system of units these are one and the same thing really. If a figure greater than 1.0 is quoted then you can be almost certain it is μ_r .

Permeability of Iron

Practical Task 1

- Using the normal magnetization curve for Iron provided overleaf, estimate graphically the materials maximum absolute and relative permeability values.
- Estimate incremental permeability values (dB/dH) and produce the estimated permeability curve for Iron.
- On your graph, identify the 4 distinct regions involved in the materials magnetization

Soft Iron B-H Magnetization Curve



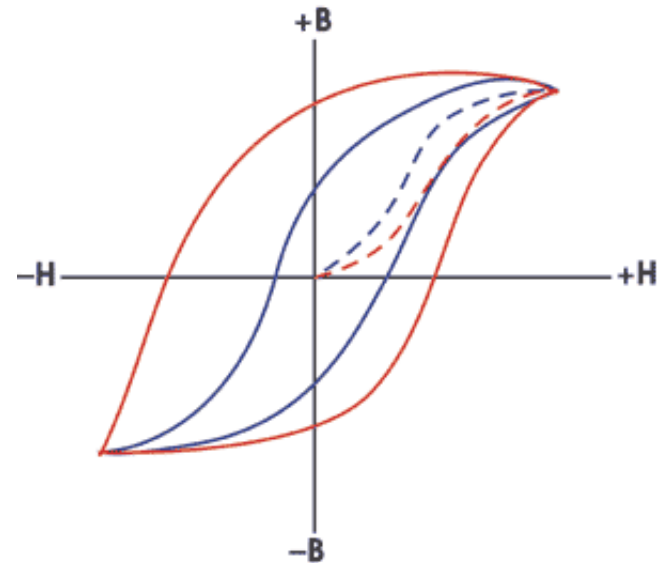
Hysteresis Loop General Consideration

Relative to other materials, a material with a wider hysteresis loop has:

- Lower Permeability
- Higher Retentivity
- Higher Coercivity
- Higher Reluctance
- Higher Residual Magnetism

Relative to other materials, a material with the narrower hysteresis loop has:

- Higher Permeability
- Lower Retentivity
- Lower Coercivity
- Lower Reluctance
- Lower Residual Magnetism.



Hysteresis Loop General Consideration

Residual Magnetism

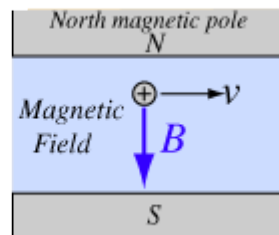
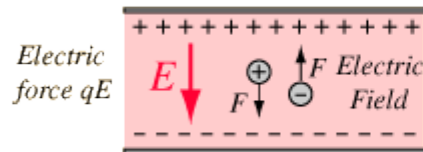
- In magnetic particle and flux leakage testing, the level of residual magnetism is important.
- Residual magnetic fields are affected by the permeability, which can be related to the carbon content and alloying of the material.
- A component with high carbon content will have low permeability and will retain more magnetic flux than a material with low carbon content.

Magnetic Fields

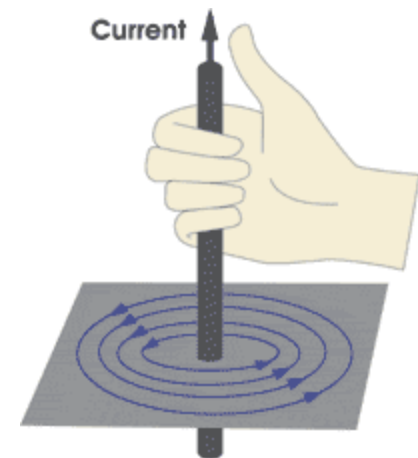
- Magnetic fields are produced by electric currents, which can be macroscopic currents in wires, or microscopic currents associated with electrons in atomic orbits.
- The magnetic field B is defined in terms of force on a moving charge in the Lorentz force law.
- The electric force is straightforward, being in the direction of the electric field if the charge q is positive, but the direction of the magnetic part of the force is given by the right hand rule.

$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$$

Electric force
Magnetic force

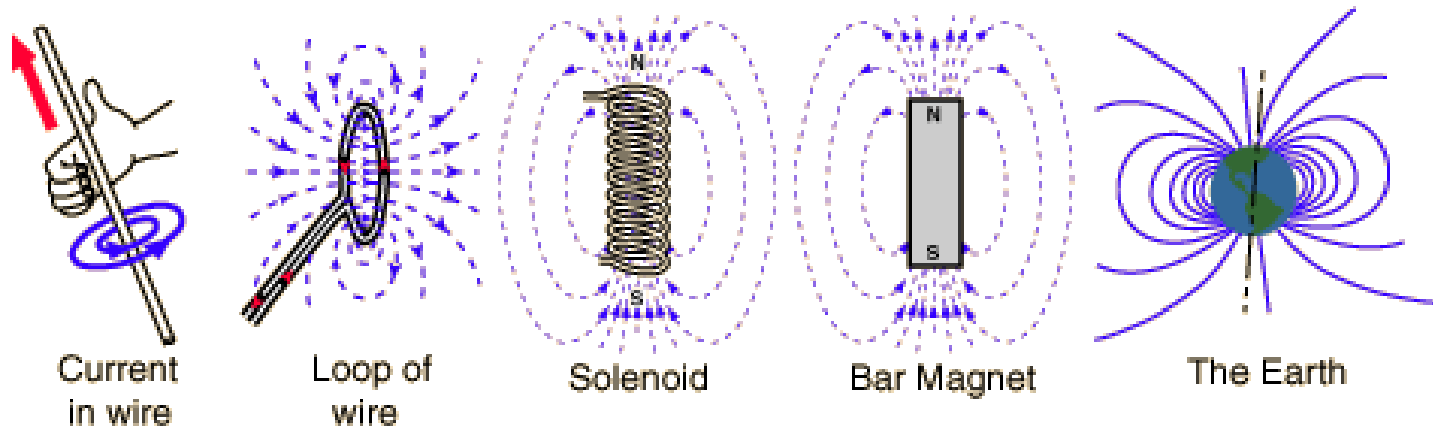


Magnetic force of magnitude $qvB\sin\theta$ perpendicular to both v and B , away from viewer.



Magnetic Fields

- Magnetic field sources are essentially dipolar in nature, having a north and south magnetic pole.
- The SI unit for magnetic field is the Tesla, which can be seen from the magnetic part of the Lorentz force law
- $F_{\text{magnetic}} = qvB$ to be composed of (Newton x second)/(Coulomb x meter).
- A smaller magnetic field unit is the Gauss (1 Tesla = 10,000 Gauss).



Magnetic Field Sources

Magnetic Field of Current

The magnetic field of an infinitely long straight wire can be obtained by applying Ampere's law.

Ampere's law takes the form

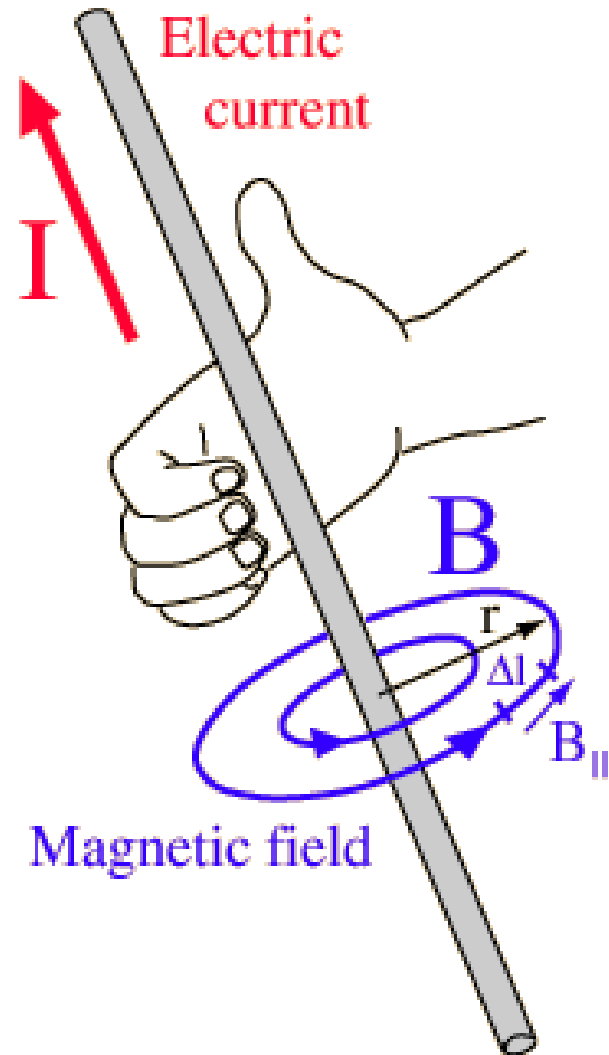
$$\sum B_{\parallel} \Delta l = \mu_0 I$$

and for a circular path centred on the wire, the magnetic field is everywhere parallel to the path. The summation then becomes:

$$\sum B_{\parallel} \Delta l = B 2\pi r$$

$$B = \frac{\mu_0 I}{2\pi r}$$

$$\mu_0 = 4\pi \times 10^{-7} \text{ T} \cdot \text{m} / \text{A}$$



Magnetic Field of Current

Practical Task 2.

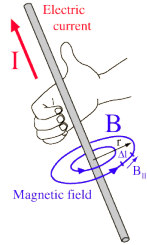
For an infinite length conductor carrying a current of 1.8A, determine the magnetic field density at a radial distance of 0.15m.

For incremental values of radial distance produce a magnetic field density/radial distance curve.

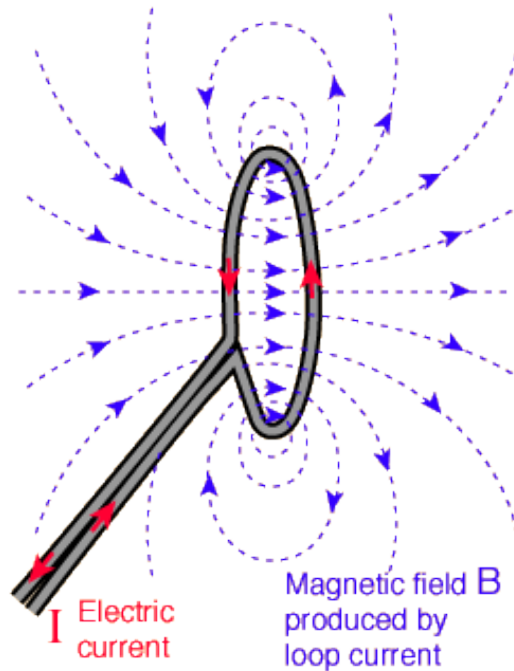
$$B = \frac{\mu_0 I}{2\pi r}$$

$$\mu_0 = 4\pi \times 10^{-7} \text{ T} \cdot \text{m} / \text{A}$$

Magnetic Field of Current Loop



Examining the direction of the magnetic field produced by a current-carrying segment of wire shows that all parts of the loop contribute magnetic field in the same direction inside the loop.



Electric current in a circular loop creates a magnetic field which is more concentrated in the centre of the loop than outside the loop. Stacking multiple loops concentrates the field even more into what is called a solenoid.

Field at Centre of Current Loop

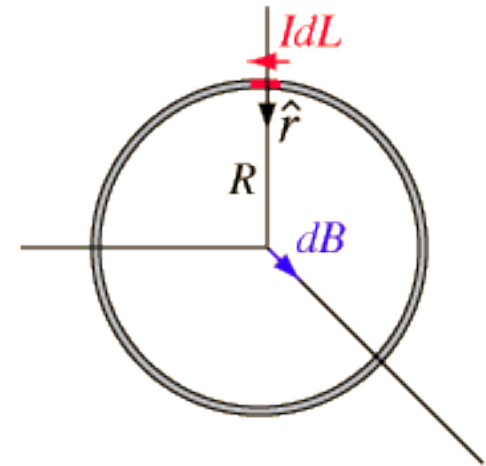
The form of the magnetic field from a current element in the Biot-Savart law becomes

$$dB = \frac{\mu_0 I d\vec{L} \times \hat{r}}{4\pi R^2} = \frac{\mu_0 I dL \sin\theta}{4\pi R^2}$$

which in this case simplifies greatly because the angle $= 90^\circ$ for all points along the path and the distance to the field point is constant. The integral becomes

$$B = \frac{\mu_0 I}{4\pi R^2} \oint dL = \frac{\mu_0 I}{4\pi R^2} 2\pi R = \frac{\mu_0 I}{2R}$$

$$\mu_0 = 4\pi \times 10^{-7} \text{ T} \cdot \text{m} / \text{A}$$



In this special case the symmetry is such that the field contributions of all the current elements around the circumference add directly at the center. The line integral of the length is just the circumference of the circle.

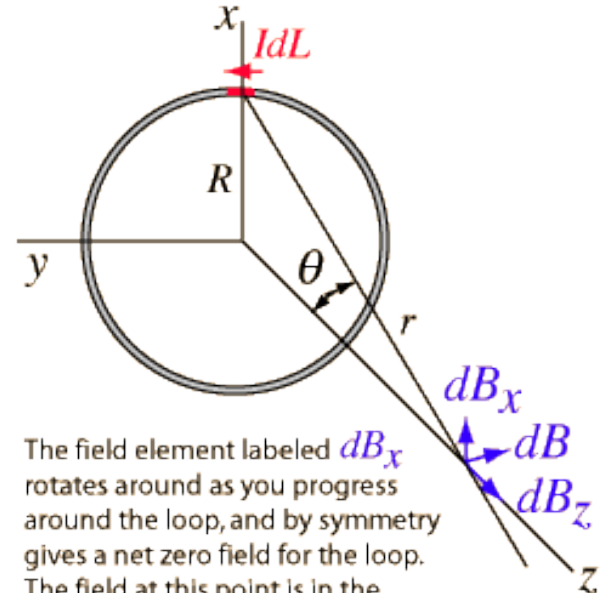
Field on Axis of Current Loop

The application of the Biot-Savart law on the centreline of a current loop involves integrating the z-component.

$$dB_z = \frac{\mu_0 IdL}{4\pi} \frac{R}{(z^2 + R^2)^{3/2}}$$

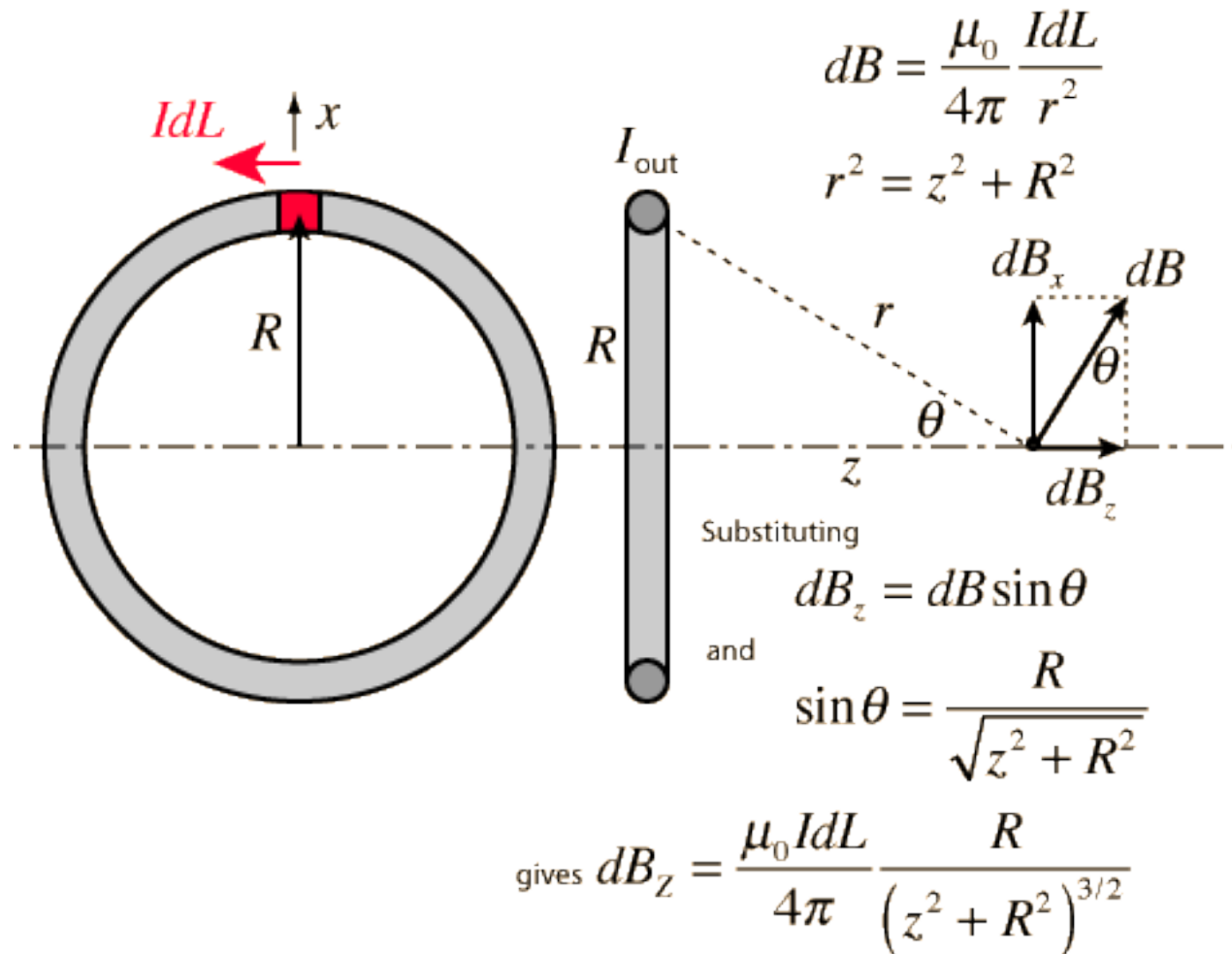
The symmetry is such that all the terms in this element are constant except the distance element dL , which when integrated just gives the circumference of the circle. The magnetic field is then

$$B_z = \frac{\mu_0}{4\pi} \frac{2\pi R^2 I}{(z^2 + R^2)^{3/2}}$$



The field element labeled dB_x rotates around as you progress around the loop, and by symmetry gives a net zero field for the loop. The field at this point is in the z-direction, along the centerline of the loop.

Geometry of Current Loop



Magnetic Field of Current Loop

Practical Task 3.

For a current loop with Current $I = 5\text{A}$ and a loop radius $R = 0.1\text{m}$, calculate the magnetic field at the centre of the loop

$$B = \frac{\mu_0 I}{4\pi R^2} \oint dL = \frac{\mu_0 I}{4\pi R^2} 2\pi R = \frac{\mu_0 I}{2R}$$

At a distance $z=0.001\text{m}$ out along the centreline of the loop calculate the axial magnetic field.

$$B_z = \frac{\mu_0}{4\pi} \frac{2\pi R^2 I}{(z^2 + R^2)^{3/2}}$$

For a range of incremental axial distances calculate the axial field strength and produce a magnetic field/axial distance correlation curve.

$$\mu_0 = 4\pi \times 10^{-7} \text{ T} \cdot \text{m} / \text{A}$$

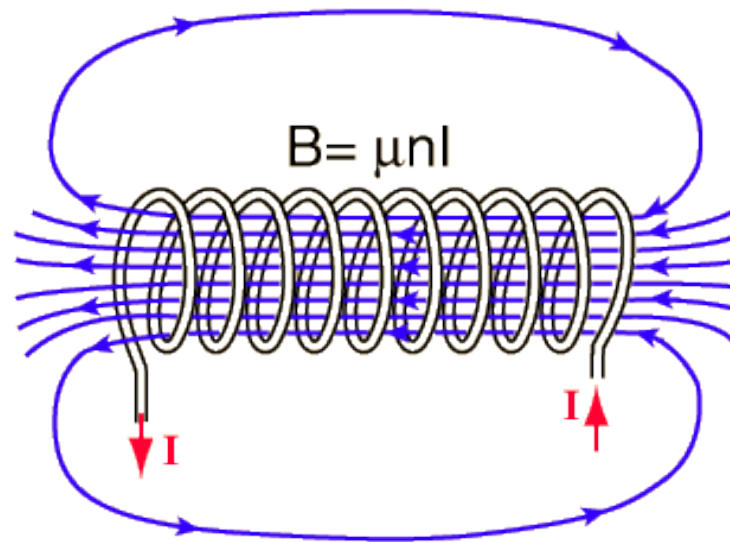
Note: The current used in the calculation will be the total current, so for a coil of N turns, the current used is Ni where i is the current supplied to the coil.

Solenoid

A long straight coil of wire can be used to generate a nearly uniform magnetic field similar to that of a bar magnet. Such coils, called solenoids, have an enormous number of practical applications. The field can be greatly strengthened by the addition of an iron core. Such cores are typical in electromagnets.

In the expression for the magnetic field $\mathbf{B}$, n is the number of turns per unit length, sometimes called the "turns density".

The expression is an idealization to an infinite length solenoid, but provides a good approximation to the field of a long solenoid.

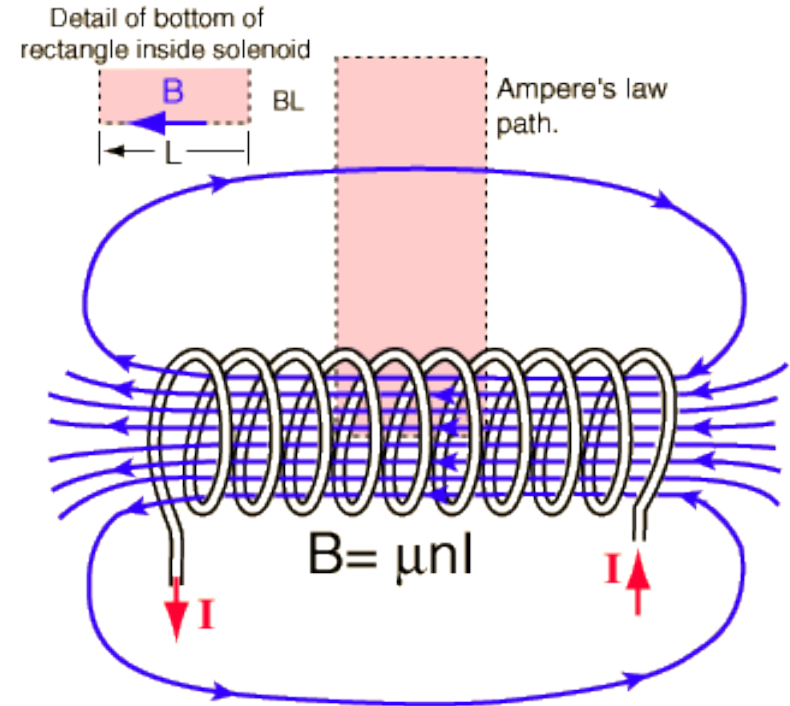


The magnetic field is concentrated into a nearly uniform field in the center of a long solenoid. The field outside is weak and divergent.

Solenoid Field from Ampere's Law

Assumptions

- Taking a rectangular path about which to evaluate Ampere's Law such that the length of the side parallel to the solenoid field is L gives a contribution BL inside the coil.
- The field is essentially perpendicular to the sides of the path, giving negligible contribution.
- If the end is taken so far from the coil that the field is negligible, then the length inside the coil is the dominant contribution.



This idealized case for Ampere's Law gives

$$BL = \mu NI$$

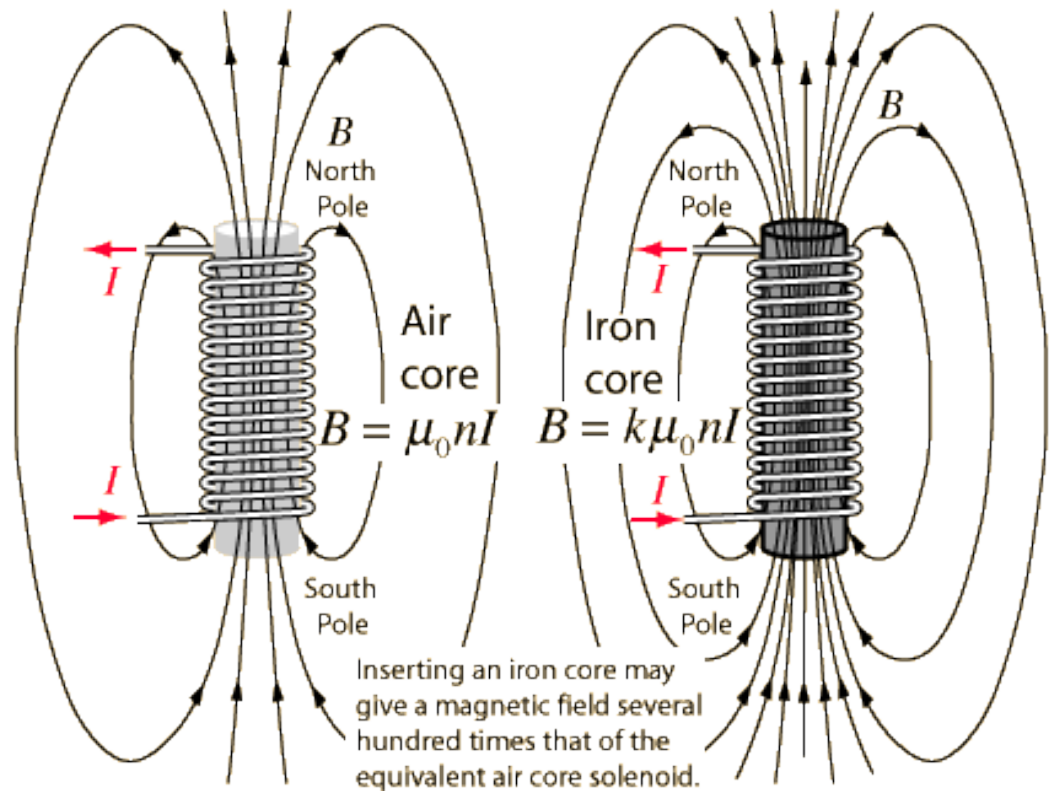
$$B = \mu \frac{N}{L} I$$

$$B = \mu n I$$

Note: This is a good approximation for the solenoid field, particularly in the case of an iron core solenoid.

Iron Core Solenoid

An iron core has the effect of multiplying greatly the magnetic field of a solenoid compared to the air core solenoid on the left.

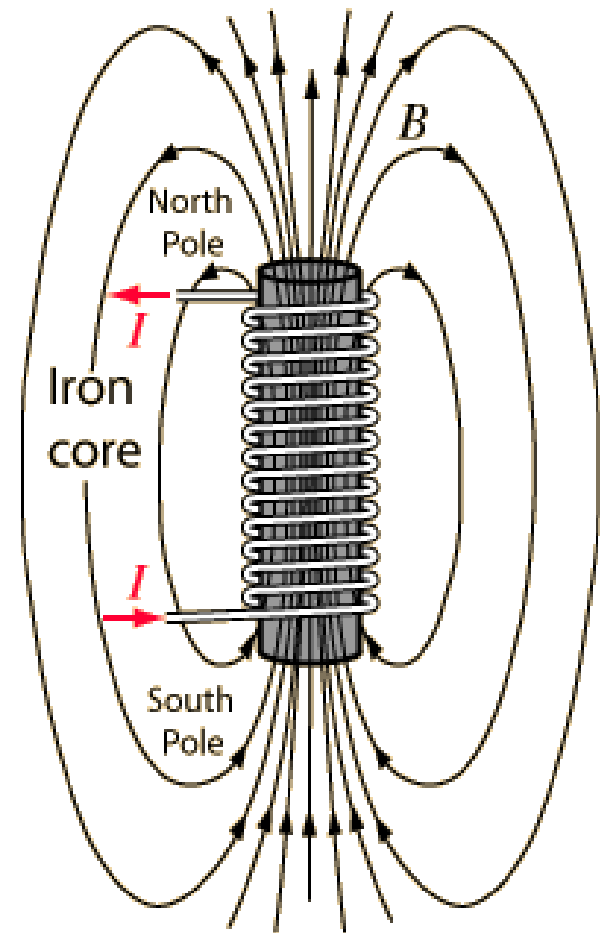


Electromagnet

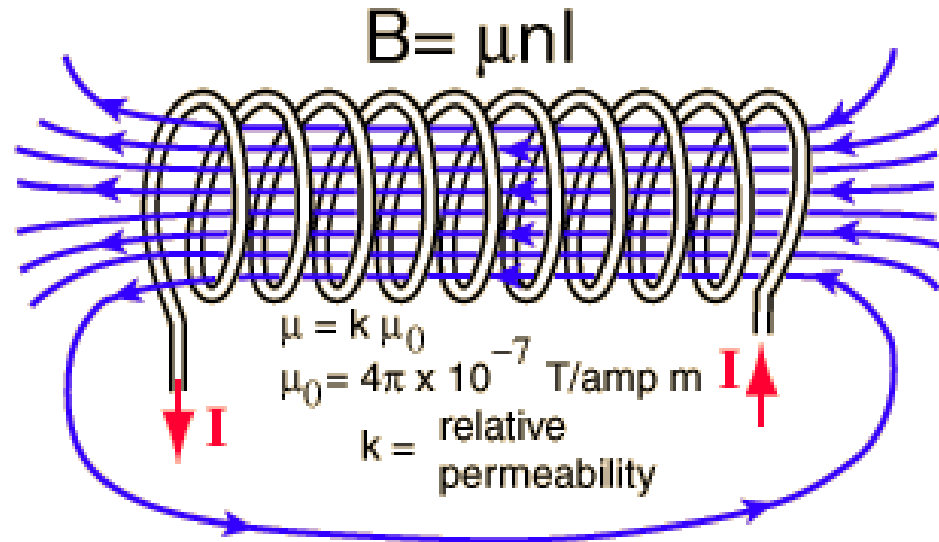
Electromagnets are usually in the form of iron core solenoids. The ferromagnetic property of the iron core causes the internal magnetic domains of the iron to line up with the smaller driving magnetic field produced by the current in the solenoid. The effect is the multiplication of the magnetic field by factors of tens to even thousands. The solenoid field relationship is

$$B = k\mu_0 nI \text{ where } \mu = k\mu_0$$

and k is the relative permeability of the iron, shows the magnifying effect of the iron core.



Solenoid Magnetic Field Calculation



Practical Task 4.

Comparison of centre field values with and without Iron core

A solenoid of length $L=0.1\text{m}$ and $N= 100$ turns and current $I = 1\text{A}$

Note: turns density $n=N/L$ turns/m.

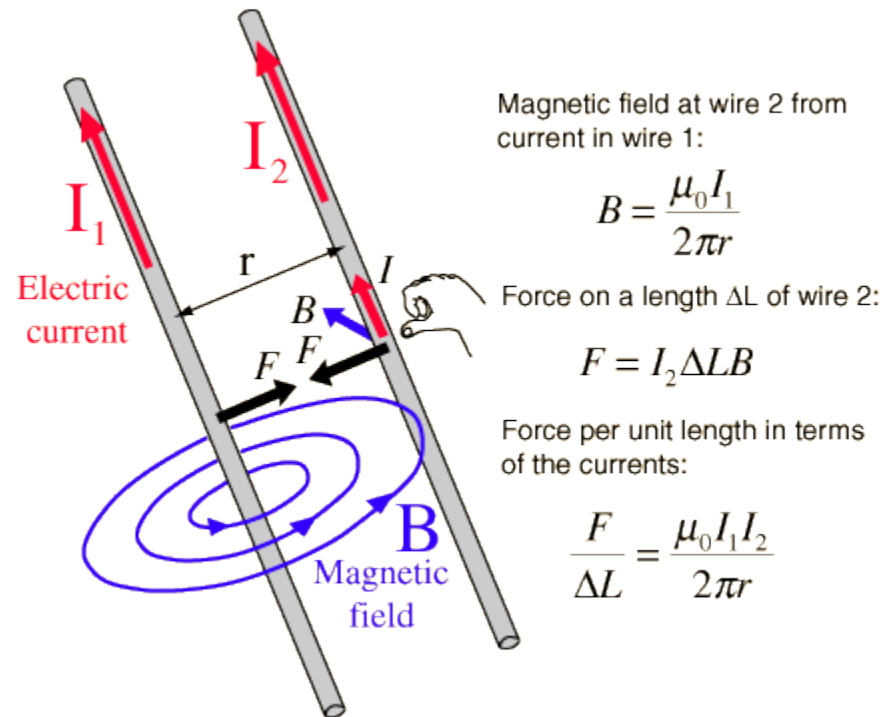
Calculate the centre field density values for

1. An air cored solenoid, and
2. An iron cored solenoid (assume relative permeability of iron, $k=200$)

Magnetic Force Between Wires

- The magnetic field of an infinitely long straight wire can be obtained by applying Ampere's law.
- Once the magnetic field has been calculated, the magnetic force expression can be used to calculate the force. The direction is obtained from the right hand rule.

Notes: The two wires carrying current in the same direction attract each other, and they repel if the currents are opposite in direction. The equations apply only to long straight wires, but is are useful for estimating forces in the ordinary circumstances of short wires. Once you have calculated the force on wire 2, of course the force on wire 1 must be exactly the same magnitude and in the opposite direction according to Newton's third law.



Magnetic Force Between Wires

Example Calculation:

For current $I_1 = 4\text{A}$, and radial separation between wires $r = 0.1\text{m}$, using:

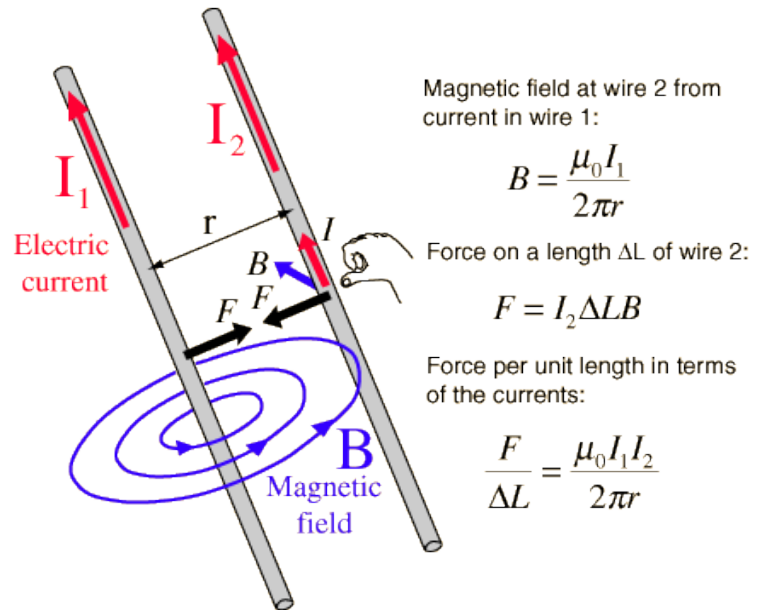
$$B = \frac{\mu_0 I_1}{2\pi r}$$

The magnetic field at wire 2,
 $B = 0.000008\text{ tesla}$ (0.8 gauss).

If the current $I_2 = 3\text{A}$, then using:

$$\frac{F}{\Delta L} = \frac{\mu_0 I_1 I_2}{2\pi r}$$

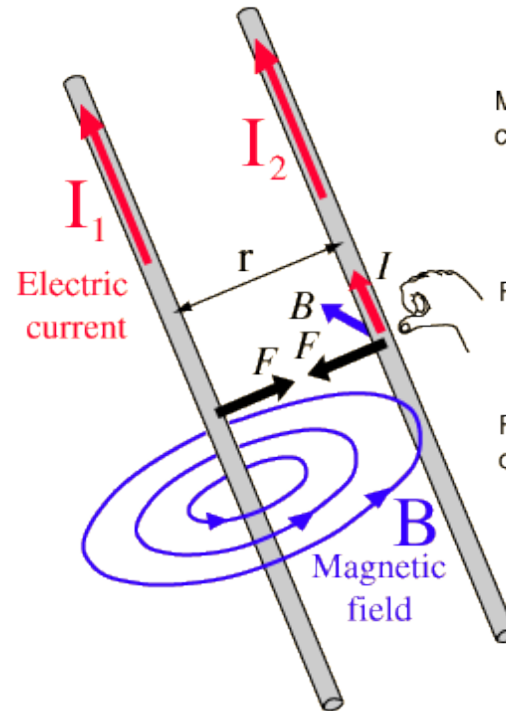
then the force per meter is $F/\Delta L$
 $= 0.000024\text{ N/m}$



Magnetic Force Between Wires

Practical Task 5

For 2 parallel current carrying wires, with $I_1 = 1.5\text{A}$ and $I_2 = 2.5\text{A}$, determine, at incremental distances from 0.1m to 1m the force per metre in N/m and produce a graph of Force per metre against wire separation distance.



Magnetic field at wire 2 from current in wire 1:

$$B = \frac{\mu_0 I_1}{2\pi r}$$

Force on a length ΔL of wire 2:

$$F = I_2 \Delta L B$$

Force per unit length in terms of the currents:

$$\frac{F}{\Delta L} = \frac{\mu_0 I_1 I_2}{2\pi r}$$

Temperature variation Effects on Soft Iron Magnetization Characteristics

Coursework 1

From the supplied magnetization curves (overleaf) of Iron at different temperatures, estimate and plot the respective incremental permeability curves. Note the effects that the temperature variations have on the absolute permeability values. How would these variations effect the field calculations of an iron cored solenoid or electromagnet.

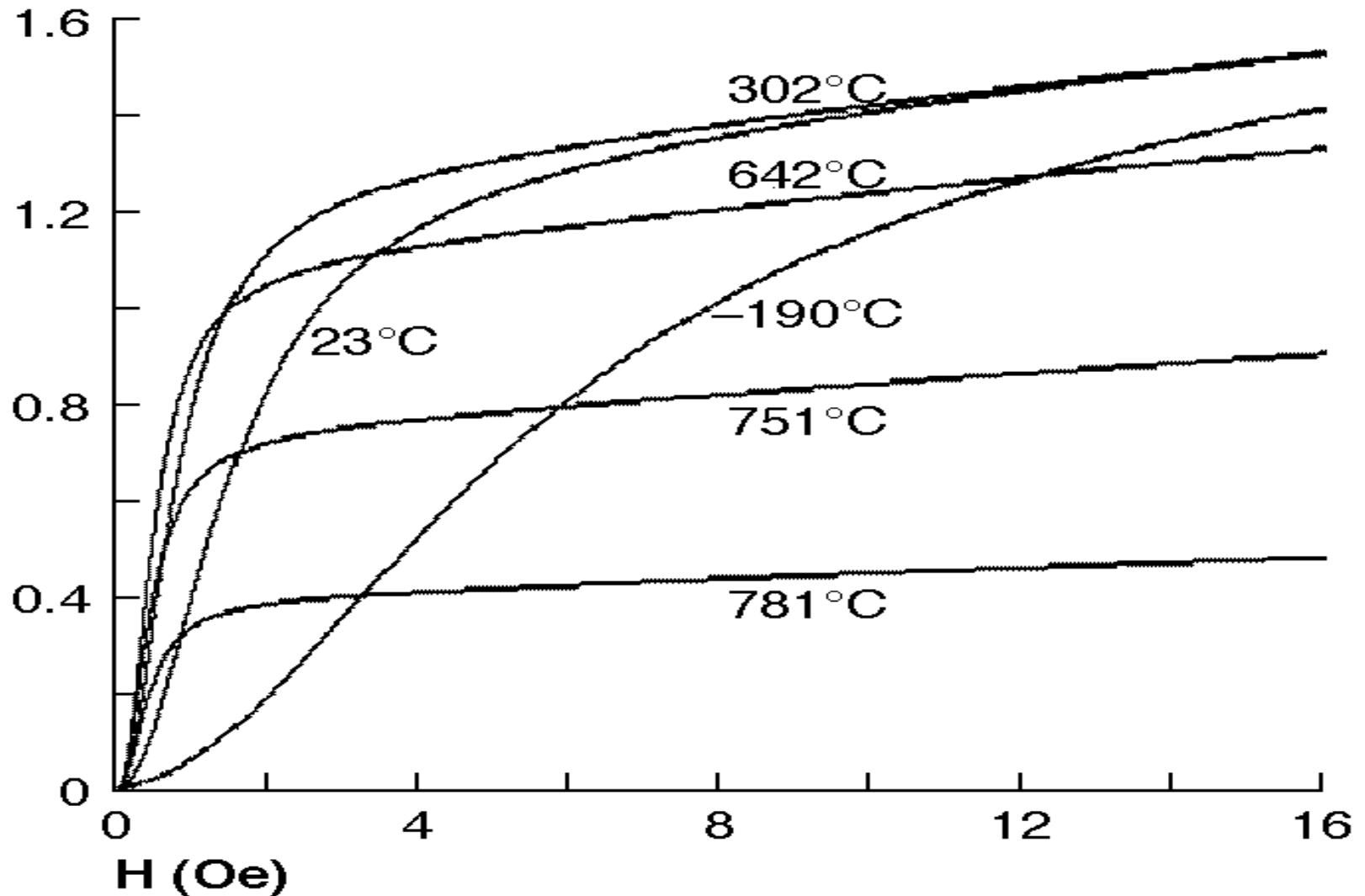
NB: You will need to convert the field intensity values into standard units.

Write the report as if you were writing a technical paper using the suggested format supplied on slide 61.

Include the 5 classroom tasks in an addendum in the report. For each task there should be a brief description, some example calculations, a table and a graph.

Assignment Title:	Investigation of Temperature Variations on the Magnetisation Characteristics of Soft Iron				
Hand Out Date:	18/02/2010	Return Date:	18/03/2010	Contribution to Overall Module/Unit Assessment (%):	20%
Upper Word Limit	2500				
Penalties for late submission: Up to one week late, maximum grade of pass. Over one week late, Fail.					

Iron Magnetization Curves at Different Temperatures



Structure of an Experimental Report

- The convention, when writing a scientific report, is to adopt a rather formalised structure. The table overleaf describes what sections a typical report should have and a brief description of what each section should contain.
- Whether the experiment is largely theoretical or more biased towards data analysis, you should still comply as closely as possible with the structure set out in the following table.
- The table also gives a typical breakdown of the marks allocated to each section (if the experiment is for assessment). Since no two experiments or investigations are the same, the relative weights of each section might well vary from one experiment to another.
- As with any open-ended piece of work, some flexibility in the marking scheme is usually required, to take account of each student's approach.
- Remember, there is no hard and fast rule about the relative importance of different sections for different experiments, so the marks in the table below are just a typical breakdown for a typical experiment.

A typical length would be 7 to 10 pages for the main body of the report (Font Size 12, use standard default margin sizes [e.g. 2.5cm]).

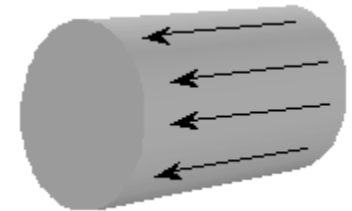
Section of Report	Typical mark
Date, title and general presentation and organisation of the report.	~5 marks
Abstract - This should be approx. 300 words, summarising what you did, how you did it, what the results (and uncertainties) were and what your conclusions were. In practice, you will write this last , so leave about half a page at the beginning of your write-up in which to put an abstract later.	~5 marks
Apparatus - List the apparatus with a diagram where necessary. Describe in particular anything different or additional to that in the script.	~10 marks
Introduction/Method/Procedure - Explain very briefly what the experiment is about. Record what you did - particularly if it differs from the script. Include problems and disasters.	~10 marks
Measurements, and Graphs of Raw measurements - Record all raw measurements (good, bad or indifferent) as and when you obtained them. If the raw data or calculations are voluminous, they could be summarised here and included in their entirety in an appendix. It is often worthwhile to plot a graph of your measurements as you go. This can save time since it indicates quickly if you need to repeat readings or if you need more.	~20 mark
Calculations and error estimates - Describe the calculations or other processing of your results. Explain what equations you used and include a sample calculation, even if you use a spreadsheet programme to carry out the calculations. Discuss the sources of error in your measurements and use these to estimate the uncertainties (or experimental error) on your final results. Include any graphs used in your analysis.	~10 marks
Results and Discussion - Discuss the interpretation of your results. The questions in the experimental script usually lead you through what is required, so you should record your responses to these questions as you come to them. Clearly state your results with estimated errors and units. This is where you should compare your results with accepted values from reference books or other sources.	~25 marks
Conclusion and bibliography - Write a conclusion drawing the results together, discussing their physical implications, the validity of the theory and the methods, and scope for improvement of the experiment. Remember to list the books, articles or web pages that you used for reference in a bibliography at the end. Use the Harvard Referencing System.	~15 marks
Appendix - Most reports will not require appendix as tables of data, calculations and graphs of results should normally be included in the main body of the report to create a coherent whole. Only relegate large volumes of data to the appendix if absolutely necessary. Don't forget to go back and write the abstract.	N/A

Magnetic Field Orientation and Flaw Detect-ability

To properly inspect a component for cracks or other defects, it is important to understand that the orientation between the magnetic lines of force and the flaw is very important. There are two general types of magnetic fields that can be established within a component.

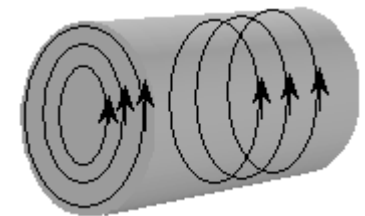
1. Longitudinal magnetic field - has magnetic lines of force that run parallel to the long axis of the part.

- Longitudinal magnetization of a component can be accomplished using the longitudinal field set up by a coil or solenoid.
- It can also be accomplished using permanent magnets or electromagnets.



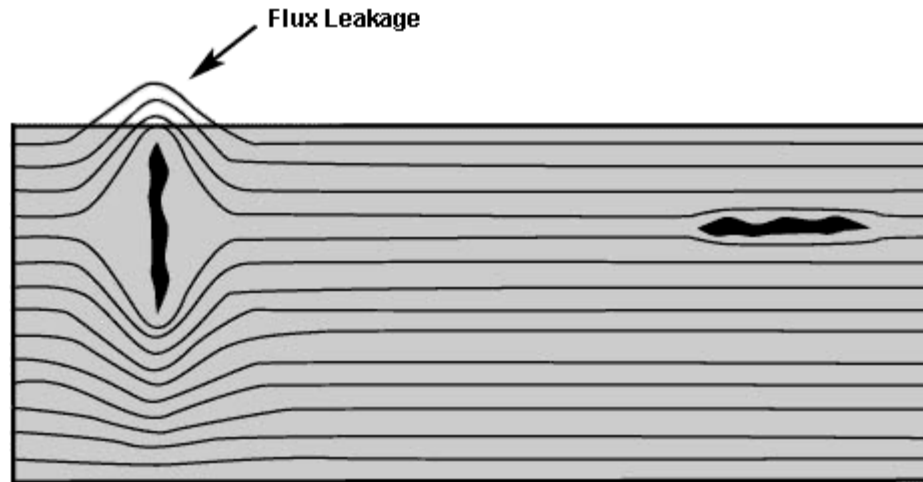
2. Circular magnetic field - has magnetic lines of force that run circumferentially around the perimeter of a part.

- Circular magnetization can be induced in an article by either passing current through the component, or
- by passing current through a conductor surrounded by the component.



Magnetic Field Orientation and Flaw Detect-ability

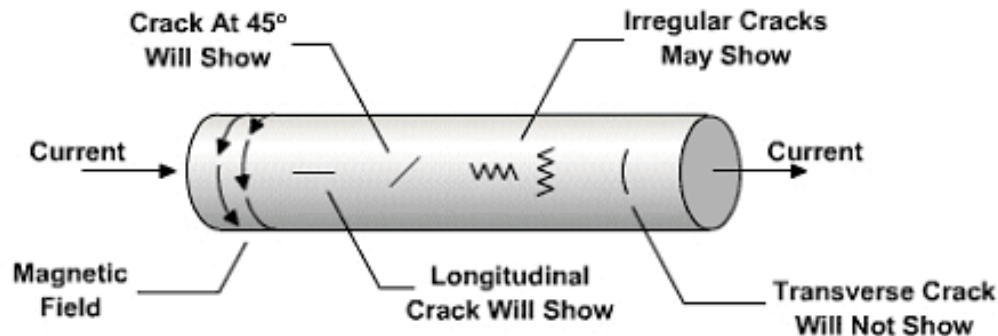
- The best detection of defects occurs when the lines of magnetic force are established at right angles to the longest dimension of the defect and therefore it is important to magnetize the part in two directions.
- This orientation creates the largest disruption of the magnetic field within the part and the greatest flux leakage at the surface of the part.
- If the magnetic field is parallel to the defect, the field will see little disruption and little or no flux leakage field will be produced.



Magnetic Field Orientation and Flaw Detect-ability

- An orientation of 45 to 90 degrees between the magnetic field and the defect is usually necessary to form an indication.
- Defects may occur in various and unknown directions, and therefore it is usual for each part to be magnetized in two directions at right angles to each other.

If the component below is considered for example, passing current through the part from end to end will establish a circular magnetic field that will be 90 degrees to the direction of the current, and defects that have a significant dimension in the direction of the current (longitudinal defects) should be detectable, whereas transverse-type defects will not be detectable with circular magnetization.

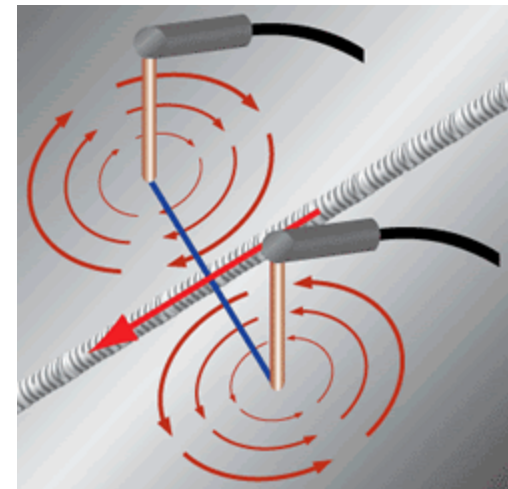
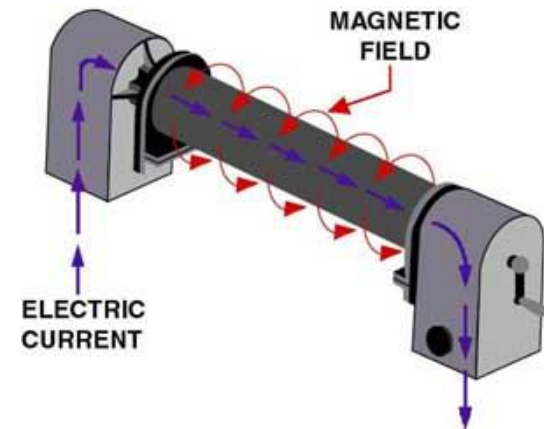


Magnetization of Ferromagnetic Materials

Magnetization Using Direct Induction (Direct Magnetization)

- Current is passed directly through the component.
- Using the right-hand rule it is known that the magnetic lines of flux form normal to the direction of the current and form a circular field in and around the conductor.

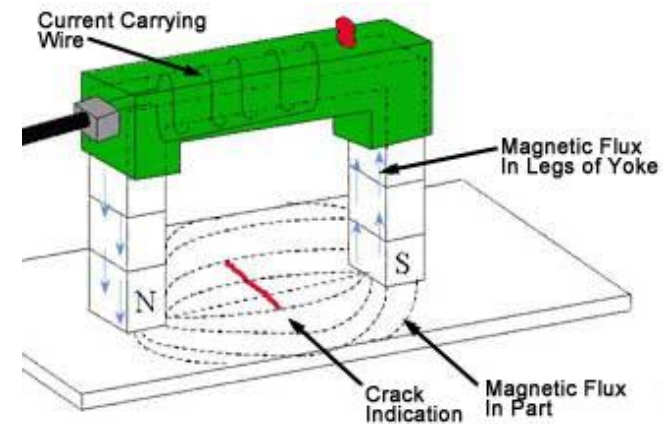
Note: Care must be taken to ensure that good electrical contact is established and maintained between the test equipment and the test component. Improper contact can result in arcing that may damage the component. It is also possible to overheat components in areas of high resistance such as the contact points and in areas of small cross-sectional area.



Magnetization of Ferromagnetic Materials

Magnetization Using Indirect Induction (Indirect Magnetization) - Accomplished by using a strong external magnetic field to establish a magnetic field within the component. There are several ways that indirect magnetization can be accomplished:

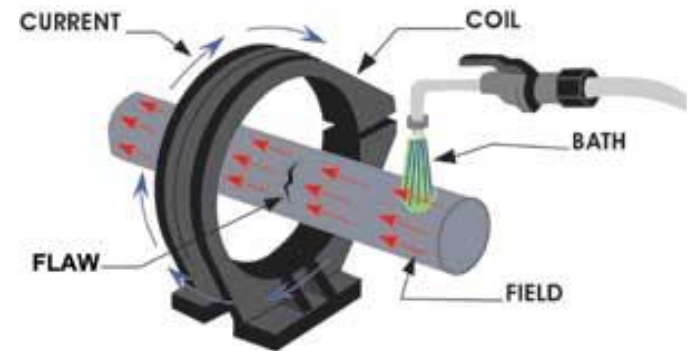
- **A permanent magnets** is a low cost method of establishing a magnetic field. *Note: Limited use in MPI, due to lack of control of the field strength and the difficulty of placing and removing strong permanent magnets from the component. Most popular in MFL floor-scanning technology.*
- **Electromagnets** in the form of an adjustable horseshoe magnet (called a yoke). These eliminate the problems associated with permanent magnets and are used extensively in industry.



Magnetization of Ferromagnetic Materials

Magnetization Using Indirect Induction (Indirect Magnetization) cont.

- A circular magnetic field can be established in cylindrical components by using a **central conductor**. Typically, one or more cylindrical components are hung from a solid copper bar running through the inside diameter. Current is passed through the copper bar and the resulting circular magnetic field establishes a magnetic field within the test components.
- The use of **coils** and **solenoids** is another alternative method of indirect magnetization. When the length of a component is several times larger than its diameter, a longitudinal magnetic field can be established in the component. The component is placed longitudinally in the concentrated magnetic field that fills the centre of a coil or solenoid. This magnetization technique is often referred to as a "coil shot".



Magnetizing Current

- Electric current is often used to establish the magnetic field in components during magnetic particle inspection.
- Alternating current and direct current are the two basic types of current commonly used.
- Current from single phase 110 volts, to three phase 440 volts, are used when generating an electric field in a component.
- Current flow is often modified to provide the appropriate field within the part.
- The type of current used can have an effect on the inspection results.

Magnetizing Current

Direct Current (DC) flows continuously in one direction at a constant voltage.

- Desirable when inspecting for subsurface defects because DC generates a magnetic field that penetrates deeper into the material.
- In ferromagnetic materials, the magnetic field produced by DC generally penetrates the entire cross-section of the component. Conversely, the field produced using alternating current is concentrated in a thin layer at the surface of the component.

Alternating Current (AC) reverses in direction at a rate of 50 or 60 cycles per second.

- In the United States, 60 cycle current is the commercial norm but 50 cycle current is common in many countries.
- Since AC is readily available in most facilities, it is convenient to make use of it for magnetic particle inspection.
- However, when AC is used to induce a magnetic field in ferromagnetic materials, the magnetic field will be limited to narrow region at the surface of the component. This phenomenon is known as the "skin effect" and occurs because induction is not a spontaneous reaction and the rapidly reversing current does not allow the domains below the surface time to align.

It is recommended that pure AC be used only when the inspection is limited to surface defects. Various forms of rectified AC are used to overcome this limitation

Demagnetization

After conducting a magnetic particle inspection, due to residual magnetism, it is usually necessary to demagnetize the component.

Remnant magnetic fields can:

- affect machining by causing cuttings to cling to a component.
- interfere with electronic equipment such as a compass.
- create a condition known as "arc blow" in the welding process. Arc blow may cause the weld arc to wander or filler metal to be repelled from the weld.
- cause abrasive particles to cling to bearing or faying surfaces and increase wear.

Removal of a field may be accomplished in several ways. Randomising the orientation of the magnetic domains can be achieved most effectively by heating the material above its curie temperature.

The curie temperature for a low carbon steel is 770°C or 1390°F. When steel is heated above its curie temperature, it will become austenitic and loses its magnetic properties. When it is cooled back down, it will go through a reverse transformation and will contain no residual magnetic field. The material should also be placed with its long axis in an east-west orientation to avoid any influence of the Earth's magnetic field.

Demagnetization

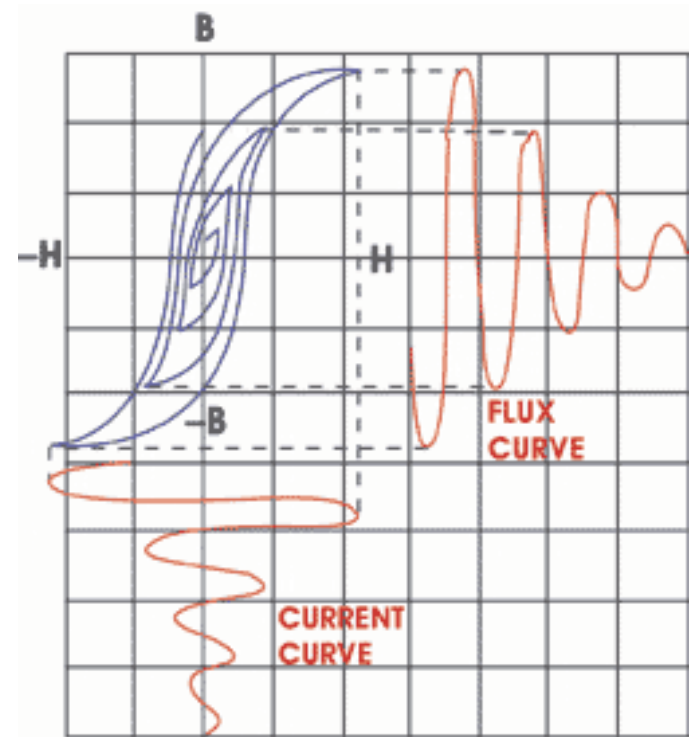
It is often inconvenient to heat a material above its curie temperature to demagnetize it. Subjecting the component to a reversing and decreasing magnetic field will return the dipoles to a nearly random orientation throughout the material.

This can be accomplished by:

- pulling a component out and away from a coil with AC passing through it, or alternately
- using an electromagnetic yoke with AC selected.

any stationary magnetic particle inspection units come with a demagnetization feature that slowly reduces the AC in a coil in which the component is placed.

A field meter is often used to verify that the residual flux has been removed from a component. Industry standards usually require that the magnetic flux be reduced to less than 3 gauss after completing a magnetic particle inspection.



Measuring Magnetic Fields

It is impractical to measure the actual field strength within a material, and therefore all the devices measure the magnetic field that is outside of the material. There are a number of different devices that can be used to detect and measure an external magnetic field. The two devices commonly used in magnetic particle inspection are the field indicator and the Hall-effect meter, which is also called a gauss meter.

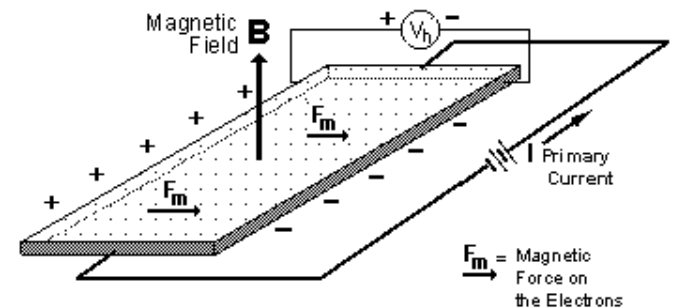
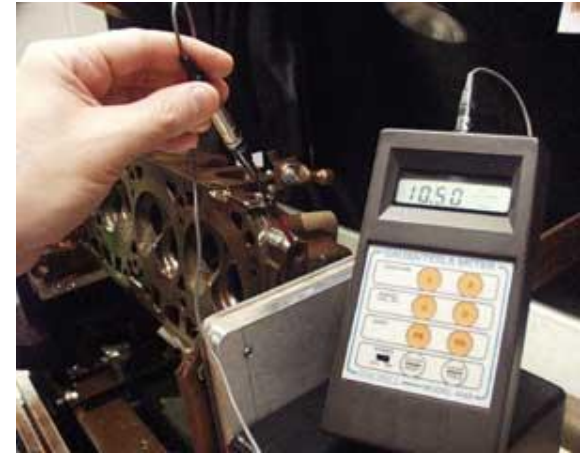
Field indicators are small mechanical devices that utilize a soft iron vane that is deflected by a magnetic field. The vane is attached to a needle that rotates and moves the pointer for the scale. Field indicators can be adjusted and calibrated so that quantitative information can be obtained. However, the measurement range of field indicators is usually small (e.g. +/- 20 gauss) due to the mechanics of the device.



Measuring Magnetic Fields

A Hall-effect meter is an electronic device that provides a digital readout of the magnetic field strength in gauss or tesla units.

- The meters use a very small conductor or semiconductor element at the tip of the probe.
- Electric current is passed through the conductor. In a magnetic field, a force is exerted on the moving electrons which tends to push them to one side of the conductor.
- A build-up of charge at the sides of the conductors will balance this magnetic influence, producing a measurable voltage between the two sides of the conductor.
- The presence of this measurable transverse voltage is called the **Hall-effect** after Edwin H. Hall, who discovered it in 1879.



Equipment and Materials

Portable yoke with battery pack



Portable magnetic particle kit



Portable Coil



Portable Prod Unit



Conductive Cable

Stationary Equipment

- Stationary magnetic particle inspection equipment is designed for use in laboratory or production environment.
- The most common stationary system is the wet horizontal (bench) unit.
- Wet horizontal units are designed to allow for batch inspections of a variety of components.
- The units have head and tail stocks (similar to a lathe) with electrical contact that the part can be clamped between.
- A circular magnetic field is produced with direct magnetization.
- The tail stock can be moved and locked into place to accommodate parts of various lengths.
- To assist the operator in clamping the parts, the contact on the headstock can be moved pneumatically via a foot switch.



Stationary Equipment

- Some units also have a movable coil so the indirect magnetization can be used to produce a longitudinal magnetic field.
- A wet magnetic particle solution is collected and held in a tank.
- A pump and hose system is used to apply the particle solution to the components being inspected.
- Either visible or fluorescent particles can be used.
- Some of the systems offer a variety the option to use AC, half wave DC, or full wave DC.
- In some units, a demagnetization feature is built in, which uses the coil and decaying AC.



Stationary Equipment

Head Shot Method (Circumferential Magnetisation)

- The part is clamped between two electrical contact pads.
- The magnetic solution, called a bath, is then flowed over the surface of the part.
- The bath is then interrupted and a magnetizing current is applied to the part for a short duration, typically 0.5 to 1.5 seconds.
(Precautions should be taken to prevent burning or overheating of the part.)
- A circular field flowing around the circumference of the part is created.
- Leakage fields from defects then attract the particles to form indications.



Stationary Equipment

Coil Method (Longitudinal Magnetisation)

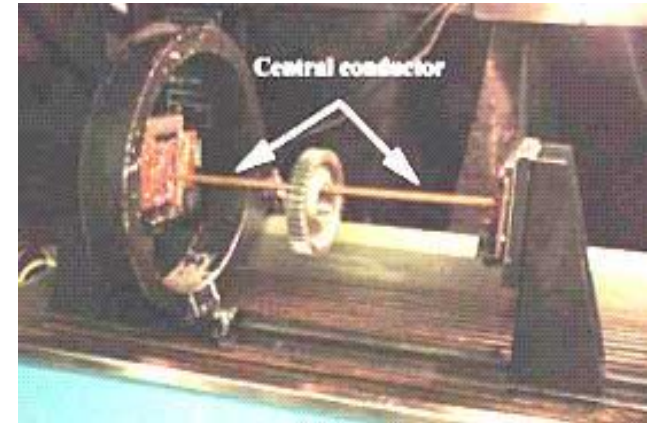
- Used to establish a longitudinal magnetic field within a part
- The part is placed on the inside surface of the coil.
- Just as done with a head shot, the bath is then flowed over the surface of the part.
- A magnetizing current is applied to the coil for a short duration, typically 0.5 to 1.5 seconds, just after coverage with the bath is interrupted.
- A longitudinal field flowing through the length of the part is created.
- Leakage fields from defects attract the particles to form visible indications.



Stationary Equipment

Central Conductor Method (Longitudinal Magnetisation)

- Used to establish a circular magnetic field using a central conductor.
- Utilised to inspect parts that have an open centre, such as gears, tubes, and other ring-shaped objects.
- The central conductor is an electrically conductive bar that is usually made of copper or aluminium.
- The bar is inserted through the opening and the bar is then clamped between the contact pads.
- When current is passed through the central conductor, a circular magnetic field flows around the bar and enters into the part or parts being inspected.



Stationary Equipment

Multidirectional Equipment

- Allow the component to be magnetized in two directions, longitudinally and circumferentially, in rapid succession.
- Inspections are conducted without the need for a second shot.
- The two fields are balanced so that the field strengths are equal in both directions.
- The quickly changing balanced fields produce a multidirectional field in the component providing detection of defects lying in more than one direction.



Note: To determine adequate field strength and balance of the rapidly changing fields, technique development requires a little more effort when multidirectional equipment is used. It is desirable to develop the technique using a component with known defects oriented in at least two directions, or a manufactured defect standard.

Lights for Magnetic Particle Inspection

Magnetic particle inspection can be performed using particles that are highly visible under white light conditions or particles that are highly visible under ultraviolet light conditions.

Visible Colour Contrast Particles

- No special lighting is required as long as the area of inspection is well lit.
- A light intensity of at least 1000 lux is recommended.
- A variety of light sources can be used.

Fluorescent Particles

- Special ultraviolet light must be used.
- Fluorescence is defined as the property of emitting radiation as a result of and during exposure to radiation.
- Particles used in fluorescent magnetic particle inspections are coated with a material that produces light in the visible spectrum when exposed to near-ultraviolet light.
- This "particle glow" provides high contrast indications on the component anywhere particles collect.
- Particles that fluoresce yellow-green are most common because this colour matches the peak sensitivity of the human eye under dark conditions. However, particles that fluoresce red, blue, yellow, and green colours are available.