KLM Technology Group #03-12 Block Aronia, Jalan Sri Perkasa 2 Taman Tampoi Utama 81200 Johor Bahru Malaysia	**Kolmetz Handbook Of Process Equipment Design** **PHYSICS AND ELECTROMAGNETISM** **(ENGINEERING FUNDAMENTALS)**	Editor / Author Karl Kolmetz

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INTRODUCTION

Scope

Electromagnetism is a branch of physics which involves the study of the electromagnetic force, a type of physical interaction that occurs between electrically charged particles. The electromagnetic force (emf) is one of the four known fundamental force of nature. The other threee fundamental interactions are the strong interaction, the weak interaction and gravitation.

The electromagnetic force plays a major role in determining the internal properties of most objects encountered in daily life. The emf is responsible for the functioning of a large number of devices that are important to modern civilization including radio, televsion, cellular telephones, computer and electric machinery.

This paper provides an overview of the basic fundamentals of electromagnetism. The knowledge of physics and electromagnetic will help you in the design and application of electrical and electronic circuits, transmission lines, and optics.

General Considerations

A. Magnet and Magnetism

Magnet

A magnet is a material or object that produces a magnetic field. This magnetic field is invisible but is responsible for the most notable property of a magnet: a force that pulls on other ferromagnetic materials, such as iron and attracts or repels other magnets.

A permanent magnet is an object made from a material that is magnetized and creates its own presistent magnetic field. An everyday example is a refrigerator magnet used to hold notes on a refrigerator door. Materials that can be magnetized, which are also the ones that are strongly attracted to a magnet, are called ferromagnetic. These include iron, nickel, cobalt, some alloys of rare earth metals, and some naturally occurring minerals such as iodestone. Although ferromagnetic (and ferrimagnetic) materials are the only ones attracted to a magnet strongly enough to be commonly considered magnetic, all other substances respond weakly to a magnetic field, by one of several other types of magnetism.

Magnetism

Magnetism is a result of electrons spinning on their own axis around the nucleus (Figure 1).

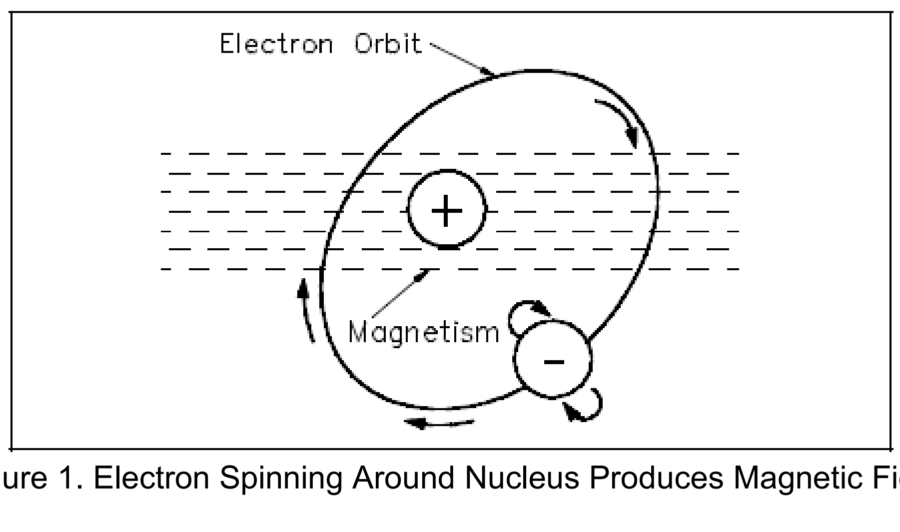

Figure 1. Electron Spinning Around Nucleus Produces Magnetic Field

Magnetism is the phenomenon associated with the motion of electric charges. Substances such as iron bar magnets maintain a magnetic field where no obvious electric current is present (Figure 2). Basic magnetism is the existence of magnetic fields which deflect moving charges or other magnets. Similar to electric force in strength and direction, magnetic objects are said to have `poles' (north and south, instead of positive and negative charge). However, magnetic objects are always found in pairs, there do not exist isolated poles in nature.

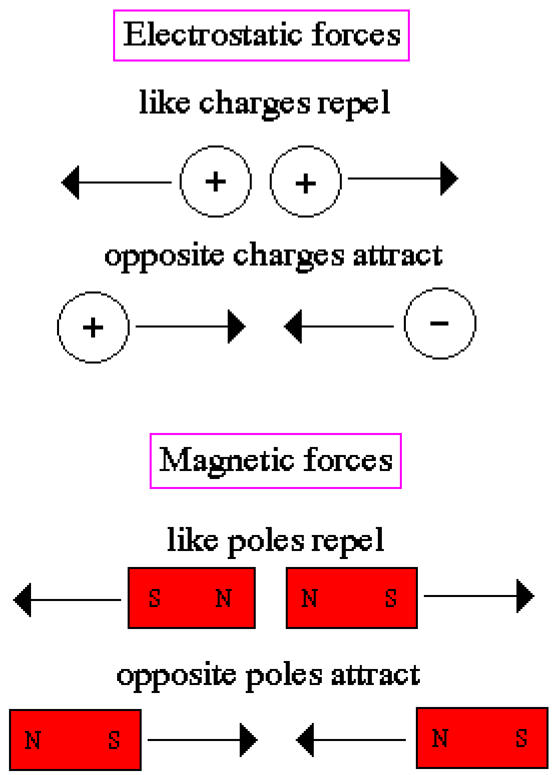

Figure 2 : Electrostatic and Magnetostatic Force

The most common source of a magnetic field is an electric current loop. The motion of electric charges in a pattern produces a magnetic field and its associated magnetic force. Similarly, spinning objects, like the Earth, produce magnetic fields, sufficient to deflect compass needles.

Today we know that permanent magnets are due to dipole charges inside the magnet at the atomic level. A dipole charge occurs from the spin of the electron around the nucleus of the atom. Materials (such as metals) which have incomplete electron shells will have a net magnetic moment. If the material has a highly ordered crystalline pattern (such as iron or nickel), then the local magnetic fields of the atoms become coupled and the material displays a large scale bar magnet behavior.

In magnetic materials, the atoms have certain areas called domains. These domains are aligned such that their electrons tend to spin in the same direction (Figure 3).

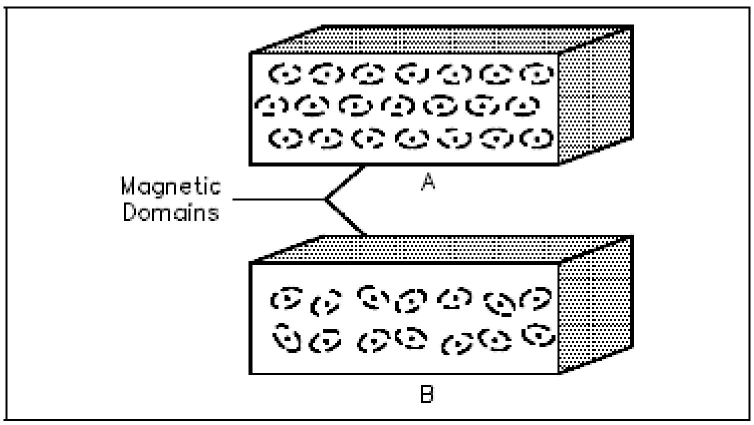

Figure 3. Magnetic Domains

The alignment of these domains results in the formation of magnetic poles at each end of the magnet. These poles are called the north pole and the south pole. The law of magnetism states that like magnetics poles repel an unlike magnetic poles attract one another (Figure 4).

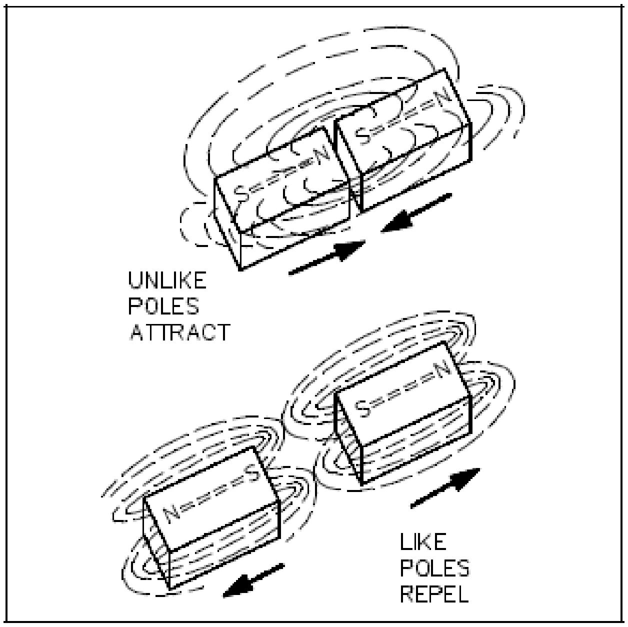

Figure 4. The Law of Magnetic Attraction and Repulsion

B. Magnetic Field

Bar magnets are permanent magnets. This means that their magnetism is there all the time and cannot be turned on or off as it can with electromagnets.
Bar magnets have two poles :

- North pole - normally shown as N
- South pole – normally shown as S

Opposite (unlike) poles attract, and like poles repel.

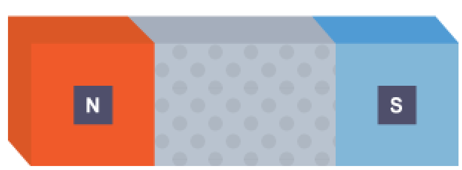

Figure 5 : Bar Magnet

If permanent magnets are repeatedly knocked, the strength of their magnetic field is reduced. Converting a magnet to a non-magnet is called demagnetisation.

Magnets are made from magnetic metals - iron, nickel and cobalt. These are the only pure metals that can be turned into a permanentmagnet. Steel is an alloy of iron and so can also be made into a magnet.

If these metals have not been turned into a permanent magnet they will still be attracted to a magnet if placed within a magnetic field. In this situation they act as a magnet but only whilst in the magnetic field. This is called induced magnetism.

Magnet create magnetic fields. These magnetic fields cannot be seen. They fill the space around a magnet where the magnetic forces work, and where they can attract or repel magnetic materials.

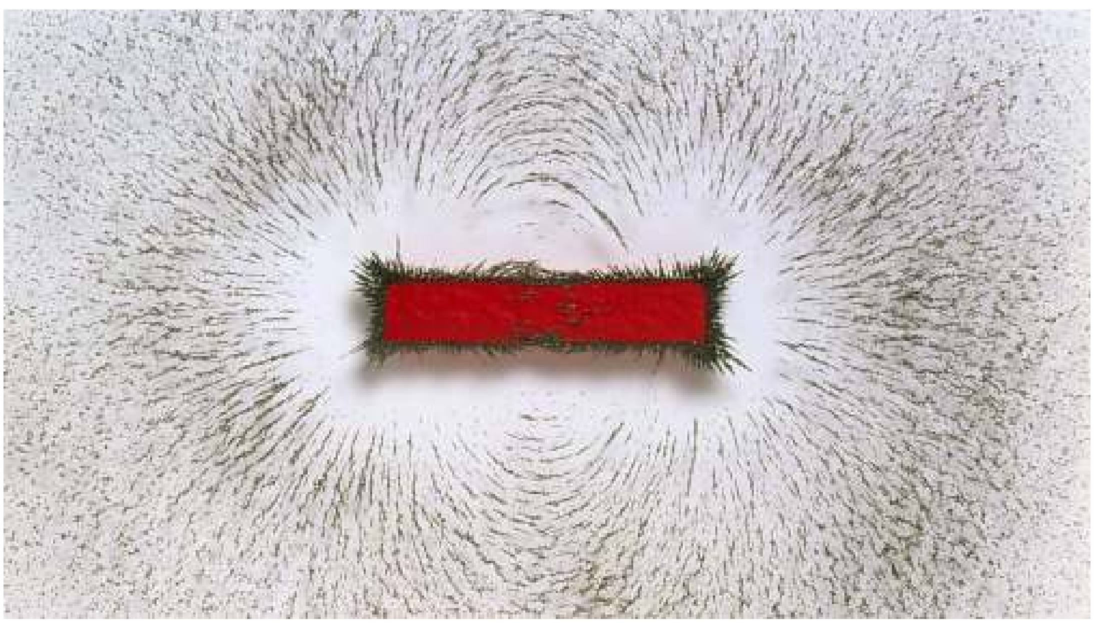

Figure 6: Magnetic Field

Although we cannot see magnetic fileds, we can detect them using iron filings. The tiny pieces of iron line up in a magnetic field.

Magnetic fields can be produced by moving charged particles in electromagnets or in permanent magnets. Figure 7 shows Faraday's concept of the magnetic flux lines or lines of force on a permanent bar magnet. The magnetic field is much stronger at the poles than anywhere else. The direction of the field lines is from the North Pole to the South Pole, and the external magnetic field lines never cross.

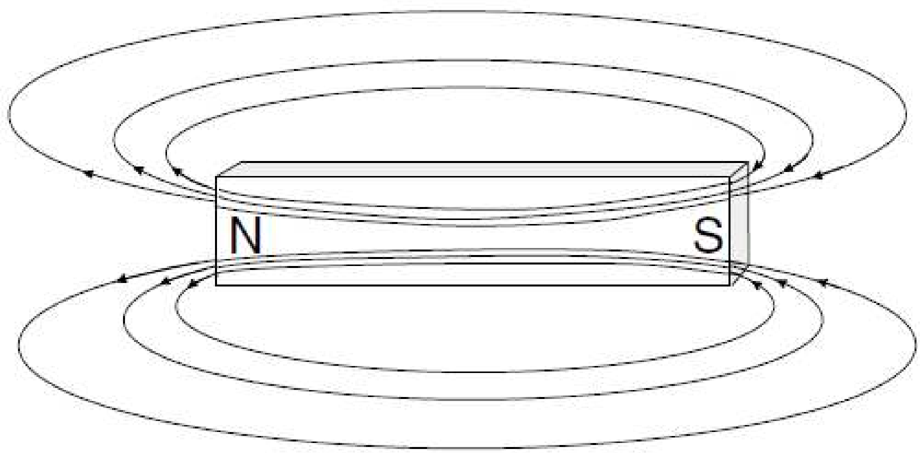

Figure 7: Magnetic Field (Φ) of a bar magnet

According to molecular theory of magnetism, within permanent magnets there are tiny molecules or domains that can be considered micromagnet. When they line up in a row, they combine to increase the magnetic field strength.

Drawing Magnetic Field Diagram

Single Bar Magnet

It would be difficult to draw the results from the sort of experiment seen in the photograph, so we draw simple magnetic field lines instead.

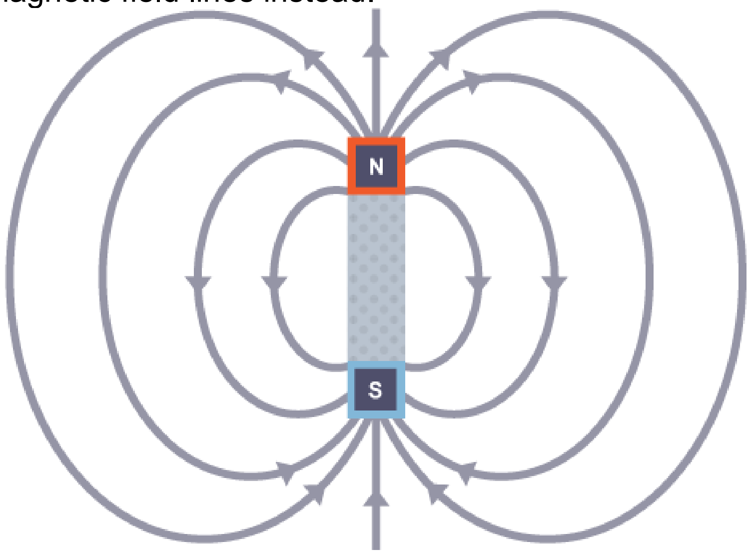

Figure 8: Magnetic Field Lines on Bar Magnet

Figure 8, a bar magnet, with several curved lines pointing from the north to south pole In the diagram, note that :

- The field lines have arrows on them
- The field lines come out of N (north pole) and go into S (south pole)
- The field are more concentrated at the poles

The magnetic field is strongest at the poles, where the field lines are most concentrated.

Two Bar Magnets

The magnetic field pattern when two magnets are used is shown in this diagram.

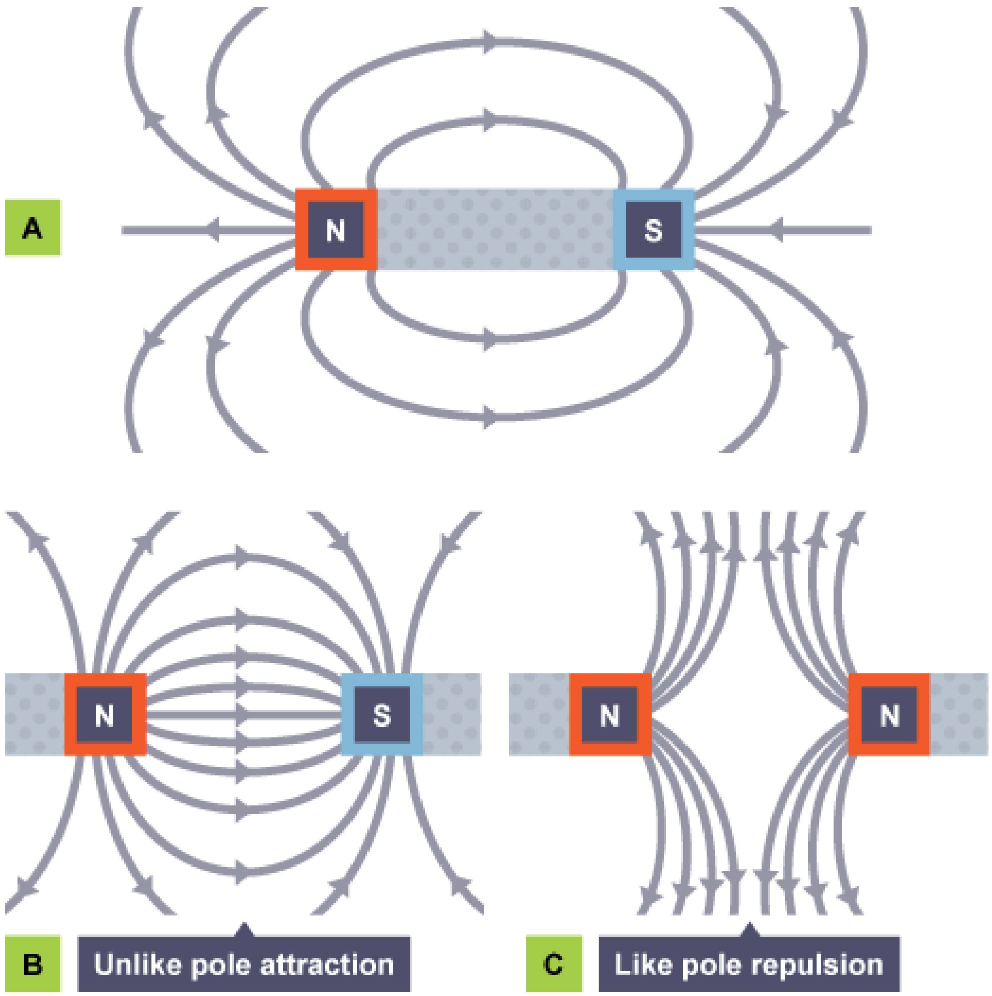

Figure 9: Magnetic field lines for fields involving two magnets

Note the different patterns seen when two like poles are used and two opposing poles are used.

Uniform Magnetic Field

When magnetic field lines are the same distance apart from each other, we say that the magnetic field is uniform. This is shown in the diagram :

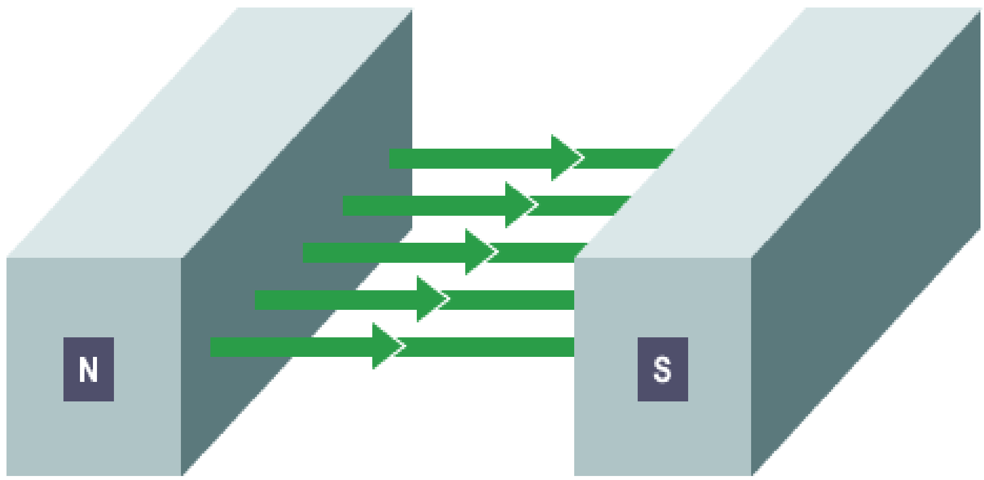

Figure 10: Magnetic field lines in a uniform field

C. Magnetic Materials and Magetic Properties

Magnetic materials are those materials that can be either attracted or repelled by a magnet and can be magnetized themselves. The most commonly used magnetic materials are iron and steel. A permanent magnet is made of a very hard magnetic material, such as cobalt steel, that retains its magnetism for long periods of time when the magnetizing field is removed. A temporary magnet is a material that will not retain its magnetism when the field is removed.

Magnetic Material Classification

Magnetic materials are classified as either magnetic or nonmagnetic based on the highly magnetic properties of iron. Because even weak magnetic materials may serve a useful purpose in some applications, classification includes the five groups described below.

- **Diamagnetic Materials**

  All materials are diamagnetic to some extent although this behaviour may be superceded by a more dominant effect, such as ferromagnetism. Diamagnetism is a classical effect produced by moving charges. The induced magnetization M is opposed to the applied B, thus reducing the total B in such a material sample. This effect is directly analogous to the polarization effects in ordinary dielectrics. These are materials such as bismuth, antimony, copper, zinc, mercury, gold, and silver. These materials have a relative permeability of less than one.

- **Paramagnetic Materials**

  Paramagnetism is a quantum mechanical effect largely due to the spin magnetic moment of the electron. These are materials such as alumunium, platinum, maganese, and chromium. These materials have a relative permeability of slihtly more than one.

- **Ferromagnetic Materials**

  There is a much stronger quantum mechanical interaction between neighboring spin moments than with paramagnetic materials. Some of the feromagnetic or nonmagnetic materials used are iron, steel, nickel, cobalt and the commercial alloys, alnico and peralloy. Ferrites are nonmagnetic, but have the ferromagnetic properties of iron. Ferrities are made of ceramic material and have relative permeabilities that range from 50 to 200. They are commonly used in the coils for RF (Ratio Frequency) transformers.

Magnetic Properties

- **Low Carbon Steels**

Low carbon steel provides the path for the magnetic flux in most electrical machines : generators, transformers and motors. Low carbon steel is used because of its high permeability, this is, a large amount of flux can be produced with the expenditure of minimal magnetizing “effort”, and it has low hysteresis thus minimizing losses associated with the magnetic field. High levels of flux mean more powerful machines can be produced for a given size and weight.

- **Hot – rolled steel**

Electrical sheet steels from which the laminations are cut are produced by a process of rolling in the steel mill. The steels have a crystalline structure and the magnetic properties of the sheet are derived from the magnetic properties of the individual crystals or grains. The grains themselves are anisotropic. That is, their properties differ according to the direction along the crystall that these are measured.

- **Grain – oriented steel**

As early as the 1920s it had been recognized that if the individual steel crystals could be aligned, a steel could be produced which, in one direction, would exhibit properties related to the optimum magnetic properties of the crystals. This material is known as cold-rolled grain-oriented steel. It is reduced in the steel mill by a hot rolling process until it is about 2 mm thick. Thereafter it is further reduced by a series of cold reductions interspersed with annealing at around 900^oC to around 0.3 mm final thickness. In order to reduce surface oxidation and prevent the material sticking to the rolls, the steel is given a phosphate coating in the mill. Gain-oriented steel has magnetic properties in the rolling direction which are very much superior to those perpendicular to the rolling direction.

- **High – Permeability Steel**

Cold-rolled steel as described above continued to be steadily improved until the end of 1960s when a further step-change was introduced by the Nippon Steel Corporation of Japan. By introducing significant changes into the cold rolling process they achieved a considerable improvement in the degree of grain orientation compared with the previous grain-oriented material. This coating imparts a tensile stress into the steel which has the effect of reducing hystersis loss. The reduces hystersis loss allows some reduction in the amount of silicon which improves the workability of the material, reducing cutting burrs and avoiding the need for these to be ground off. This coupled with the better insulation properties of the coating means that additional; insulation is not required. The core manufacturing process is simplified and the core itself has a better stacking factor.

- **Domain-refined steel**

Crystals of grain-oriented steel become aligned during the grain-orientation process in large groups. These are known as domains. There is a protion of the core loss which is related to the size of the domains so that this can be reduced by reducing the domain size. Domain size can be reduced after cold rolling by introducing a small amount of stress into the material. This is generally carried out by a process of laser etching so that this type of steel is frequently referred to as laser-etched. Improvements to the rolling process have also enabled this material to be produced in thinner sheets, down to 0.23 mm, with resulting further reduction in eddy-current loss.

- **Amorphous Steel**

Amorphous steels have developed in a totally different direction to the silicon steels described above. Amorphous steels have a non-crystalline structure. The atoms are randomly distributed within the material. They are produced by very rapid cooling of the molten alloy which contains about 20% of a glass forming element such as boron. The material is generally produced by spraying a stream of molten alloy onto a rapidly rotating copper drum. The molten material is cooled at the rate of about 106 degrees C per second and solidifies to form a continuous thin ribbon. This requires annealing between 200 and

280C to develop the required magnetic properties. The earlies quantities of the material were only 2 mm wide and about 0.025 – 0.05 mm thick.

- **Designation of core steels**

Specification of magnetic materials including core steels is covered internationally by standards. There is a multi-part document covering all aspect and types of magentic materials used in the electrical industry.

- **Permanet Magnets (Cast)**

Great advances have been made in the development of materials suitable for the production of permanent magnets. The earliest materials were tungsten and chromium steel, followed by the series of cobalt steels.

Alni was the first of the alumunium-nickel-iron alloys to be discovered and with the addition of cobalt, titanium and niobium, the Alnico series of magnets was developed, the properties of which varied according to composition. These are hard and brittle and can only be shaped by grinding, although a certain amount of drilling is possible on certain composition after special heat treatment. The Permanent Magnet Association (disbanded March 1975) discovered that certain alloys when heat-treated in a strong magnetic field became anistropic. That is they develop high properties high properties in the direction of the field at the expense of properties in other direction.

- **Permanent Magnets (Sintered)**

The techniques of powder metallurgy have been applied to both the isotropic and anisotropic Alnico types and it is possible to produce sintered permanet magnets which have approximatelly 10% poorer remanence and energy than cast magnets. More precise shapes are possible when using this method of production and it is economical for the production of large quantites of small magnets.

Sintering techniques are also used to manufacture the oxide permanent magnets based on barium or strontium hexaferrite. These magnets which may be isotropic or anisotropic, have higher coercive force but lower remanence than the alloy magnets. They have the physical properties of ceramics, and inferior temperature stability, but their low cost makes them ideal for certain applications. Barium ferrite bonded in rubber or plastics is available as extruded strip or rolled sheet. The neewst and most powerful permanent magnets discovered to date, based on an intermettalic compound of cobalt and samarium, are also made by powder metallurgy techniques.

Table 1. Properties of Permanent Magnets

Material	Remanence	Coercive force	BHmax	Sp. Gr.	Description
	T	kAm^{-1}	kJm^{-3}		
ISOTROPIC					
Tungsten steel 6%W	1.05	5.2	2.4	8.1	Rolled or forged steel
Chromium steel 6%Cr	0.98	5.2	2.4	7.8	Rolled or forged steel
Cobalt steel 3%Co	0.72	10.4	2.8	7.7	Rolled or forged steel
Cobalt steel 6%Co	0.75	11.6	3.5	7.8	Rolled or forged steel
Cobalt steel 9%Co	0.78	12.8	4.0	7.8	Rolled or forged steel
Cobalt steel 15%Co	0.82	14.4	5.0	7.9	Rolled or forged steel
Cobalt steel 35%Co	0.90	20	7.6	8.2	Rolled or forged steel
Alni	0.55	38.5	10	6.9	Cast Fe-Ni-Al
Alnico	0.75	58	13.5	7.3	Cast Fe-Ni-Al
Feroba 1 (Sinetered)	0.21	136	6.4	4.8	Barium ferrite
Bonded feroba	0.17	128	5.6	3.6	Flexible strip or sheet
ANISTROPIC					
Alcomax II	1.20	46	41	7.35	Cast Fe-Co-Ni-Al
Alcomax III	1.30	52	44	7.35	Cast Fe-Co-Ni-Al-Nb
Alcomax IV	1.15	62	36	7.35	Cast fe-Co-Ni-Al-Nb
Columax	1.35	59	60	7.35	Grain Oriented Alcomax III

Hycomax II	0.75	96	32	7.3	Cast Fe-Co-Ni-Al-Nb-Ti
Hycomax III	0.92	132	44	7.3	Cast Fe-Co-Ni-Al-Ti
Hycomax IV	0.78	160	46	7.3	Cast Fe-Co-Ni-Al-Ti
Columnar Hycomax III	1.05	128	72	7.3	Grain Oriented
Feroba II	0.35	144	26.4	5.0	Barium Ferrite
Feroba III	0.25	200	20	4.7	Barium Ferrite
Sintered Sm CO_5	0.8	600	128	8.1	Cobalt-samarium

DEFINITIONS

Conductors – Materials with electrons that are loosely bound to their atoms, or materials that permit free motion of a large number of electron.

Cosmic rays – Hghly penetrating particle rays from outer space.

Current – The density of the atoms in copper wire is such that the valence orbits of the individual atoms overlap.

Electromagnetic spectrum – EM radiant energy arranged in order of frequency or wavelength and divided into regions within which the waves have some common specified charachteristics.

Gamma rays – Electromagnetic radiation of very high energy (greather than 30 keV) emitted after nuclear reactions or by a radioactive atom when it nucleus is left in an excited state after emission of alpha or beta particles.

Inductance – The property which opposes any change in the existing current. Inductance is present only when the current is changing.

Inductor – A conductor used to introduce inductance into a circuit.

Insulators or nonconductors – Material with electrons that are tightly bound to their atoms and require large amounts of energy to free them from the influence of the nucleus.

Light – white light, when split into a spectrum of colors, is composed of a continuous range of merging colors : red, orange, yellow, green, cyan, blue, indigo, and violet.

Magnet – a vector that characterizes the magnet's overall magnetic properties.

Magnetic Flux – the group of magnetic field lines emitted outward from the north pole of magnet.

Magnetic Flux Density – The amount of magnetic flux per unit area of a section, perpendicular to the direction to the direction of flux.

Permanent magnet – an object made from a material that is magnetized and creates its own presistent magnetic field.

Radio waves – Electromagnetic radiation suitable for radio transmission in the range of frequencies from about 10 kHz to about 300 MHz.

Reflection – The abrupt change in the direction of propagation of a wave that strikes the boundary between different mediums.

Refraction – The change in direction of a wave passing from one medium to another caused by its change in speed.

Resistance – The ratio of the potential difference along a conductor to the current through the conductor

Ultraviolet (UV) radiation – Electromagnetis radiations having wavelengths in the range from 0.4 nm to 3 nm.

X Rays – Electromagnetic radiation of short wavelengths produced when cathode rays impinge on matter

NOMENCLATURE

A : Area of the cross section, m^2
B : Magnetic flux density, tesla
E : Electric field
f : Frequency, Hz
F_m : Magnetomotive force, mmf
H : Field Intensity, At/m
I : Current, Ampere
J : Volume Current Density
L : Length between poles of coil, m
M : Mutual Inductance, H
N : Number of turns
q : Charge, C
R : Reluctance, At/Wb
t : Time, seconds
v : Average velocity, m/s
V : Voltage, V

Greek Letter

α :Temperature Coefficient
μ : Permeability
ε : Permetivity
θ : Angle
Φ : Magnetic flux, Webers
σ : Electrical conductivity