PURPOSE

Magnetic materials are vital components of most electromechanical machines. An understanding of magnetism and magnetic materials is therefore essential to the design of modern day devices. The magnetic components are usually concealed in subassemblies and are not directly apparent to the end user. Unlike other material characteristics, magnetic properties cannot be felt, tasted, seen, or heard. This makes the concepts associated with magnetism difficult to comprehend. It is the purpose of this manual to be a practical guide to:

- Understanding magnetism
- Magnetic materials and their manufacturing methods
- Design of systems utilizing permanent magnets
- Provide an appreciation for the wide variety of applications which use magnets

Permanent magnets have been used for hundreds of years!

Permanent magnets have been used in electrical machinery for over one hundred years. Developments in materials and manufacturing methods from the early 1940's to the present have improved the properties of permanent magnets and made the use of magnetic devices common. A list of some devices/applications using permanent magnets include:

Magnetic fields cannot be seen, felt, tasted, seen or heard.

- Advertising and signs
- Communication applications in telephones, microwave tubes and filters
- Automobile accessories including ignition systems, starter motors, door locks, electric windows, windshield wiper motors and gauges
- Computer peripherals and office equipment including fax machines, printers and copiers
- Industrial motors, actuators for robotics and flight control systems
- Suspension and propulsion units for magnetically levitated vehicles
- Sound reproduction systems (e.g. loudspeakers), watches, weighing systems, microwave ovens
- Small motors and actuators in cameras and recorders (both voice and video)
- Particle accelerators and free electron lasers used in physics, industry and defense
- Nuclear magnetic resonance imaging devices for medical and industrial applications
- Home appliances such as vacuum cleaners, washing machines and dryers
- Shop tools: power saws, sanders, drills
- Promotional items and toys

Ancient Chinese and Greeks discover naturally occurring permanent magnets and use them for navigation.

HISTORY OF MAGNETISM

The ancient Greeks and Chinese are credited as the first to find and use a naturally occurring iron ore called magnetite. The key to their discovery was that magnetite is able to attract other iron bearing materials. The earliest application of this permanent magnet material was in the mariner's compass and pieces of magnetite became known as lodestone. The word lode means "to lead" and lodestone led the mariners to safe harbor.

From the time of the discovery of lodestone until 1600, when Gilbert published his results on observed magnetic phenomena, progress in the understanding of magnetism was limited. Gilbert was the first to apply scientific methods into the study of magnetism and is credited as the first to discover that the earth is one giant magnet. His efforts in separating the difference between electric charges and magnetic charges became the foundation of the science of electricity and magnetism.

The next milestone in magnetics occurred in 1785 when Charles Coulomb published the inverse square law of attraction and repulsion between electrical charges and magnetic poles. Because these early contributions originated from force concepts, the first definitions and units were based on forces between poles.

In 1820, Hans Oersted discovered that an electric current would deflect a magnetic needle. Using Oersteds' discovery, Ampere magnetized steel needles by placing them in a helix of wire carrying an electric current.

Around 1830, Joseph Henry and Michael Faraday independently discovered electromagnetic induction. Their concepts of converting magnetism into electricity were then used to make the first transformers. The invention of the dynamo in 1865 naturally followed and began the era of electricity.

James Maxwell formulated the relationships of electricity and magnetism based on the discoveries of Gauss, Ampere and Faraday, which he published in 1873. These relationships are known today as Maxwell's equations and form the backbone of modern electromagnetism.

In 1907 Pierre Weiss postulated the first modern theory of permanent magnets being comprised of tiny individual magnetic domains. A more complete history of the developments in magnetism can be found in the texts of Hadfield[(1)], Parker and Studders[(2)], McCaig[(4)], and others[(3)(5)].

Between Oersted's discovery in 1820 and through the early 1920's, advances in the understanding of magnetism were theoretical in nature. The physical development of magnetic materials beyond magnet steels began in 1921 with the introduction of cobalt chrome steel. Subsequent work on alloys with nickel, aluminum, copper and platinum led to the introduction of precipitation hardened alnico (<u>al</u>uminum <u>ni</u>ckel <u>co</u>balt) in 1935, Cunife (<u>cu</u>pper <u>ni</u>ckel <u>i</u>ron) in 1935 and Platinum Cobalt in 1936. The alnico magnets were further improved in 1940 with the introduction of domain oriented alnico V that is still in frequent use today. The alnico family of magnets, with much improved properties compared to steel magnets, opened the door to new markets. For example, alnico speaker designs helped make radio and television possible in

1600 William Gilbert publishes <u>de Magnete</u>

1785 Charles Coulomb: inverse square law of attraction and repulsion

1820 Hans Oersted: electric current creates magnetic field

1830 Michael Faraday and Joseph Henry discover electromagnetic induction

1865 Era of Electricity starts

1873 James Maxwell publishes Maxwell's equations

1907 Pierre Weiss' theory of magnetic domains

1921 Cobalt Chrome Steel

1935 Alnico and Cunife

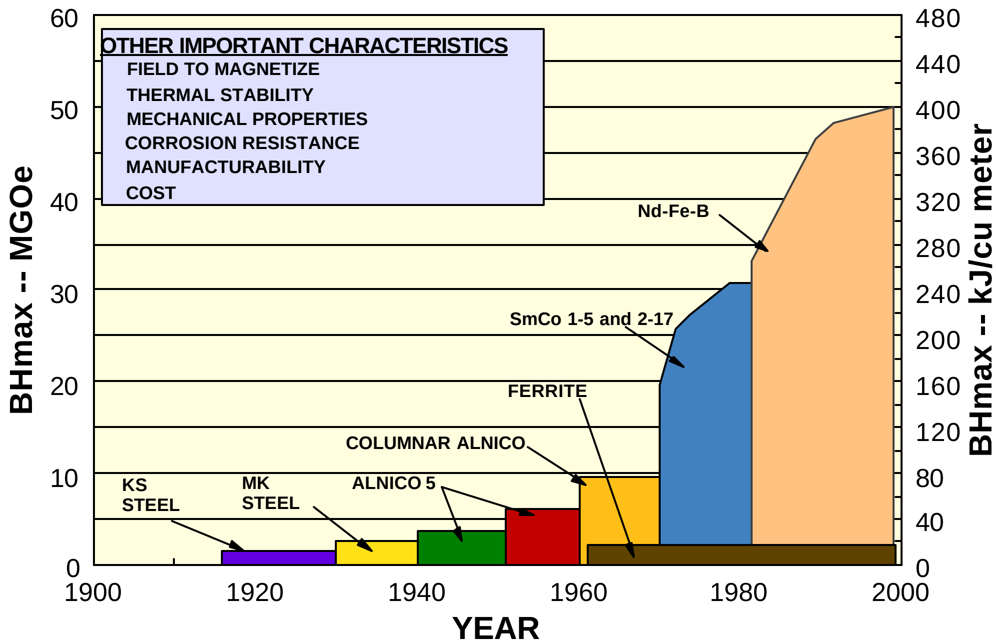
1936 Platinum Cobalt

millions of homes starting at the end of World War II. Figure I presents the development of modern permanent magnet materials.

Philips Corporation produced the first non-metallic magnets in the 1950's. These ceramic (ferrite) magnets used strontium or barium compounds together with iron oxide. The properties of ferrite magnets coupled with low raw material costs led to very useful, low-priced magnets which today dominate the

1951 Ferrite Magnets

Figure I
Development of Permanent Magnets in the 1900's

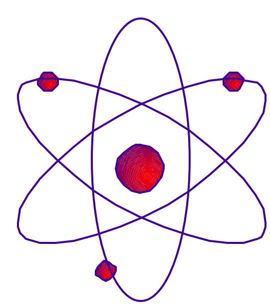


consumer and industrial marketplace. Estimates indicate that ferrite magnets comprise over 80% of world consumption by weight.

1969 Samarium Cobalt

1983 Neodymium-Iron-Boron

Stronger magnet types were introduced in the 1970's and 1980's. These magnets became known as the rare earth family of magnets since they were made from samarium or neodymium, two of the rare earth elements found in the Lanthanide series of the periodic table. Rare earth magnets made it possible to make some devices both smaller and more powerful at the same time. The term "rare earth" implies a scarcity of these elements when, in fact, both are readily available.



WHAT IS MAGNETISM?

Magnetism is the study of phenomena involving magnetic fields and effects on other materials exposed to a magnetic field. Through the work of Coulomb and Oersted, we see that fields from permanent magnets and from eletromagnets have the same affect on surrounding objects. Physicists refer to fields from both sources simply as the "electromagnetic" field. The force generated by an electromagnetic field together with gravity, the weak atomic force and the strong atomic force, constitute the four fundamental forces of nature.

Magnetic fields from permanent magnets arise from two atomic sources: the spin and orbital motions of electrons. Therefore, the magnetic characteristics of a material may change as a function of alloying with other elements. For example, a non-magnetic material such as aluminum can become magnetic in materials such as alnico or manganese-aluminum-carbon. It may also change from mechanical working or any other stress to the crystal lattice.

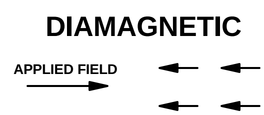
All materials were found to have a permeability, which is the ability of a material to modify a magnetic field that is applied to it. Permeability came to be defined as the amount of magnetic flux density produced in a material divided by the strength of the magnetic field applied to it. Free space is defined as having a relative permeability of 1 and the field obtained is equal to the field applied. This led to the realization that all materials could be grouped by their magnetic behavior. These classifications are:

Permeability: The property of a magnetizable substance that determines the degree to which it modifies the magnetic flux in the region it occupies.

The permeability of free space is defined as 1.

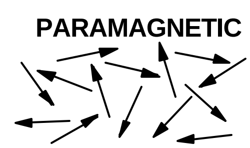
Diamagnetism

Materials that are diamagnetic become weakly magnetized in the opposite direction to that of an applied magnetic field. This results in the material having a force of repulsion to the source of the applied field. The strength of response is very small and the material has a relative permeability that is a little less than 1. The cause of this reaction is associated with Lenz's Law in which small, localized currents are generated in the material in such a way as to create their own magnetic field in opposition to the applied changing field. Examples are copper and helium.



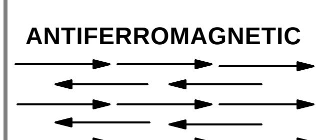
Paramagnetism

Materials that are paramagnetic become magnetized in the same direction as that of an applied magnetic field and the amount of magnetization is proportional to that of the applied magnetic field. Paramagnetic materials have a relative permeability slightly greater than 1 and the effects are nearly undetectable except at extremely cold temperatures or very high magnetic field strengths. They are often considered to be equivalent to air in magnetic design. Examples are aluminum and sodium.



Antiferromagnetism

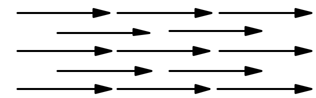
Antiferromagnetic materials have a natural state in which the atomic magnetic fields are arranged anti-parallel within the material. The anti-parallel magnetic fields are opposite and equal resulting in no net external magnetic fields. This natural state makes it difficult for the material to become magnetized in the direction of the applied field but still demonstrates a relative permeability slightly greater than 1. Above a critical temperature known as the Neel temperature, the material becomes paramagnetic. Examples are manganese oxide and iron oxide (FeO).



Ferromagnetism

Ferromagnetic materials have atomic magnetic fields that align themselves parallel to externally applied magnetic fields. This creates a total magnetic field within the material much greater than the applied field. Materials of this nature may demonstrate a relative permeability considerably greater than 1. Above a critical temperature known as the Curie temperature, the material becomes paramagnetic. Examples are iron, cobalt, nickel and most steels.

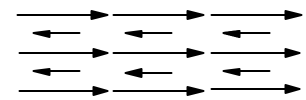
FERROMAGNETIC



Ferrimagnetism

Materials that are ferrimagnetic have atomic magnetic fields that align themselves both parallel and anti-parallel to the externally applied magnetic field. The parallel components are stronger than the anti-parallel components resulting in a net parallel magnetic field that can be substantial. While these materials may also demonstrate a relative permeability greater than 1, their temperature dependencies are not as consistent as with ferromagnetic materials and can result in some very unusual results. Examples are iron oxide (Fe_3O_4) and ferrite.

FERRIMAGNETIC



For the remainder of this text, ferromagnetic and ferrimagnetic materials will be the primary topics of discussion.

WHAT IS A PERMANENT MAGNET?

A magnet is any object that exhibits an external magnetic field. However, this does not necessarily make it a permanent magnet as it also includes electromagnets made of current carrying wire.

A permanent magnet is a material that when inserted into a strong magnetic field will not only begin to exhibit a magnetic field of it's own, but also continue to exhibit a magnetic field once removed from the original field. This field would allow the magnet to exert force (ability to attract or repel) on other magnetic materials. The exhibited magnetic field would then be continuous without weakening provided the material is not subjected to a change in environment (temperature, demagnetizing field, etc.). The ability to continue exhibiting a field while withstanding different environments helps to define the capabilities and types of applications in which a magnet can be successfully used.

A magnet is any object that exhibits an external magnetic field.

Soft magnetic materials will also be discussed, particularly in sections devoted to magnetic design. They are similar to permanent magnets in that they exhibit a magnetic field of their own when in the presence of an external magnetic field. However, they do not continue to exhibit a magnetic field once the applied field is reduced to zero. These materials are useful for carrying, concentrating and shaping magnetic fields. They are used throughout the magnetic industry and are often as vital in the design of a magnetic assembly as the permanent magnet.

Chapter 1 Bibliography:

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