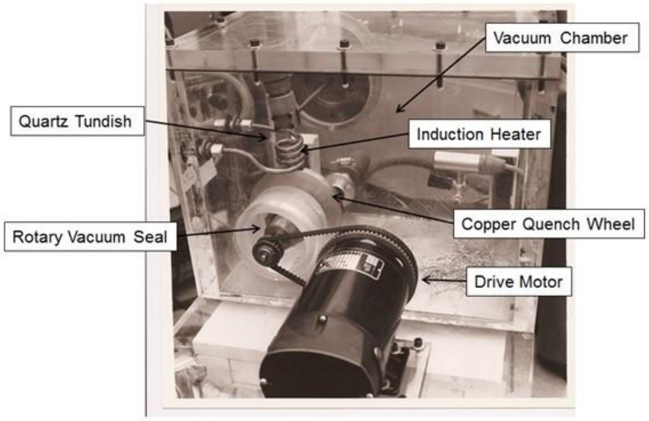
THE DISCOVERY OF NdFeB PERMANENT MAGNETS

History of Magnets — Around 4,000 years ago Greeks discovered a natural mineral, magnetite (iron oxide Fe_2O_3 or ferrite), that stuck to iron nails at the time, the first natural magnet. Later Vikings made compasses to navigate oceans. After World War 2, ferrite magnets were used in automotive accessory windshield wiper motors, and General Motors produced such motors. GM Research Laboratories scientists developed improvements to those production ferrite magnets. In the 1970s GMRL began to research samarium-cobalt (SmCo) magnets, recently announced by General Electric. Samarium is a rare earth (RE), including neodymium (Nd), and fifteen others, but really not rare, as RE mineral deposits are found in China, USA and other locations. SmCo magnets are five times stronger than ferrite magnets.

Discovery of NdFeB magnets — Dr. John Croat, a Ph.D. metallurgist, in the Magnetics group of the Physics Department of GMRL, embarked on mischmetal (MM)-cobalt research to achieve a lower cost RE magnet. MM is a lower cost natural mix of rare earths. He succeeded, but cobalt, mined in Zaire Africa, was high cost so the MM-Co magnet was not cost effective. This led to research to replace cobalt. For several years Dr. Croat investigated combinations of rare earths and iron to produce new inter-metallic alloys by using rapid solidification. The technique is a process called melt spinning, where a thin stream of molten alloy is directed onto the surface of a spinning copper water cooled disk to produce a ribbon-like material. The photo shows the original apparatus that had a small copper disk rotated at a precise speed. In this process, the rare earth-iron alloy was contained in a quartz crucible, or tundish, and ejected onto the surface of the spinning disk using pressurized argon gas. Because rare earths are easily oxidized at high temperatures, this process is done in a sealed vacuum chamber. Quench rates as high as 10,000oC/second are obtained with this device. In 1982 Dr. Croat added other elements to NdFe to further improve magnetic properties.



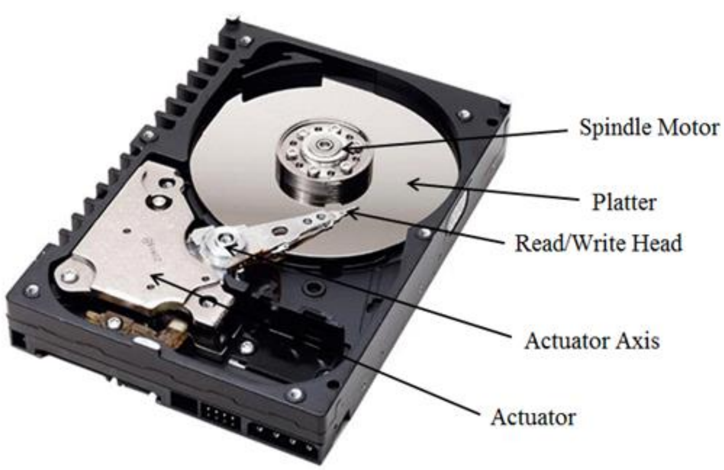
GMRL original melt spinner

Production spinner

When he added a small amount of Boron (B) to NdFe, he immediately noticed the MAGNETIC STRENGTH was TEN TIMES HIGHER than ferrite, so products using this magnet could be much lighter and smaller. Dr. Croat had discovered a new, technologically important inter-metallic compound $Nd_2Fe_{14}B$. This compound is the basis of all NdFeB permanent magnets. Today, over a billion NdFeB permanent magnets are produced each year for computers, autos and other high-tech applications. General Motors went into NdFeB production at Anderson, Indiana at a new facility named Magnequench in 1987. A production melt spinner (photo) produces 2.5 tons of NdFeB magnet powder per run. Annual production worldwide of Magnequench powder is now around 6,000 tons.

Worldwide Applications of Rare Earth Magnets — General Motors Magnequench grew rapidly to a $100 million business. Magnequench sold powder to companies who made magnets for many non-automotive applications. This includes epoxy bonded NdFeB magnets used in spindle micro-motors in hard disk drives (HDD). GMRL also discovered hot pressing the powder produced higher magnetic strength magnets and those are used in servo motors for robots and vehicle electrical power steering. In 1995, General In 1995, General Motors sold Magnequench to a China company and the USA plant equipment was shipped to China. Today Magnequench, with plants still in China, is owned by a USA company, Molycorp, that purchased it from the Chinese for $1.3 billion in 2012. Also, around 1982, Dr. Masata Sagawa, at Sumitomo Special Metals Company in Japan, was researching sintering of NdFeB to create a magnet. First the alloy is crushed into a fine powder and compacted in a magnetic field to align the powder. This compact is placed in a furnace and heated until the powder particles sinter (coalesce into a solid) with the desired final microstructure. Although the Sumitomo and General Motors manufacturing methods are quite different, the final magnets have identical properties and are used in similar applications. Magnets made by the General Motors process are used where ring shaped magnets are required, since sintering a ring magnet is very difficult.

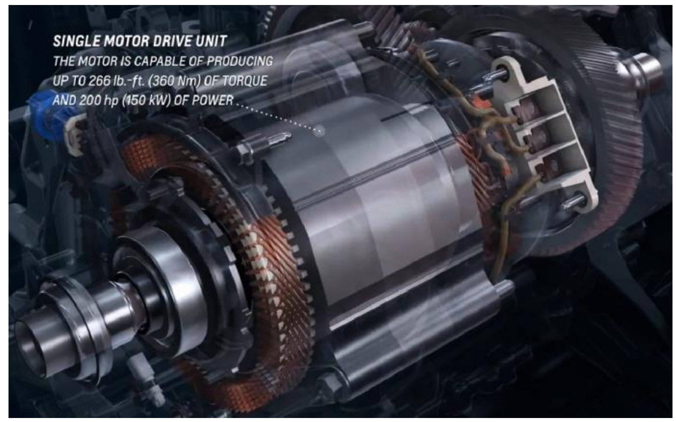
Today magnets are used in many applications, and the most common by far is in motors. Motors are a combination of a permanent magnet rotor and a wire wound coil stator, which turns when a magnetic field is produced by passing electricity through the wire wound coil and the coil is then pulled toward the permanent magnet. NdFeB magnets are used in many different applications including computers, automobiles, robots, medical devices and computer controlled industrial machines, such as lathes and milling machines.



Hard Disc Drive

Many high-end applications where intelligent, variable motion is required are switching to NdFeB magnets. Although the HDD in many computers is being replaced by flash drives using memory chips, with no moving parts, the magnet driven spindle motor for the HDD is still one of the biggest applications for NdFeB magnets. Electric bike motors, up to 500 watts and higher, all use NdFeB magnets with nearly 50 million made each year, mainly in China. Many electric and hybrid vehicle motors, 200 horsepower (150,000 watts) and higher, use over 25 kg of NdFeB magnets. Cost is very important and many of these vehicles still use traditional wire wound motors. Magnetic resonance imagining (MRI), that allows disease detection in patients, uses tons of NdFeB magnets in each imaging device.

Bosch mid-drive DC motor



Chevy Bolt DC motor NdFeB magnets on rotor

The discovery of NdFeB magnets by research from 1970 to 1980s has provided smaller, lighter, powerful permanent magnet motors and allowed application to new products heretofore unimagined.
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Published March 2019

References

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HOW MAGNETS WORK

Elements are made of atoms 10-8 cm in size. A stack of one million atoms equals the thickness of a sheet of paper, 0.1 mm. Atoms have electrons, sized 3x10-13 cm, a millionth smaller than an atom. The electron has an electric charge and circles the nucleus, or core, of the atom. These electrons also spin around their axis like a top. These two motions, referred to as the orbital and spin momentum, generate a local electric current and causes each electron to act like a microscopic electromagnet. In most substances, equal numbers of electrons spin in opposite directions, which cancels out their magnetism. That is why cloth and paper are non-magnetic. However, in the metals iron (Fe), cobalt (Co), and nickel (Ni) some of the electrons spin in the same direction, making these metal atoms magnetic, with a magnetic moment. Although these metals have strong magnetic moments, they are not aligned. In fact the moments point in all directions so that the net magnetism is zero. This is the situation shown in Figure 1 (a). However, if we apply a magnetic field to the Fe, the magnets will align with the magnetic field and it becomes a temporary magnet as shown in Figure 1 (b). It is temporary because if the magnetic field is removed, the moments again become random, like in (a). But adding other elements to Fe, like barium or strontium, it will become a permanent so-called ferrite magnet.

Fig. 1 (a) Random magnetic moments
(b) Aligned moments in magnetic field

Figure 2 Nd 4f orbital moments align Fe moments to create a powerful magnet

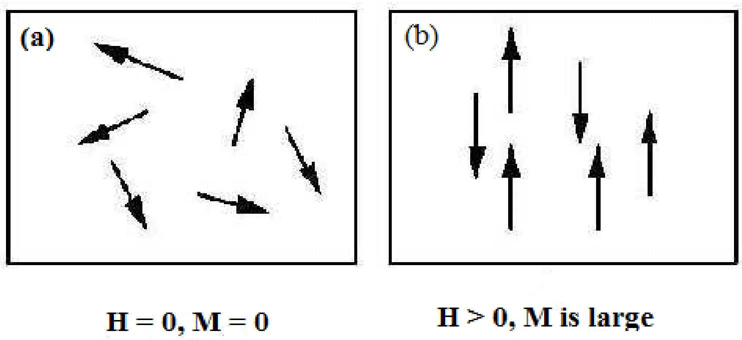

Figure 1

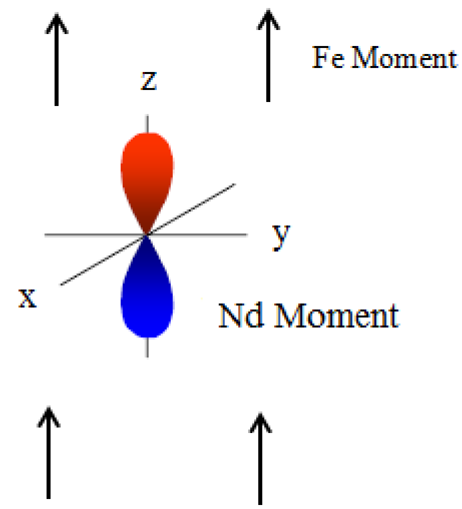

Figure 2

Research using rare earth elements with cobalt to increase magnetic strength over ferrite magnets was begun in the 1960s. Cobalt is expensive, so these magnets were not widely accepted and research evolved into studies of rare earths with lower cost iron (Fe). The use of the abundant, less expensive light rare earth Neodymium (Nd) possibly would provide a cost-effective magnet. However, Nd and Fe do not form crystalline compounds, which is an essential requirement of all permanent magnets. Researchers found Nd and Fe form a compound if a small amount of Boron (B) is added. These three elements in combination form a very important crystalline compound Nd2Fe14B and this compound is the basis of all NdFeB magnets produced today. The reason that Nd2Fe14B is such a powerful permanent magnet is because the Nd atoms produce a highly anisotropic internal magnetic field, called the crystalline field, that forces the iron moments to stay aligned once it has been magnetized. Nd can do this because the 4f electrons in the Nd atom forms into a non-uniform shape that creates a highly anisotropic crystal field. Anisotropic means properties are much different from one direction to another. For example, the shape of the Nd moment in Figure 2 is much different along the z direction than the x or y direction. It is this highly anisotropic crystal field that holds the Fe magnetic moments in alignment and makes NdFeB magnets such powerful permanent magnets. The Fe moments provide most of the magnetic strength of NdFeB magnets, but the Nd atoms make it a permanent magnet.

April 2019

"Arbor Scientific would like to thank Frank Jamerson for this interesting and insightful article."