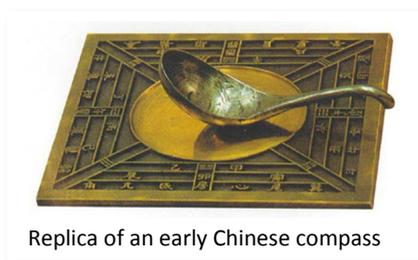


What are permanent magnets?

The phenomenon of magnetism has greatly interested people since its discovery, which is believed to be about 3.000 years BC. However, its 'attraction' was not in the first place scientific; they were used by 'medicine men' and magicians to impress their audience¹. It was the force to attract other materials that gave the magnets their supernatural aura. Even nowadays you can find adverts in which so-called scientists want to help you stop smoking or heal your migraine using magnetic forces. Other peoples first thought when hearing the word 'magnet' is the well-known children's toy where the black and white billy goats are banging their heads together. Some think of the compass and there are also some people who think first at the clasp of a handbag...



These days however, the magnet is much more than a cheap toy, our world is moved and controlled by magnets. In more and more electric motors an arrangement of permanent magnets is ensuring the movement – not only in hybrid or electrical cars: Even in a modern ICE driven car up to 200 little electrical motors are controlling e.g. ignition, starter or automatic braking; others are helping to adjust your seat, windows or headlights etc. In automation, multitudes of sensors and stepping motors are relying on permanent magnets, as are the generators in modern wind turbines. New applications like e.g. magnetocaloric cooling would not be possible without the appliance of permanent magnets.



But the first magnets were nowhere near as effective as today. The lodestone (or loadstone), a form of magnetite (Fe_3O_4), is believed to be the first magnetic material used by the Chinese as a compass as early as 2.500 BC². It took about 3.700 years before it was introduced to Europe; however the first documentary evidence of the ability of lodestone to attract iron was made by the Greek philosopher Thales of Miletos in the sixth century BC.

A number of accounts of magnetism had already been written when in 1600 William Gilbert, a court scientist to Queen Elisabeth I of England, wrote his famous book "De Magnete", which is believed to be one of the first systematic treatises of experimental physics in the modern sense. In the following 350 years, a lot of scientific discoveries around the magnet were made, e.g. the magnetic effect on an electric current, the magnetisation and demagnetisation (hysteresis loop) of iron in a magnetic field or the elaboration of the physics of magnets with the theories of electron spins, exchange forces etc.

But still, magnets out of lodestone were made by stroking with another magnet, or sometimes by cooling it down in the Earth's magnetic field. The successes achieved by such methods were remarkable: Gowin Knight for example, an 18th century scientist, was reported to have made a magnet 'capable of lifting 28 times its own weight'³.



Gowin Knight's famous lodestone

¹ This advertisement for W.D. Jones' National School of Magnetic Healing appeared in the July 22, 1899 Pantagraph (US, image courtesy by the McLean County Museum of History)

² http://www.smith.edu/hsc/museum/ancient_inventions/compass2.html

³ www.earlytech.com

In spite of such successes it was necessary to develop new magnetic materials. This began around 1900 with the introduction of **steels** containing tungsten, and rather later, chromium. In 1917, **cobalt steels**, which represented a big step forward, were discovered in Japan. Also in Japan, 1931 the **AlNiCo alloys** were developed, the first improvement over steel. These alloys are based mainly on the elements nickel, cobalt and iron with smaller amounts of aluminium and copper. Because of the high stability of the magnetic properties up to the Curie temperature of $\sim 850^\circ\text{C}$, they still represent a significant percentage by value of the magnet production.

In the early 1950s the **ferrites**, ceramically processed oxide permanent magnets, were developed in Holland and Germany, based either on a cubic or hexagonal structure. Despite their low performance, they account for about half the weight of the permanent magnets produced today, as they are easy to process and the raw materials are cheap. On the other end of the performance side, major effort has been directed towards the rare-earth(RE)/transition metal (TM) permanent magnetic materials. Starting in the late 1960s with YO_5 , soon followed by SmCo_5 (often referred to as '1:5 type' magnets) the development lead to a dramatic increase of the energy product with a $\text{Sm}_2\text{Co}_{17}$ type alloy ('2:17') in the mid-1970s. This was achieved by a carefully engineered microstructure, controlled by substituting some of the cobalt with iron, copper and zirconium.

The main problem with **samarium-cobalt** magnets however is the expense of the raw materials. Unfortunately, samarium is much less abundant than the other light rare-earth elements, and is also classified as a strategically important metal.

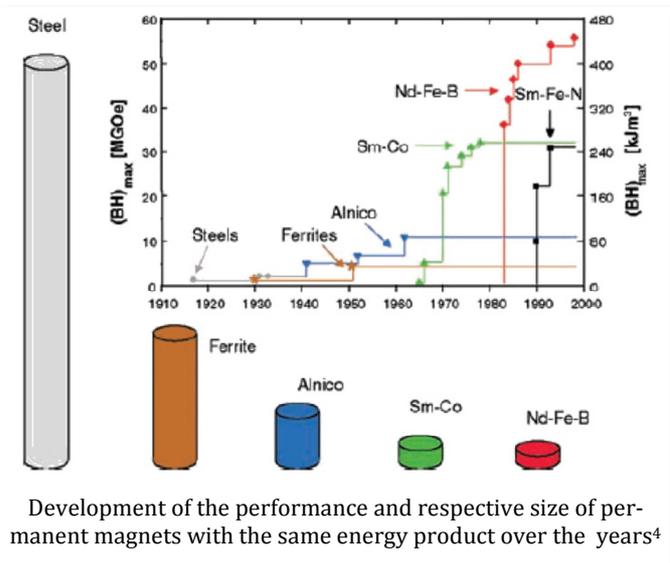
Therefore the main aim of the research in magnetic materials was to find cheaper materials with properties as good as or better than samarium-cobalt 2:17-type magnets. Iron (Fe) is the cheapest of the ferromagnetic materials and, having the highest saturation magnetisation, it is material wise an obvious candidate for cheap high performance magnets. However, there is no stable binary phase with one of the cheaper rare earth elements, which is suitable for the production of magnets. (There are stable $\text{RE}_2\text{Fe}_{17}$ intermetallics, however their magnetic stability (Curie temperature) is so low, that the magnetic properties are unstable even at room temperature). The major breakthrough came by looking at ternary and quaternary systems of rare-earth/transition metal/boron alloys in the early 1980s. This resulted in the development of **Neodymium-Iron-Boron** (NdFeB) alloys, whose theoretical energy product (BH_{max}) can reach more than 500 kJm^{-3} (up to 64 MGOe). The major drawback of NdFeB type magnets however is their low Curie temperature of $\sim 310\text{-}400^\circ\text{C}$; they also show a high tendency to corrode, which requires a suitable coating of the magnets.

Today major efforts are made to find new magnetic phases and to replace Neodymium by other, more stable and cheaper elements with a better availability, but to date no such magnetic phase seems to appear on the horizon. Therefore, the 'attraction' of NdFeB as a magnetic material currently remains unbowed, and extensive research is being carried out to find new ways of sustainable, resource efficient production of high-performance magnetic materials.

For more information: www.repromag-project.eu



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⁴<http://m.iopscience.iop.org>