Magnetism: It is Permanent

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Abstract

Permanent magnet materials have one of the longest histories of any technological phenomenon, stretching from before 4000 BC to now. The early history of lodestones (naturally occurring magnets), their applications and their use to make artificial magnets is described. The early work of the Chinese and European magnet users culminated in the classic text '*De magnete*' published by William Gilbert in 1600. The developments of the next two centuries were based on Gilbert's work until the development of the electromagnet enabled steels to be magnetized without recourse to a lodestone. The improvements in the magnetic properties of permanent magnets then took place gradually, by the development of steels and by optimizing alloy compositions and heat treatments. In the 20th century, three major families of permanent magnet materials (metal, ceramic and rare earth) have been developed. The composition, properties and the method of manufacturing these metal (aluminum-nickel-cobalt-iron), ceramic (barium or strontium ferrite) and the three generations of the rare earth (RCo_5, R_2Co_{17} and NdFeB) magnets are described, and the possible applications of permanent magnetic materials are briefly tabulated. Finally using performance indicators that have been defined earlier, it is shown that the performance of permanent magnet materials have increased two-hundred-fold in the 20th century. The past and future of these important commercial engineering materials is permanent.

1. Introduction

Permanent magnet materials are important components of consumer, transport, industrial, military and aerospace systems. There has been an increasing use of permanent magnet materials as the properties of these materials have been improved over the centuries. The first improvements in properties of permanent magnets were achieved in early modern times by 'giving' the magnetic effect of naturally occurring permanent magnets to manufactured steel or by concentrating the magnetic effect by the use of end caps, i.e. making 'armed' lodestones.

Later improvements of permanent magnetic materials have been achieved by developing new materials and by optimizing the properties of those materials. The improvements have therefore been by major transitions caused by the development of a new material followed by gradual improvements until another new material is produced. Typically, in the 20th century, the transitions have been caused by the development of metal, ceramic and rare-earth magnets. The definition of improvements in permanent magnets is difficult because there is no single figure of merit; the values of several magnetic, electrical and mechanical properties are important. The numerous applications of permanent magnets all require different properties, and the production of materials to meet these needs is a major modern industry.

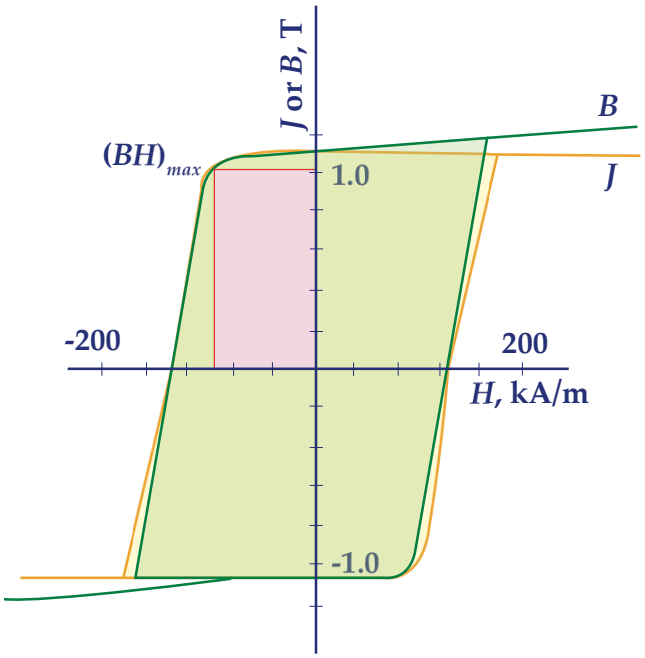


Figure 1a — Flux density *B* and magnetic polarization *J* against magnetic field strength *H*, Low coercivity permanent magnet (steels, Alnicos)

- In SI units, $B = \mu_0 H + \mathcal{J}$, where $\mathcal{J}$ is the sample magnetization Remanence is the value of *B* after *H* is reduced to zero.
- Coercivity H_c is the reverse field required to reduce *B* to zero.
- The maximum energy product $(BH)_{max}$ is the area of the largest rectangle in the second quadrant of

the B/H loop, and is the same for the two magnets shown.

- For magnets of type *a*, the energy product depends strongly on coercivity. but for magnets of type *b*, the energy product depends mostly on remanence, Buschow.[1]

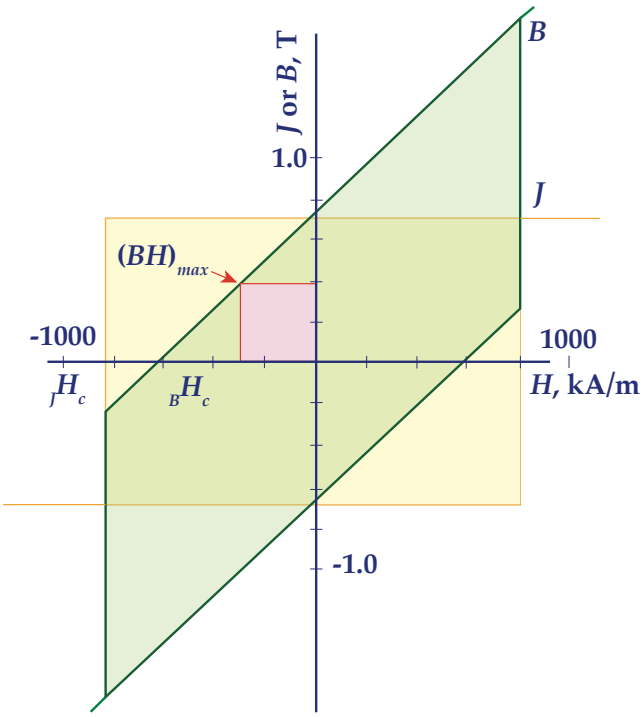


Figure 1b — Flux density B and magnetic polarization J against magnetic field strength H, High coercivity permanent magnet (ferrites, rare earths)

However, to restrict the technical complexity of this paper, each permanent magnet material will be assessed by considering three magnetic parameters only defined[1] in Figure 1, namely

(i) remanence B_r, measured in tesla

(ii) coercivity H_c, measured in kilo amperes per meter

(iii) maximum energy product $(BH)_{max}$, measured in kilo-joules per cubic meter.

2. Early Magnets

2.1 In the East.

The first reported application of naturally occurring permanent magnet material is in the Chinese chronicles. It has been reported[2] that the best prepared caravans that crossed the Gobi desert, from the minarets of the kingdoms of the Kushans to the imperial pagodas on the banks of the Yangtze, contained a white camel. In a clay pot full of water, protected by a carved wooden box mounted between the humps of the albino beast, floated a cork containing a piece of magnetized iron. The edges of the pot were painted in four colors: red for south, black for north, green for east and white for west. This primitive compass enabled the caravaner to navigate across the sands.

In the Chinese chronicles there are also descriptions of magnetic gates, which restricted the access of armed ill wishers, and magnetic roadways made possible by the magic stone chu-shih.

These stones, simply magnetic iron ore, were also known as 'loving stones' because their attraction for pieces of iron was similar to the love parents have for their children.[3]

One Chinese legend relates that Emperor Huang-Ti, nearly 5000 years ago, had a chariot made on which was mounted a small man with an outstretched arm. This arm, Figure 2, always pointed South, so that Huang-Ti's armies were able to attack their enemies from the rear in a fog and defeat them.

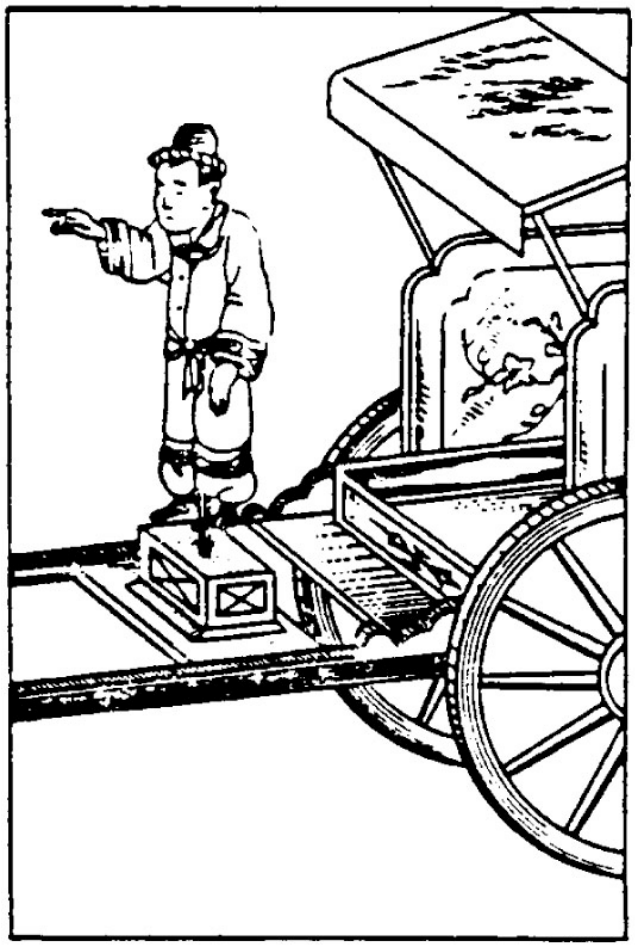


Figure 2 — Man-shaped compass mounted on a chariot, after Kartsev.[2]

The stories of camel and chariot mounted compasses may be apocryphal, but Chinese encyclopedias state that magnetic needles were used as compasses on ships in

400 BC, and there exists a 1000 year-old Chinese compass resembling a traditional painted spoon, see Figure 3.

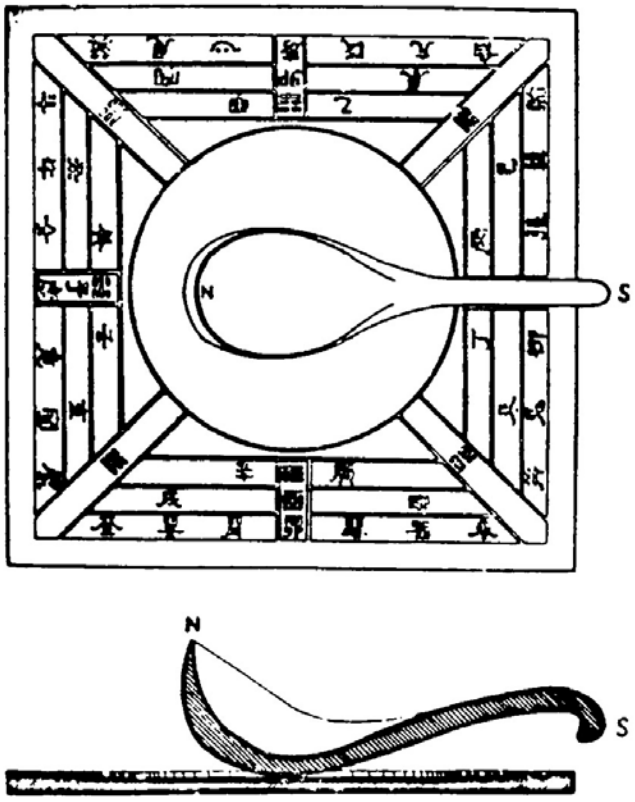


Figure 3 — Chinese spoon compass

Notwithstanding these early oriental excursions into permanent magnetism, the principal development of permanent magnet materials has been undertaken in Europe.

2.2 In Europe

A naturally occurring permanent magnet material, a variety of magnetite, Fe_3O_4, known as a lodestone was known to the Greeks.[4] The name lodestone, or alternatively and incorrectly loadstone, was derived from its navigational property of seeking the lodestar. The names magnetite, magnetism and all their derivatives stem from the name of the district where lodestones were found to be plentiful, Magnesia.

The microstructural origin of the coercivity of lodestones, typically 10 kA/m,[5] was shown to be due to a fine intergrowth of Fe_2O_3 produced by oxidation in the Fe_3O_4 material. This fine microstructure acts as an inhomogeneity impeding magnetic reversal, by restricting the motion of the magnetic domain walls, thereby increasing the coercivity of the material.

Thales of Miletus, *circa* 600 BC, and many other Greek philosophers of the period from 400 to 200 BC described the attractive property of lodestones. Later, Lucretius in "*De natura rerum*" described the repulsion of lodestones, but it was the development of artificial permanent magnets made by 'touching' iron needles with a lodestone which was the first transition in the improvement of permanent magnet materials.

It is not possible to locate accurately the first production of artificial permanent magnets. At the beginning of the 13th century, the French troubadour Guyot de Provins (called Hugue de Bercy by Hoppe)[6] describes, in his satirical poem "*La Bible*," the use of a touched needle in a straw floating on water. It is claimed that the inhabitants of Amalfi (particularly the jeweler Flavio Gioia) made compasses, similar to today's instruments with a rotating disc marked out in divisions, at the beginning of the 13th century. Peter Peregrinus, in his famous treatise "*Epistola and Sygerum de Foucoucourt militem de magnete*," in 1269, stated that an oblong piece of iron which had been touched by a lodestone would turn toward the pole if floated on a piece of wood. He also discovered that two regions of the magnetite, now called magnetic poles, attracted a piece of iron more strongly then the rest of the magnetite.

During the next three centuries, the alchemists attempted to develop lodestones as a facilitator for the change of base metal into gold, as an aphrodisiac, as a talisman to attract the opposite sex, etc.

This extensive period, which produced no improvements in the properties of permanent magnets, was terminated by the publication of the first great work in the field of magnetics.

2.3 De magnete by William Gilbert

The famous treatise "*De magnete magneticisque corporibus et de magno magnete tellure physiologia nova*" by William Gilbert, which was published in 1600, is one of great classical works in experimental physics.[7] Galileo[8] wrote:

> "I extremely praise, admire and envy this author ..."

Gilbert experimented with lodestones and iron magnets, described correctly the basics of terrestrial magnetism, and refuted many of the traditional properties attributed to permanent magnets. Gilbert demonstrated that the attractive power of lodestones was not neutralized by garlic, goat's blood or diamonds as had been claimed by some of the alchemists.

Furthermore, he described methods of making lodestones more powerful attractors by 'arming' them, i.e. by attaching soft-iron caps as shown in Figure 4. He was able by the use of this arming technique to increase the weight of iron lifted by a particular magnet from 4 to 20 oz, a fivefold enhancement.

Figure 4 — Gilbert's method of 'arming' lodestones to improve their attractive force by attaching soft iron caps

Gilbert required artificial magnets for the manufacture of compasses and dip circles which were used as navigation instruments. He recognized that 'iron made hard' was the best material for artificial magnets. His dip circles used a magnet 10 to 12 inch long, and he described a magnet as thick as a goose quill and about 8 inch long.

Gilbert described three methods by which permanent magnetism (or verticity as he called it) could be given to steel:

(i) touching with a lodestone, which was drawn from the middle of the needle to the end, or touching opposite ends with the different poles of the lodestone

(ii) forging a horizontal specimen or drawing a wire pointing north-south in the earth's magnetic field, see Figure 5

(iii) magnetizing by long exposure to the earth's magnetic field without the plastic deformation required in (ii) above.

Figure 5 — Method of forging in the earth's magnetic field to produce permanent magnets

Robison[9] claimed in 1822 that Gilbert's *De magnete*, written in 1600, contained everything that was then known about magnetism. However, a few advances were made in the 17th and 18th centuries, for example the shape of armed lodestones was improved, principally by squaring the ends. Boyle, in 1675, showed that magnetic effects in materials could be destroyed by heat without any apparent physical change taking place. He postulated that magnetism was due to the 'disposition or internal constitution' of the iron. Gilbert had earlier observed that, if heated iron fire tongs were allowed too cool in an upright position, close to the direction of the earth's magnetic field, in London, they sometimes became strongly magnetic.

2.4 London Magnets

The driving force for the improved manufacture of permanent magnets during the 18th century was financial, since lodestones were very expensive. In 1711, Hartsoeker[10] was asked 3000 guilders, equivalent then to £250 and equivalent now to £30,000, for a lodestone as big as his fist. London became the centre of the world's permanent magnet manufacturing industry. Many of the techniques were kept secret and were not all based on sound scientific reasoning; e.g. the exact number of touchings by a lodestone was not as crucial as some magnetic entrepreneurs led their customers to believe.

Servington Savery[11] described, in 1730, the process by which he made strong permanent magnets. He took steel wire, 0.05 in in diameter and 2.75 in long, which he 'seasoned very hard,' and he then magnetized the wire by touch with a lodestone. He used 37 wires to make a hexagonal bundle which, with soft-iron end pieces, was the first compound magnet. These magnets were used to magnetize wires, placed end to end to decrease the demagnetization factor, which were able to lift 12 times their own weight.

The London magnet business reached its zenith in the middle of the 18th century with the entrepreneurial and technical skills of Gowin Knight. He made a fortune by manufacturing magnets, sold at 10 guineas per bar, to meet the market for compass needles and as a remedy for all known illnesses, complaints and agues. Like all successful industrial concerns Knight did not fully publish the methods by which he made magnets. However, he did describe[12] a method of producing 5 inch-long compass needles by repeatedly increasing the gap between two magnets bridged by the needle.

George Adams the Elder made instruments using Knight's compass needles, and his son, George Adams[13] described a method, used by Knight, in which the ends of the bar to be magnetized were supported by permanent magnets and the method of divided touch, with inclined magnets, was used to magnetize the bar.

Knight made a very powerful compound magnet built from steel bar magnets each 15 x 1 x 1/2 inch. The bars of this 'magnetic magazine' were 'impregnated by repeated attritions'. Each half of the compound magnet consisted of 240 bars with 4 sections, each being 6 magnets deep and 10 magnets wide, so that the overall dimensions were 64 x 6 x 5 in. This 'magnetic magazine' was later arranged in two halves to form a horseshoe magnet and

was used in 1831 by Faraday in his famous rotating copper disc experiment.

One of Knight's magnets was capable of lifting 28 times its own weight. The magnets produced throughout Europe and by his local competitors in London used Knight's magnets as standards with which they compared their magnets generally unfavorably. However, his competitors did publish descriptions of their methods of making magnets. Wilson[14] described in 1779, after the death of Knight, a method used by Knight which consisted of panning a slurry of iron filings to obtain a suspension of very finely divided iron oxide. This fine oxide powder was mixed with a linseed paste shaped into blocks, baked and then magnetized by the 'magnetic magazine' to produce very strong magnets. This technique for producing magnets was re-invented nearly two centuries later and is not dissimilar to ceramic magnet manufacturing methods.

The works of other magnet makers such as Canton, Michell, who published the first book on making steel magnets, Aepinus, Duhamel, Robison, Haldat, Scoresby, Coulomb and Jamin are described in the classic paper by Andrade.[4]

However, all the efforts by these workers were a refinement of the methods of making magnets described by Gilbert in 1600. The development of the electromagnet by Sturgeon[15] solved the problem of magnetizing materials which were principally carbon steels. The permanent magnet properties of carbon steels were probably due to a martensitic microstructure, and the coercivities obtained were typically 4 kA/m, with maximum energy products typically about 2 kJ/m^3.[16]

2.5 Early Alloys

As early as 1758 it was found that brass, an alloy of copper and zinc with no ferrous content, could be made magnetic by hammering and 'touching' with a magnet.

Similarly, in 1786, it was recorded that brass could be made magnetic by hammering and that its magnetic effect could be destroyed by heat. This property was sometimes attributed to inclusions of iron in the zinc, but by the middle of the 19th century it was recognized that magnetic materials could be made using nonmagnetic elements alloyed with iron and nickel.

It had been recognized that iron that had been made mechanically hard possessed a higher value of coercivity than untreated iron. Probably, the hardened steel contained a martensitic microstructure or sufficient carbide particles and other inclusions to restrict the domain wall motion, thereby increasing the coercivity of the material.

The generic names 'hard' magnetic materials for permanent magnet materials and 'soft' magnetic materials for materials that are easy to magnetize and demagnetize arose because, in the 19th century, the hard magnetic materials were mechanically hard and soft magnetic materials were mechanically soft. Nowadays, nothing could be further from the truth. There are now hard (permanent) magnetic materials which are mechanically soft and vice versa. The permanent magnet (hard) materials of the 19th century would now be considered to be soft magnetic materials. But the descriptions, 'hard' and 'soft' for magnetic materials, are so well entrenched in the literature that these misnomers will continue to be used.

This correlation between hard mechanical properties and permanent magnetic materials encouraged the metallurgists of the 19th century to introduce hardening additions (such as tungsten, chromium and molybdenum) to iron to produce improved permanent magnet materials.

Tungsten steel was introduced in 1857, and 7.7% W steel was found, by Madame Curie, to have a coercivity of 7 kA/m. Chromium steel become widely used when tungsten became unavailable during the First World War.[16]

About 1917, cobalt magnet steels were developed by Honda and Takagi in Japan, who showed that a steel containing 30 to 40% cobalt plus tungsten and chromium had a high coercivity. This cobalt steel was developed, by using a complex triple stage heat treatment, to have a coercivity of 20 kA/m and a maximum energy product of 8 kJ/m^3.

The cost of the raw materials, particularly cobalt, and the triple stage heat treatment, shown in Table I, made cobalt magnet steels expensive, but they were the best magnet steels available in the 1920s.

Table 1 — Triple Heat Treatment for Magnet Steels

Treatment	Result
First stage Heat to 1150-2000°C (possibly in salt bath) Rapid cooling in air or oil	Introduces austenite, and and carbides dissolved
Second state Heat to 700°C	Decomposes austenite into ferrite and cementite — exothermal reaction
Third stage Rapid heating and quenching	Highly strained tetragonal crystals martensite

However, the inherent metallurgical instability of steels and their tendency to demagnetize easily, coupled with the increasing number of uses for magnets, encouraged the development of new permanent magnet materials.

3. Metal Magnet Materials

The first major improvement in permanent magnet materials in the 20th century was made possible by the development of the aluminum-nickel--cobalt-iron family of materials. This system can be called metal magnets if one does not want to use the more familiar commercial name Alnico.

The first alloy discovered by Mishima[17] did not contain any cobalt and had a coercivity nine times greater than tungsten steels and two and a half times greater than the best cobalt magnet steels. These aluminum (10%) - nickel (25%) - iron (65%) alloys were cheaper than cobalt steels, had higher coercivity and did not require quenching, and for the next twenty years were extensively researched throughout the world. The effects of annealing temperature, cooling rates, alloy additions, compositions, manufacturing methods etc.; were fully investigated, and many companies competed to maximize the value of the then accepted figure of merit for permanent magnet materials, namely the maximum energy product.

Over these 20 years, four families of metal magnet were developed;

(i) Isotropic alloys, containing 12% Co or less

(ii) Moderate coercivity field treated alloys, containing 20 to 25% Co

(iii) High coercivity alloys containing more than 30% Co

(iv) columnar varieties of either (ii) or (iii) above.

3.1 Isotropic Al-Ni-Co Alloys

These alloys were based on Mishima's original work, with the nickel composition varying from 22 to 30% and with the aluminum content varying from 10 to 12%, but the control of cooling rate and subsequent heat treatment were crucial and difficult to reproduce. It was found beneficial to include some copper and cobalt in the alloy,[18] as can be seen by comparing the first two rows of Table 2.

Table 2 — Composition and Properties of Typical Alnico (metal) Magnets, McCaig[18]

Nominal Composition Weight %									Properties	
Grade	Al	Ni	Co	Cu	Nb	Ti	Fe	B_r T	H_c kA/m	$(BH)_{max}$ KJ/m^3
A1	10	16	—	—	—	—	74	0.55	38	10
A1	13	28	13	6	—	—	40	0.75	58	13
A2	9	16	26	4	1	—	44	1.30	52	44
A3	9	16	26	4	3	1	41	1.15	62	36
A4	8	16	35	4	2	5	30	0.92	132	44
A5	8	16	40	4	2	8	22	0.78	160	46
A4 col	6.5	13	30	2	—	3	45.5	1.00	120	64
A4 col	8	16	35	4	2	5	30	1.05	128	72

These materials are isotropic; i.e. they have similar properties in all directions, but improved properties of soft magnetic materials had been achieved by manufacturing materials which were anisotropic, i.e, they had directional properties.

3.2 Anisotropic Al-Ni-Co Alloys

In 1938, Oliver and Sheddon[19] showed that cooling in a magnetic field produced anisotropic magnets with improved properties in the field-annealed direction. Later workers showed that a large improvement in maximum energy product could be obtained by the field cooling of alloys with more than 20% cobalt, see the third row, (A2) of Table 2. It was shown by De Vos,[20] using electron microscopy techniques, that this magnetic annealing produced preferential alignment of the (Fe, Co)-rich particles along or near the field direction.

The process of producing these metal magnets varied between manufacturers and was often clouded in patent and commercial secrecy licenses. A basic process is shown in Table 3.

Table 3: Basic method of producing anisotropic Alnico (metal) magnets

Process	Treatment
Solution	Heat to 1250°C
Field treatment	Cool at 1.2 degrees C/s in DC magnetic field of 80 kA/m*
Final heat treatment (tempering)	2 hour at 625°C, Cool from 625°C to 560°C in 6 hour, 16 hour at 560°C

*Field is obligatory only from 750 to 850"C to prevent spinodal decomposition which deleteriously affects properties

Many methods were investigated in attempts to increase the coercivity of these materials by trading this required increase against a reduction in the maximum energy product, i.e. by optimizing the shape of the *B*/*H* loop.

3.3 High coercivity Al-Ni-Co alloys

An increase in the Niobium content to 2-3% without increasing the cobalt content above 26% raises the coercivity to 60 kA/m, but the $(BH)_{max}$ value is reduced to 36 kJ/m^3; compare row 3 (A2) and row 4 (A3) in Table 2.

Alternatively, by increasing the cobalt content and adding titanium and possibly niobium, even higher coercivities are achievable. Many possible compositions have been used by the various manufacturers in order to achieve increased market penetration, e.g. grades A4 and A5 in Table 2.

The manufacturing process for this family of magnet materials can be continuous cooling in a magnetic field or by the use of an isothermal treatment. In this latter operation the magnets are maintained in a magnetic field for several minutes at a constant temperature, typically 800°C.

These high coercivity metal magnets can be produced by sintering or casting but then they are always brittle and liable to breakage.

3.4 Columnar Al-Ni-Co alloys

The anisotropic properties of Alnico alloys are optimized if the field during magnetic annealing is along a <100> direction, because a columnar texture is produced which gives improved properties, see A4 col rows in Table 2. Several methods, such as

(a) Moulds preheated in a furnace with heat extracted by a chill plate

(b) Moulds heated by an exothermic reaction produced by their special composition

(c) Continuous casting

(d) Zone melting.

have been used to encourage the necessary columnar crystal structure.

3.5 Conclusion

The Alnico magnets revolutionized the permanent magnet industry in the first half of the 20th century, but the manufacturing processes are complex and the raw materials are expensive. In particular, cobalt is a strategic material whose supply is subject to changes in the world's political climate.

The domination of the permanent magnet market by the Alnico (metal) magnets was challenged by the introduction of ceramic ferrite magnets in the 1950s. The use of ferrite magnets surpassed the use of metal magnets in the late 1960s.[21,22]

4. Ceramic Magnet Materials

The second major family of permanent magnet materials was developed by the Philips organization in the 1940s, These ferrite or ceramic materials possess permanent magnet properties because of the phenomenon of ferrimagnetism (i.e. the magnetic moments of some Fe ions are antiparallel to the others) whereas the properties of the metal magnets are due to ferromagnetism.

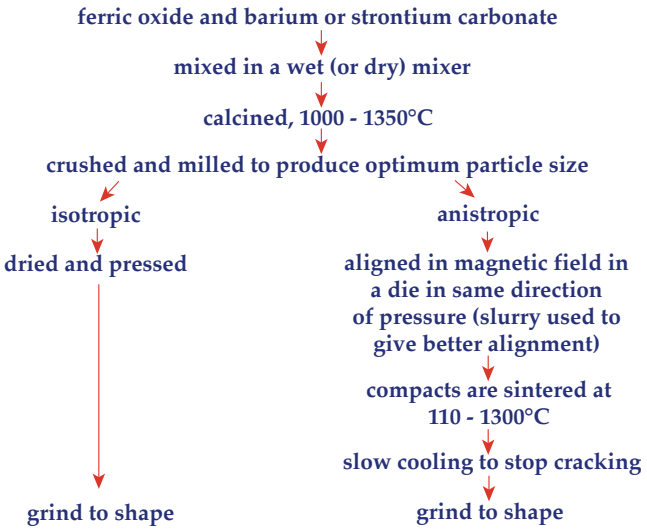
The coercivity of the Alnico alloys arises from the shape anisotropy of small ferromagnetic particles, approximately 20 nm in diameter, whereas the coercivity of the ferrite alloys is produced by the high magnetocrystalline anisotropy of the hexagonal crystal structure of the material, $MO.6Fe_2O_3$ where M is barium (Ba) or strontium (Sr). The difference in magnetization properties along the hexagonal axis, an easy direction of magnetization, and other directions impedes the rotation of the magnetization, thereby impeding magnetic reversal and giving the material a high coercivity.

These ferrite magnets, being ceramic, and hence brittle, have a high resistivity of typically 10^{10} μΩm compared with the value of 0.5 μΩm of the metal magnets. Therefore, ferrite magnets have negligible eddy-current losses when subjected to high frequency alternating fields.

The method of making both isotropic and anistropic magnets involves ball milling to obtain particles about 1 μm in diameter and pressing wet powders, in a magnetic field to align the particles for anisotropic magnets, and sintering the compacts to produce regular shapes, see Table 4. It is possible to manufacture flexible rubber magnets and plastic magnets by mixing ferrite powder with the base material when compounding the rubber or

plastic. These flexible magnets have many uses varying from magnetic string to magnetic signs and games.

Table 4 — Basic Method of Manufacturing Isotropic and Anistropic Ferrite Magnet Materials



The use of ferrite magnets was restricted in the early 1960s, particularly in the United Kingdom, because of a lack of appreciation of the difference in the magnetic properties of the ceramic and metal magnets.

The ferrite magnets have a high coercivity, typically 160 to 400 kA/m, compared with a maximum value of 150 kA/m for an Alnico magnet, but the maximum energy product of a ferrite material is about 30 kJ/m³, see Table 5, compared with 40 to 60 kJ/m³ for the Alnico magnets.

Table 5— Typical Properties of Ceramic Magnets, after McCaig[18]

Material	Description	B_r T	H_c kA/m	$(BH)_{max}$ KJ/m³
F1	isotropic	0.23	152	8.4
F2	anisotropic	0.39	200	30.4
F3	anisotropic	0.37	265	26.5
F4	bonded, flexible isotropic	0.17	128	5.6
F5	bonded, flexible isotropic	0.25	168	12.0

The higher coercivity of the ferrite magnets means that short magnetic circuits with large cross sectional areas should be used, since the high coercivity restricts the tendency for the magnets to self demagnetize. In contrast, metal magnets should be used in long magnetic circuits with small cross-sectional area.

Ferrite materials cannot be used at high temperatures owing to their low Curie temperature and the high rate of decrease of remanence and coercivity with temperature.

The great advantage of ferrite magnets is their cost. Enz[21] has shown, see Figure 6, that ferrite magnets give the lowest value of the price per unit of energy product.

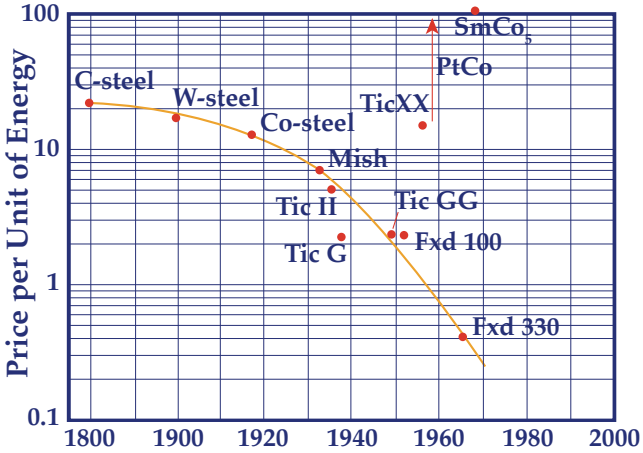


Figure 6 — Price per unit of energy product for permanent magnets from 180010 1965, after Enz[21]

- 'Mish' refers to original Mishma alni alloy
- 'Tic' refers to Alnico alloys
- 'Fxd' refers to ferrite magnets

Today, ferrites comprise 90% of the world's magnet production by tonnage and about 50% of the market measured in financial terms.

5. Rare-Earth Magnet Materials

The third major family of permanent magnet materials to be developed in the 20th century are based on the rare earth elements, such as samarium, cerium, yttrium, praseodymium, neodymium, gadolinium etc. However these materials were first reported in 1935, even before the ceramic materials were reported, but have only been developed commercially during the last 20 years.

Drozzina and Janus[23] reported in 1936 that an Nd-Fe alloy had a coercivity of over 340 kA/m, but rare earth metals did not become readily available until the 1950s, when research into the properties of rare-earth transition metal compounds consequently became possible.

It was reported[24] in 1967 that RCo_5, where R is one or more of the rare-earth elements, had high crystal anisot-

ropy and a hexagonal structure with an easy direction of magnetization, and these similarities to ferrite materials encouraged their development as permanent magnet materials. These 'first generation'[5] rare-earth permanent magnet materials were produced by liquid phase sintering of magnetically aligned powders,[25,26] and $SmCo_5$ magnets with coercivities of more than 4 MA/m and energy products of over 200 kJ/m³ were developed, see Table 6.[27] These materials immediately found use in space and military applications because of their high energy product per unit volume (or unit weight) compared with those of other materials.

Table 6 — Typical Properties of Rare-Earth Permanent Magnet Materials

Composition	B_r T	H_c kA/m	$(BH)_{max}$ KJ/m³
$SmCo_5$	1.0	4,000	210
$Sm_2(Co, Fe)_{17}$	1.1	3,500	260
$Nd_2Fe_{14}B$	1.4	4,000	400

The second generation' rare-earth magnets were based on R_2Co_{17}. In the first instance, iron was substituted for some of the cobalt but it required the addition of copper and the development of casting and heat treatment sequences for a satisfactory product, namely $Sm_2(Co, Fe, Cu)_{17}$ to be produced. These magnets have coercivities lower than those of $SmCo_5$ magnets but remanences and energy products of, typically, 260 kJ/m³, which are higher, see Table 6.

The third generation' of rare-earth permanent magnets began in 1983, when General Motors[28] and Sumimoto[29] simultaneously announced the development of neodymium-iron-boron, $Nd_2Fe_{14}B$, magnets. The Sumimoto magnets were made by sintering aligned powders, and the General Motors magnets were produced by the hot pressing of melt-spun ribbons. It is this latter technique which has produced most commercial interest, since the deformation of these hot-pressed magnets in compression at 700°C produces an anisotropic structure.

These rapidly solidified neodymium-iron-boron magnets demonstrated such promising properties[30] at a reasonable cost that major investments in manufacturing plant have been made in the late 1980s, particularly by the automobile industry.

Each of the three generations of rare-earth magnets has acquired a niche in the market so that a penetration of 30% of the total market, measured in financial terms, has now been achieved by rare-earth magnets.

6. Other Permanent Magnet Materials

The metal-ceramic and rare-earth magnets now satisfy nearly 100% of the market needs, but there are still a number of other permanent magnet materials that have been, or are, commercially available, such as ESD magnets, Vicalloy, Cu-Ni-Fe, Cu-Ni-Co, PtCo and Comol, see Table 7 for their properties.

Other permanent magnet materials such as MnBi, Silmanal (86.8% Ag, 8.8% Mn, 4.4% Al), cobalt, MnAl and cold worked stainless steel (12% Ni, 12% Cr, 76% Fe, and 18% Ni, 8% Cr, 74% Fe) have been fully investigated but have not made any major inroads into the marketplace, even for specialized applications.

Table 7 — Properties of other permanent magnet materials. after McCaig[18]

Material	B_r T	H_c KA/m	$(BH)_{max}$ kJ/m³
CoPt	0.64	400	76
Remaloy, 12% Co, 15% Mo, 73% Fe	1.00	28	10
ESD, Fe-Co, anisotropic	0.68	80	24
Vicalloy I	1.10	24	10
Vicalloy II	1.27	33	27
Cunife	0.55	42	11

Stoner and Wohlfarth[31] predicted theoretically that the shape anisotropy of elongated single domain (ESO) particles could be used to produce permanent magnets. Luborsky[32] has described a method of making acicular Fe or Fe-Co particles by electrodeposition which enabled commercial magnets with coercivities of about 80 kA/m to be produced. The theoretically predicted values for the coercivity of ESD magnets have never been achieved.

The Fe-Co-V family of alloys are used as magnetically soft materials which have high mechanical strength. By increasing the vanadium content, two permanent magnet materials have been developed: Vicalloy I(10% V, 52% Co, 38% Fe) is produced by quenching from 1200°C and tempering at 600°C for 8 hours, and Vicalloy II (13% V, Fe, Co) is cast, hot worked to an intermediate size, cold reduced by 90%, aged for 8 hours at 600°C and is anisotropic owing to an easy axis along the direction of elongation. Both Vicalloy alloys are ductile and are commercially available as permanent magnet wires which have a use in recorders.

The Cu-Ni-Fe and Cu-Ni-Co alloys, were developed in the 1930s and were used because of their high ductility. Cunife (60% Cu, 20% Ni, 20% Fe), which is produced in a similar way to Alnico, possesses an acceptable coercivity because of the shape anisotropy of the single domain particles of the Fe-Ni rich phase.[33]

The Fe-Co-Mo alloy (12% Co, 15% Mo, 73% Fe) was the first carbon-free permanent magnet material developed and has been commercially named Remalloy, Comol or Comalloy. It has been extensively used as a bias magnet in telephone receivers.

The equiatomic alloy CoPt was the most expensive permanent magnet material in commercial production and found applications in wristwatches and traveling wave tubes for space satellites before rare-earth magnets were readily available. The high coercivity, 400 kA/m, justified the use of the two expensive elements, cobalt and platinum, in a permanent magnet material, but these properties are now achievable by a cheaper but less romantic route.

7. Applications of Permanent Magnetic Materials

The compass was the first application of the lodestone, but the development of artificial permanent magnets has widened the applications area of magnets enormously. A major survey would be required to identify every use to which permanent magnets are put in the modern world.

Croat and Herbst[30] have shown that there are approximately 30 separate applications for permanent magnets in a typical automobile. Many of these separate applications are duplicated, e.g. there are usually four window lift motors and four door lock motors, thereby making approximately 100 separate devices with permanent magnets as components in a car.

A recent count in a home in the USA identified over 300 permanent magnets. A similar survey in a British home produced a count of over 100 permanent magnets the most obvious domestic uses being in washing machines, refrigerators, telephones, radios, televisions, video recorders, audio systems, earphones, clocks, security systems and meters,

In industry, the uses of permanent magnets are myriad but are principally in sensors and transducers, motors and generators, actuators, measuring instruments, couplings and catches. It has been suggested that permanent magnets can do anything that electromagnets can do and do it more neatly, more smartly, more cheaply and with lower running costs, McCaig[18] has attempted to list typical devices in which permanent magnets are utilised and the specific methods of application, see Table 8.

Table 8 — Typical Applications of Permanent Magnets, after McCaig[18]

Specific Method of Applications	Typical Devices
Torque on magnet in magnetic field	Compass magnetometer
Attraction between magnet and iron or other magnets	Holding devices, notice boards, games, door catches, magnetic filtration, retrieval devices, drives and couplings, window cleaning, switches, thermostats, thickness gauges, magnetic tools
Attraction induced between other iron parts	Reed switches, warning systems, magnetic clutches
Repulsion: magnet and magnet	Bearings, levitated transport, toys
Electromagnet and magnet	Brake for coil winder, etc
Induced repulsion	Sheet floater
Moving coil devices	Loudspeakers and telephone receivers, instruments, DC motors
Moving magnet devices	Synchronous and brushless motors, clocks
Moving iron devices	Telephone receivers, polarized relays
Relative motion coil and magnet	Flux measurement, generators, sensing devices, microphones, pick-ups, alternators
Eddy currents	Damping devices, brakes, speedometers

Specific Method of Applications	Typical Devices
Focusing	TV, electron microscopes, klystrons, traveling wave tubes
Crossed field action	Switches, generators, magnetrons, mass spectrometers, ion pumps, omegatrons, TV picture shift
Kerr and Faraday effects	Domain studies, memory stores
NMR	Chemical analysis, accurate field measurements, body scanners
Magnets in magnetic circuits	Saturistors, magnetizers and magnetic heat treatment
Electronic and semiconductor	Wave guides, circulators, Hall and magneto resistance devices

8. Improvements in Permanent Magnet Materials

There have been many attempts to demonstrate the improvements that have been made to permanent magnets during the 20th century. The improvements to the magnetic properties of permanent magnet materials made by the London magneticians, who transferred the magnetic effects of lodestones to iron, and by the magnet steel makers of the 19th century, were minimal compared with the advances made in the 20th century.

Buschow[1] has elegantly shown, see Figure 7, that there has been a 200-fold increase in the maximum energy product $(BH)_{max}$ of permanent magnet materials in the 20th century. The energy product of the magnet steels available in 1900 were 2 kJ/m^3, but the latest commercial magnets have energy products which exceed 400 kJ/m^3. It is difficult to find another material or device whose principal figure of merit has been increased by a factor of 200 within a century. Figure 7b also shows, by its similarity to a staircase, that the improvements have been made principally by the developments of new materials. Points 1 to 3 in Figure 7a are for steels, 4 to 8 for Alnico and 9 to 12 for rare-earth magnets. The development of the ferrite materials did not create records for the value of $(BH)_{max}$, because their increase in coercivity was accompanied by a decrease in remanence.

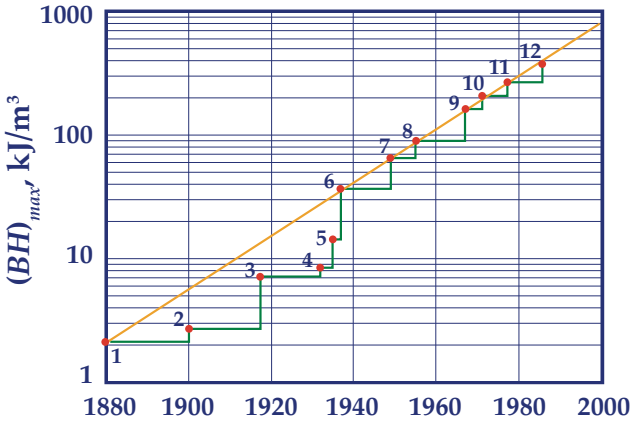


Figure 7a — Development of permanent magnets, History of $(BH)_{max}$ values achieved since 1880

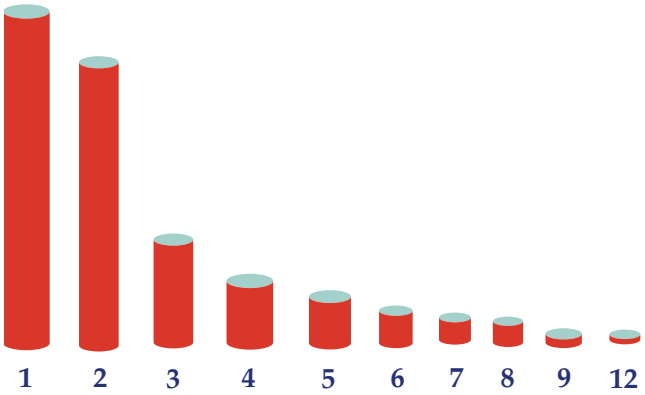


Figure 7b — Development of permanent magnets, Schematic representation of change in magnet size required for a specific application

The rare-earth magnets have set even higher values for attainable coercivity with, if anything, an increase in remanence. It has been forecast that permanent magnet materials with energy products of the order of 600 kJ/m^3 will be achieved by the end of the 20th century.

However, not even magneticians (who have demonstrated their undoubted ability by increasing their principal performance indicator by a factor of 200) can promise to continue to increase $(BH)_{max}$ in the logarithmic manner shown in Figure 7a.

Figure 7b shows how the quantity of permanent magnet materials required for a specific application has been reduced during the 20th century owing to the improvement in the magnetic performance of the materials. If the latest decrease in required magnet volume, and hence weight, is not accompanied by a large increase in cost per unit weight, further advantages in using permanent magnets will follow. Therefore, many device manufacturers, particularly those of automobile components are awaiting the complete commercial exploitation of

the neodymium-iron-boron magnets. If the downward trend of the price-per-unit-of-energy characteristic, shown in Figure 6, can be continued in the future, then the permanent magnet engineer will have performed a magic equivalent to turning base metal into gold, something never achieved by his predecessor, the alchemist.

Whatever this outcome, one can be assured that the future for these materials, and their form of magnetism, is permanent.

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