5   Magnetic Alloys

Introduction

The use of magnets goes back deep into history with the early magnetic stones being varieties of magnetite (Fe_3O_4). Practical magnets however came much later and were based on quenched carbon steels. At this stage, it is best to introduce the "hysteresis loop", the basic tool of the magnetician. Ferro-magnetic materials – cobalt, nickel, iron – are characterised by having unbalanced electron spins. The electrons circuiting the nucleus spin, hence being charged, generate a field in one or another direction. If even numbers spun in opposite directions, the net result/atom would be nil. However, in Co, Ni, Fe, these spins are unbalanced and a net field results. The material would still be non-magnetic as each atom is producing a randomly orientated net field. Applying an external field can persuade these internal fields to line up (in fact small patches – domains of similarly orientated atoms line up). The hysteresis loop describes the relationship between the magnetising force H compared to the magnetic flux B generated by the magnetic material. A typical curve is shown below.
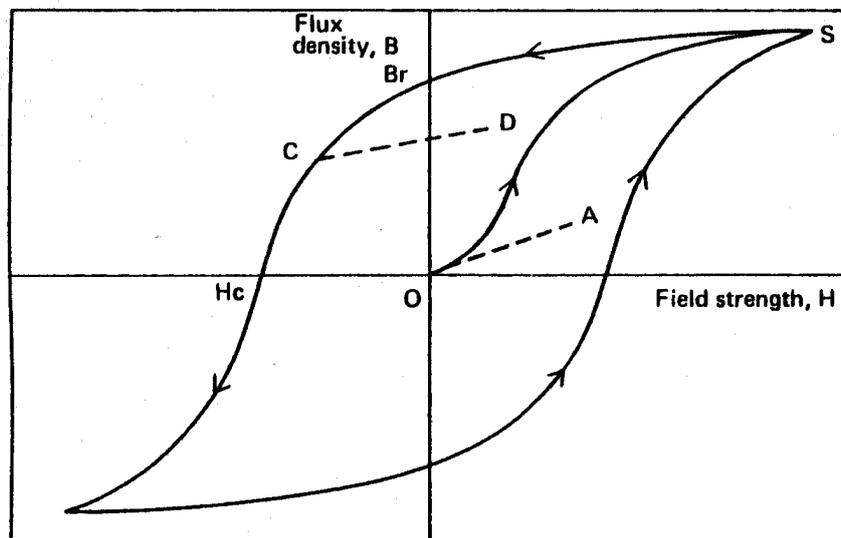

Figure 1 – Hysteresis loop of ferromagnetic material

Br: Remanence   Hc: Coercive force   Slope OA: Initial permeability
S: Saturation   Slope CD: Recoil permeability   Units: H-Oested, B - Gauss

Initially, the plot of BH follows OS to a point were saturation occurs (saturation level). On reversing the field, hysteresis occurs and the curve hits the B axis at a point B_r. This is now a permanent magnet and B_r is the remanence level. In practice, a magnet exerts a demagnetising force and a magnet will exist on the next part of the curve where H is reversed until B reaches zero. This force H_c is the coercive force (coercivity).

Here we now have the most important measurements of a magnet, hard or soft:

a)   Remanence B_r – Flux density

b)   Saturation level – S

c)   Coercivity – H_c

d)   Not shown, but B x H in the demagnetising quadrant reaches a maximum at some point (Bhmax)

In a good magnetic circuit, the permanent magnet used will operate at this point, thus generating the largest field possible for its size.

Cobalt is vital in the magnet industry in that is the only element which when added to iron actually increases the value of S (saturation magnetisation) and it also has one **UNIQUE** feature. Temperature destroys permanent magnetism as the atomic activity increases and removes the order required. The temperature at which this occurs is the Curie Point. Cobalt has a Curie Point of 1121°C (the highest known).

Table 1 – Magnetic Properties of Ferromagnetic Metals & Alloys			
Material	**Curie Temperature** **°C**	**Saturation Magnetisation** $4\pi I$**, gauss**	**tesla**
Fe	770	21,500	2.15
Ni	368	6,200	0.62
Co	1,121	18,000	1.80
65Fe-35Co	900-950	24,000	2.43

Hard and Soft Magnets

These are the common names for two classes of magnetic substances – hard magnets/high coercivity; soft/high saturation, minimum coercivity. The origin of these terms is in the second generation of magnets, the quench hardened steels. Here coercivity is raised by the internal strain caused by martensitic transformation, hence coercivity was indirectly related to hardness.

Cobalt was introduced into magnet steels in 1917 at a level of 35% and greatly increased the properties (Figure 2). Although the importance of magnet steels has decreased with newer materials, they do have an advantage the latter do not, in that unhardened, they can be machined in any way one likes.

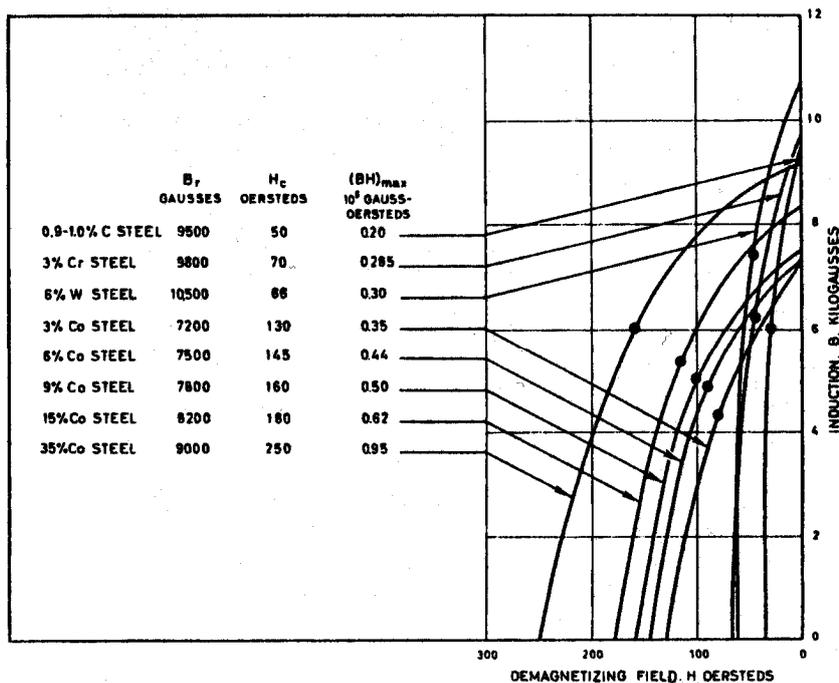Before continuing into Alnicos, the use of cobalt in soft magnets will be covered.

	B_r GAUSSES	H_c OERSTEDS	$(BH)_{max}$ 10^6 GAUSS-OERSTEDS
0.9-1.0% C STEEL	9500	50	0.20
3% Cr STEEL	9800	70	0.285
6% W STEEL	10500	66	0.30
3% Co STEEL	7200	130	0.35
6% Co STEEL	7500	145	0.44
9% Co STEEL	7800	160	0.50
15% Co STEEL	8200	180	0.62
35% Co STEEL	9000	250	0.95

Figure 2 – Typical demagnetisation curves for quench-hardened steels
(after Hozelitz)

Soft Magnetic Materials

Contrary to the high coercivity permanent magnet materials whose use depends on their ability to retain a magnetic field, soft ferromagnetic materials are characterised by their inability to retain the magnetism induced by a field when it is removed, i.e. the domains simply randomise themselves again. In hard magnets, domains are pinned.

The main applications are in rotating machines – generators, motors and in static transformers. Cobalt does not enter into most soft magnet compositions with Fe/Si being used for the largest application – transformer laminations – as core losses are low with this material.

The important series of alloys from cobalt's point of view, are the Co/Fe series typified by Permendur – this alloy being modified by vanadium additions to improve ductility. The reason for the use of cobalt is that in this classic alloy, one obtains the maximum saturation known, 23,500 gauss (2.35 Tesla), with a square shaped hysteresis loop. One has also the benefit of the high Curie Point.

These alloys because of their higher strength also find application in rotating equipment but their main use is in top performance electrical machines where weight and size are at a premium and cost is of lower importance. The properties which make them unique are:

➢ A high saturation induction, the highest known
➢ Good permeability in fields ≥ 16,000 Gauss compared to other materials such as Fe and Fe/Si alloys
➢ A Curie Point of 950/980°C so that magnetic properties remain little changed up to 500°C. In modern tightly packed systems this is a great advantage.

Table 2 lists typical alloys and properties (courtesy of Telcon, Metal, Metal Imphy and Vacuumschmelze).

Table 2 – Soft Magnetic Cobalt Alloys Typical Properties							
Alloy Name	**Co**	**Fe**	**V %**	**Si**	**B**	**Saturation Induction (Gauss)**	**Supplier**
Permendur 49	49	49	2	–	–	23,400	Telcon
Permendur 24	24	76	–	–	–	23,400	Telcon
Rotelloy 3	49	49	2	–	–	23,400	Telcon
AFK 524	52	4	44	–	–	20,000	Imphy
AFK 4025P	49	49	2	–	–	23,800	Imphy
Vacoflux 50/48/2	49	49	2	–	–	23,500	Vacuumschmelze
Vitrovac 6030	95	–	–	Balance		8,200	Vacuumschmelze

A new series of materials is also available, cobalt-based but with metalloid additions – e.g. boron. These are amorphous alloys and the series based on cobalt Vitrovac 6000 demonstrate two unique features: The lowest to date realised coercivity and magneto-striction (i.e. dimensional change under a field) close to zero.

Table 2 is just a minute portion of the array of alloys available to meet specific requirements – Permendur type alloys have the highest saturation available but Vitrovac amorphous alloys have the lowest coercivity and power losses. To decide which is best, one needs to talk to the specialist companies. What is clear is that its unique ferromagnetic properties are indispensable to all of them.

Hard Magnetic Material

As far as cobalt is concerned, these are magnetic steels (see Figure 2), Alnico type magnets, samarium-cobalt-rare-earth and latterly neodymium-iron-boron magnets.

The term hard magnets as we have seen earlier, originates from hard steels with magnetic properties. It has come to mean any magnetic material which can be permanently magnetised by applying a magnetic field.

The introduction page to this subject shows a hysteresis loop. A typical loop for a hard magnet would show a square curve with B_r-remanence as high as possible, coupled with a high value of H_c-cercivity. Such a combination of properties would ensure a high value of the factor (B x H)max – the energy product. Essentially, the higher the (BH)max is, the smaller the magnet needed to generate the magnetic flux required in any application. Unfortunately, one cannot simply get B_r x H_c to be infinite values at will and one often has to sacrifice one at the expense of the other. Hard magnets have developed over many years and up until earlier this century, only steels were available. Figure 3 charts the BH factor against time/material and shows the massive leaps which have been made.
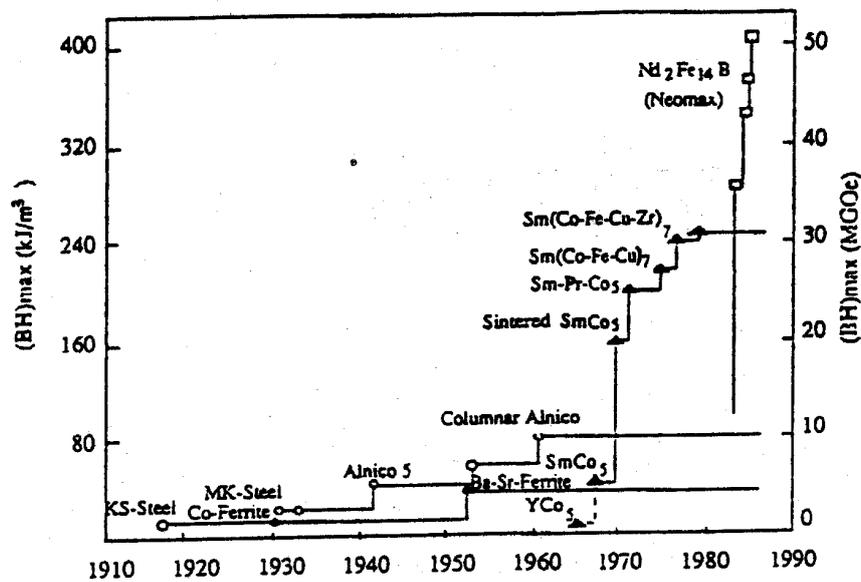

Fig.3 – Variation of maximum energy product (BH)max with time from 1910-1990

Alnico

The story of modern permanent magnet materials began in 1932 when Mishima of Tokyo University unveiled a new series of Al-Ni-Fe alloys (25%Ni, 10%Al, balance Fe) with coercivities 9 times that of the magnet steels available. This discovery led to 20 years of development and research to improve these alloys. The main enhancement of properties came from adding COBALT and this was added to the AlNi name, hence the Al-NiCo series of alloys.

Table 3 – Typical Alnico Compositions						
Alloy	**Fe**	**Al**	**Ni**	**Co**	**Other**	**Comment**
AlNi	56	12	27	2	3Cu	Isotropic
Anico	62	12	21	5	–	Isotropic
Alcomax	50.4	8	13.5	24.5	3Cu .6Nb	Anisotropic
Columax	50.4	8	13.5	24.5	3Cu .6Nb	Anisotropic - cast
Hycomax 2	39	7	15	29	4Cu 2Nb 4Ti	Anisotropic
Hyxomax 3	35	7	15	34	4Cu 5Ti	Anisotropic

Since then, not only as a series of alloys been developed but other processing changes have further improved properties, in no small way due to the effort of the now defunct Permanent Magnet Association in the UK and to CDI sponsored research in the 1960's and 1970's. The process techniques are complex but simply, one can get magnetic anisotropy by cooling Alnicos in a magnetic field, growing columnar grains in a magnetic field, etc. (papers are available at the CDI on all these subjects). All in all, one can generate higher values of Br or Hc although not at the same time by varying composition and process method. Some the common alloys and properties are shown in Table 3 and Figure 4.
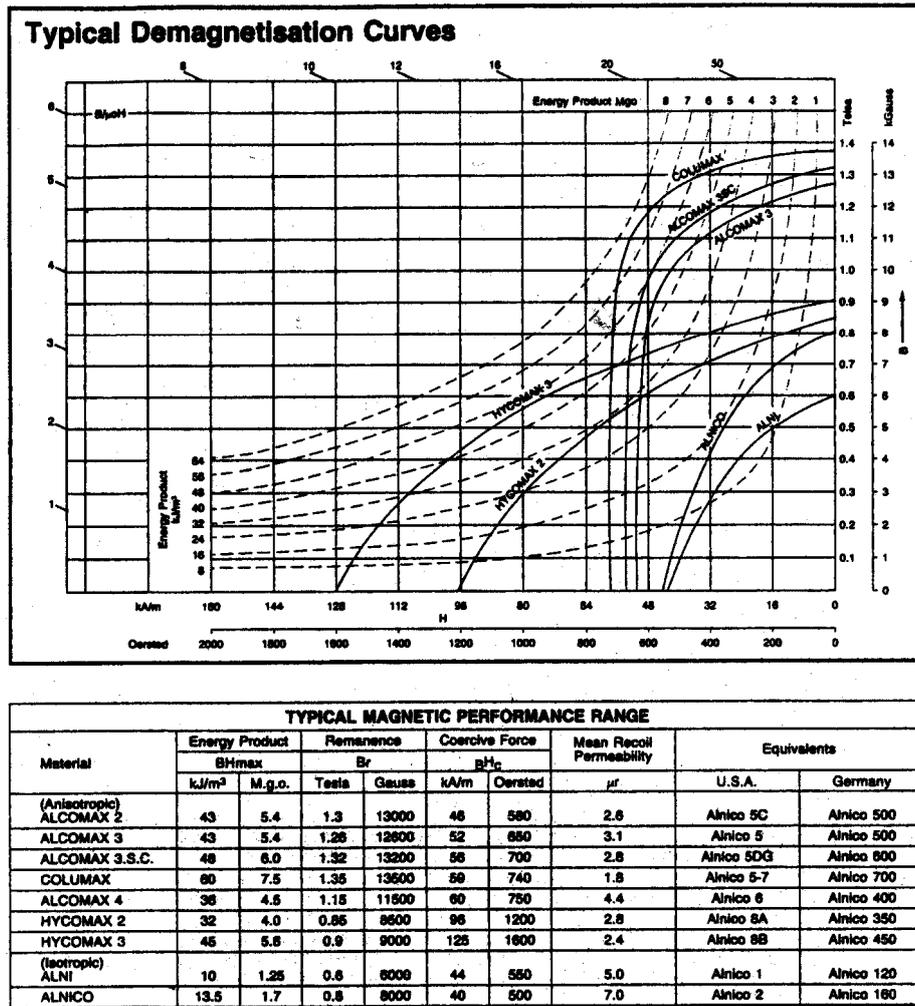

TYPICAL MAGNETIC PERFORMANCE RANGE								
Material	Energy Product BHmax		Remanence Br		Coercive Force BHc		Mean Recoil Permeability	Equivalents	
	kJ/m³	M.g.o.	Tesla	Gauss	kA/m	Oersted	μr	U.S.A.	Germany
(Anisotropic) ALCOMAX 2	43	5.4	1.3	13000	46	580	2.6	Alnico 5C	Alnico 500
ALCOMAX 3	43	5.4	1.26	12600	52	650	3.1	Alnico 5	Alnico 500
ALCOMAX 3.S.C.	48	6.0	1.32	13200	56	700	2.8	Alnico 5DG	Alnico 600
COLUMAX	60	7.5	1.35	13500	59	740	1.8	Alnico 5-7	Alnico 700
ALCOMAX 4	36	4.5	1.15	11500	60	750	4.4	Alnico 6	Alnico 400
HYCOMAX 2	32	4.0	0.85	8500	96	1200	2.8	Alnico 8A	Alnico 350
HYCOMAX 3	45	5.6	0.9	9000	128	1600	2.4	Alnico 8B	Alnico 450
(Isotropic) ALNI	10	1.25	0.6	6000	44	550	5.0	Alnico 1	Alnico 120
ALNICO	13.5	1.7	0.8	8000	40	500	7.0	Alnico 2	Alnico 160

Figure 4 – Properties of selected Alnico alloys

Samarium COBALT – Rare Earth Magnets

In 1935, a note in nature (via Leningrad!) mentioned that Nd-Fe alloys had a high coercivity. Nothing more seems to have happened until the 1960's when the rare-earths became more available and, in 1967, Strnat, et al. reported that Co_5-Rare Earth compounds were promising permanent magnet materials.

By 1970, dense Co_5Sm magnets had been produced by sintering and the rare-earth magnets had arrived (new generations have reverted to the original 1935 type Neodymium-boron-iron).

The properties of Rare-Earth magnets are a quantum leap from Alnico, just as Alnico was from steel (see Figure 3). It is not even possible to put them on the same graph. For example, Supermagloy I, a sintered

magnet, has B_r value of 8,000 Gauss – like alnico! But its coercivity H_c is 8,000 Oersted (Alnico is 600) and Bhmax is 15-17 Megagauss Oersted whereas even Hycomax is only 5.6. These massive changes have led to a revolution in instrumentation, telephones, electronics and even motors. Remember BH(max) relates to size – the larger it is, the smaller the magnet (in theory).

However, in recent years Samarium cobalt has faded in importance due to its high cost and has been eclipsed by a more powerful, less costly and more versatile sister rare-earth material invented in 1983, Neodymium-iron-boron (NdFeB).

NdFeB Magnets

The development of NdFeB magnets since 1983 has resulted in energy products climbing from 28 Megagauss Oersted (MGOe) to the current commercial standard 45 MGOe. This ten-fold increase in available magnetic energy has opened doors to the designers of such varied devices as disc drives, magnetic resonance imaging, high efficiency dc motors, etc.

Early versions of these magnets had two weaknesses – thermal instability and poor corrosion resistance. Significant advances have been made during the past two years to overcome these deleterious characteristics by the use of coating techniques and the development of alloys with higher corrosion resistance. The latter development has often been achieved by the addition of cobalt to the alloys. Nevertheless, the cobalt contents of these magnets is low in comparison to Alnicos – typically between 1 and 5% although some melt spun magnets do contain up to 16% cobalt.

Market

Our statistics suggest that 5,500-6,000 tonnes of cobalt are used in magnets each year. Approximately 50% in Alnicos, 40% in rare earth magnets (SmCo and NdFeB) and 10% in all other magnetic alloys including FeCrCo. Alnico and SmCo magnets are used in relatively niche markets, including electric motors, guitar pickups, microphones, sensors, loudspeakers, medical instruments and generators

By contrast, the use of NdFeB magnets has been growing rapidly in the market place in a host of applications requiring miniaturisation such as efficient motors and actuators or disc drives, sensors, etc. Since only a small proportion of manufacturers add cobalt in minor amounts to these alloys for corrosion resistance and coercivity improvement, growth in cobalt consumption is only expected to be limited.