# Permanent magnets

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**Abstract**

*An outline is given of the state of the art in permanent magnet technology with a brief discussion of the future perspectives opened up by the new materials. There is a growing demand for better performances associated with the expansion of applications and reduction in prices. The general principles that govern permanent magnet behaviour are discussed in some detail and a comparison of the variety of materials now available, with regard to both the intrinsic properties and technical characteristics, is presented.*

**Riassunto**
**Magneti permanenti**

Rassegna dello stato attuale della tecnologia dei magneti permanenti con breve descrizione delle prospettive future aperte dai nuovi materiali. La crescente domanda di migliori caratteristiche tecniche e di riduzione dei prezzi è collegata all'espansione del numero di applicazioni.
Vengono esaminati i principi generali che regolano il comportamento dei magneti permanenti e la varietà dei materiali attualmente disponibili, confrontandone le proprietà intrinseche e le caratteristiche tecniche.

## Introduction

Recent development in permanent magnet technology is characterized both by the introduction of new materials and by a wide spread in their applications. This rapid change on the permanent magnet scene occupies roughly the past fifteen years and important consequences for related branches of modern engineering are to be expected in the near future. As a matter of fact the new permanent magnets, where they are employed, in most cases merely replace the older permanent magnets in a very straightforward way, especially in electrical machinery. The redesign of the machines for optimum performances is a necessary step for full exploitation of the characteristics of modern permanent magnets. In some instances it is even necessary to go to completely new or reversed concepts, as witnessed by the actual emphasis toward rotating magnets in contrast to the old rotating coil geometry.
The following is an outline of the state of permanent magnet technology with the aim of giving information about the various types of permanent magnet now available to the design engineer, and about the possibilities they offer for the solution of a variety of technical problems.

## Working conditions of a permanent magnet

A permanent magnet can be regarded as a simple means of generating something equivalent to a constant electric current without losing energy. Thus an associated magnetic moment and an external magnetic energy field is produced, that can be used to interact with matter in a variety of ways. The analogy of permanent magnets with superconductivity currents is not merely an academic curiosity but is put into practice with the continuous expansion of technical applications of hard superconductors, from the early stage of materials for high-field solenoids to the present variety of superconducting devices. In terms of performances expressed by the magnetic energy/weight ratio, superconductors are superior to anything else, and, moreover, they are unique in the intensity of field they provide; but the necessary cooling-power consumption, in fact, places superconducting coils somewhere between electromagnets and permanent magnets. So the unique feature of permanent magnets is to provide a virtually zero-cost magnetic field. The interaction with matter or with external magnetic fields is utilized for achieving a variety of working conditions. Magnets are thus employed for generating magnetic fields, as in the case of electric motors, or for producing mechanical action on electric currents or other magnets.
Ordinary magnetic materials are in general soft magnets, i.e. they are easily magnetized by relatively weak magnetic fields and their magnetization is immediately reversed as soon as the applied field is directed in opposite direction. The magnetic permeability $\mu$ is in general relatively high and for special materials such as permalloy it can be 100 thousand times bigger than that of vacuum or even more. On the contrary hard magnetic materials, which are used for permanent magnets, are characterized by having low permeability and large hysteresis loops, as shown in Fig. 1 that reports the graph of magnetic induction B vs. magnetic field H for a typical permanent magnet, barium ferrite.
The essential feature of a permanent magnet material is its capability of withstanding the action of a strong

reversed magnetic field without loosing its magnetization. Hence the normal situation for a permanent magnet under working conditions is to have inside it the magnetic field direction opposite to that of the magnetic induction. If we further increase H, the magnetic induction B reduces its amplitude and eventually vanishes for a well defined field value $H_c$ that is called "coercive field" and is characteristic of a certain permanent magnet material. Figure 1 indicates the most typical points of the hysteresis loop, namely the coercive field $H_c$, the "remanent induction" $B_r$ which is the point at zero magnetic field, and the "energy product" $BH_{max}$, the point of the demagnetization curve where the product B.H has its maximum value. The last is a very important parameter that characterizes a permanent magnet material. In fact it can be demonstrated that the magnetic energy $E_g$ in the gap is proportional to the product $B_m.H_m$ in the volume of the magnet, that is

$$E_g = B_m H_m V_m/(8\pi C_1 C_2), \tag{1}$$

where $V_m$ is the magnet volume, and $C_1$ and $C_2$ are the leakage constants that account for the leakages in the magnetic circuit of the flux and of the magnetic potential respectively. They are defined by the equations

$$C_1 B_g A_g = B_m A_m \text{ and } C_2 B_g L_g = H_m L_m. \tag{2}$$

where $A_g$, $L_g$ and $A_m L_m$ denote the area and the length of the gap and the magnet respectively. A part from the factor $C_1.C_2$, essentially eq. (1) defines a kind of equivalence between the energy of B in the gap and that defined by the product $B_m.H_m$ in the volume of the magnet. The optimum operation of the magnet is obtained when the working point on the demagnetization curve corresponds to the maximum value for the product BH. The values of B and H at this point are usually denoted by $B_d$ and $H_d$ respectively. In the case of a perfect magnet – i.e. with $4\pi M = B_r =$ const., where M indicates the magnetization – $BH_{max}$ occurs for $H = B_r/2$ and is thus equal to $B_r^2/4$. When, during normal operation, a permanent magnet changes its gap, the working point is no longer static and must move following the variations of the magnetic reluctance of the circuit (Fig. 2). The excursions of the working point occurs on inner lines (recoil lines) of slope $\mu_r$, the recoil permeability. The "useful recoil product", $BH_u$, which represents the maximum magnetic energy that can be obtained in dynamic conditions, is only a part of the product BH because a fraction of it is lost in the leakage circuit. The evaluation of the leakages is one of the most difficult problems, as a rigorous approach to specific problems can only be made with computer aided design. However various manuals (1, 2) give at least the typical magnitudes of $C_1$ and $C_2$ in various configurations, or simple pseudo-empirical formulae. In practice, it happens that low coercitivity permanent magnets are generators of low magnetic potentials and this implies great lengths; on the other hand their high flux density allow us to adopt relatively narrow cross-sections.

The requirement of better performances, that modern permanent magnets make possible, imposes in many cases the redesign of important machines where permanent magnets are, or can be, emploied. For this purpose it is necessary to use in the calculation of fields exact vector relations, that are more appropriate to the actual behaviour of permanent magnet materials. A

Fig. 1 - Demagnetization curve of a permanent magnet material, barium ferrite.

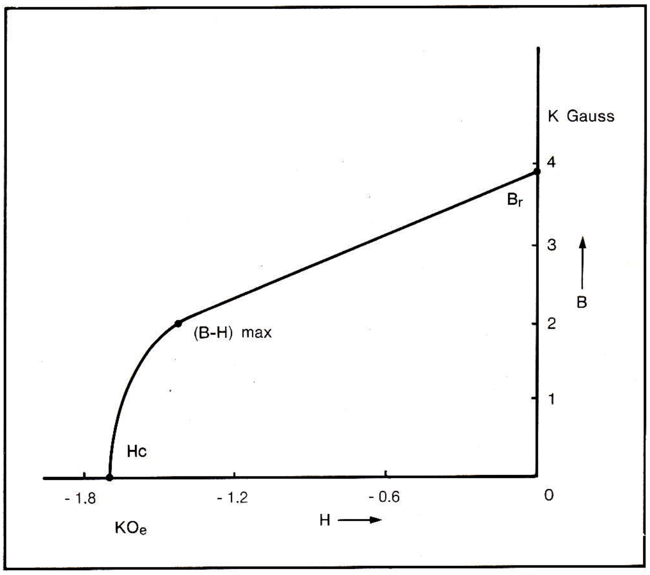
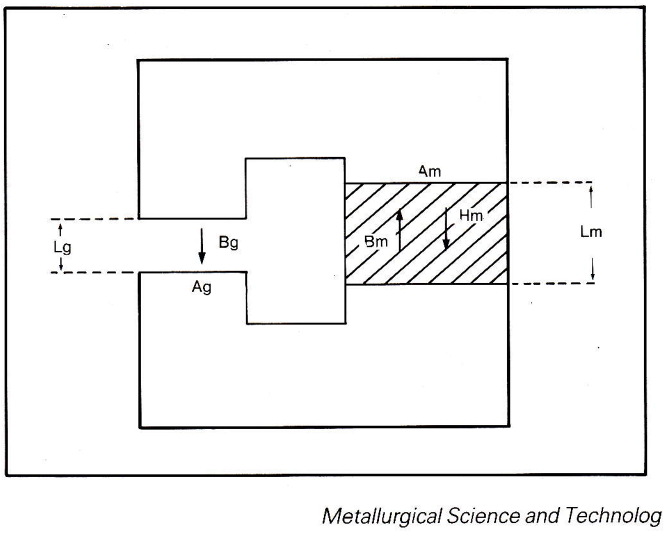


Fig. 2 - Scheme of a typical magnetic circuit containing a permanent magnet.



model proposed by Zijlstra (3) seems particularly useful because it is based on simple fundamental principles and is in perfect agreement with experiments. This approach is particularly convenient for oriented ceramic permanent magnets and leads to a form of M(H) dependence, that includes an anisotropic susceptibility matrix

$$\chi = \begin{vmatrix} \chi_{\parallel} & 0 \\ 0 & \chi_{\perp} \end{vmatrix} \qquad (3)$$

For the case of oriented ceramic permanent magnet the ordinary data given by the manufacturer suffice in obtaining all the necessary parameters; in fact the slope of the M(H) curve parallel to the easy axis gives $\chi_{\parallel}$, while $\chi_{\perp}$ is taken as equal to $M_s/H_a$, the ratio of the saturation magnetization to the anisotropy field; the critical field $H_{cr}$ is deducible from the knee of the demagnetization curve.

## Permanent magnet materials

### Properties

In 1917, the discovery in Japan of high-cobalt steels marks the first step forward in artificial magnets. Further advances came with the development by Mishima of Al-Ni-Fe (alni type alloys) in 1931 and Al-Ni-Co-Fe (alnico type) shortly after. Each of these alloys brought about significant increases in coercive force (about one order of magnitude) with respect to previous materials, i.e. tungsten and chromium steels (4). Subsequent improvements in alnico alloys were made in Britain and Holland, leading to the alloy with the highest energy product and remanence, alnico 5. In those years a number of alloys were also discovered having the distinct advantage of being ductile: Fe-Ni-Cu (Cunife alloys) and Fe-Co-V (Vicalloy). The most important advance since the war came in 1950 with the discovery, at Philips laboratories, of the magnetoplumbite type of hard ferrites: $BaFe_{12}O_{19}$ and $SrFe_{12}O_{19}$, a remarkable example of magnetic insulator characterized by a very high coercivity and low production cost (5). Ferrite powders are now widely used in bonded magnets using various resins and plastics to obtain rigid or flexible products.

Ductility and, in general, good mechanical properties for magnetic materials are receiving renewed attention and emphasis (6). Ductile alloys of Fe-Cr-Co, first reported by Kaneko (7), have recently been discovered to possess equivalent magnetic characteristics to Alnico 5. The well known rare earth – transition metal compounds ($SmCo_5$ type magnets) are remarkable examples of the new classes of magnetic materials recently discovered, and represent the most notable advances in permanent magnet technology after magnetoplumbite magnets. In this domain, a remarkable improvement is the recent development of Nd-Fe-B magnets. These are based on a new family of rare-earth iron compounds that are stabilized by the presence of a small quantity of boron (about 1% by weight). Among these compounds the most important is $Nd_2Fe_{14}B$, a tetragonal phase having high uniaxial anisotropy and a magnetization higher than that of $SmCo_5$. Its maximum energy product can be as high as 40 MGoe, a value substantially above those of the other known magnets. There is now a great deal of effort to further improve the properties of this material by suitable substitutions. An important goal is to increase the Curie temperature in order to improve its thermal stability, which at present is rather poor. Another important class of permanent magnets, of which the promising intrinsic properties have been known for two decades, are Heusler type alloys with Mn (typically Mn-Al). Matsushita obtained substantial improvements in the production of Mn-Al-C permanent magnets by extrusion (8). This procedure leads to anisotropic magnets of high coecivity and remanence of 5-6000 gauss. They are made from low-cost raw materials, but there are still problems concerning thermal stability and the complexity of the production process.

Other types of permanent magnets were also developed at various stages, but their importance is limited by very high cost, either of the production process or of the material components. Examples in this category are elongated single domain particle magnets (ESD), PtCo, MnBi, etc. Yet they are important because considerable progress in the understanding of permanent magnet behaviour came from the research of these different types of magnetic material: prominent examples of phenomena that have been clarified are fine particle behaviour and exchange anisotropy.

Table 1 gives a list of some important permanent magnets indicating typical composition, method of preparation, type of microstructure and important characteristics of the material. For a comparison of the various types of permanent magnet that are now commercially available, it is convenient to distinguish between technical characteristics, necessary to the design engineer, and intrinsic properties that give evidence of the fundamental process responsible for the permanent magnet behaviour. The technical properties of permanent magnets are summarized in Table 2. Some important applications involve dynamic conditions, so that in specifying the properties of permanent magnets we must provide, together with the value of the maximum energy product, $BH_{max}$, also the value of the maximum useful energy product, $BH_u$. These parameters are directly compared in a vertical scale in Fig. 3 for the various types of permanent

## TABLE 1 - Different types of permanent magnets

| Type | Description | Composition | Production method | Microstructure | Peculiarities |
|---|---|---|---|---|---|
| $C_1$ | ceramic, Ba ferrite isotropic | $BaFe_{12}O_{19}$ | sintering | micron-size random crystallites | large temp. coeff.<br>low remanence, cheap |
| $C_2$ | ceramic, Ba ferrite oriented, high Br | $BaFe_{12}O_{19}$ | field pressing<br>sintering | oriented crystallites | large temp. coeff. |
| $C_3$ | ceramic, Sr ferrite oriented, high Hc | $SrFe_{12}O_{19}$ | field pressing<br>sintering | oriented crystallites<br>gran-size-1 µm | large temp. coeff.<br>high coerc. force |
| $A_1$ | alloy, alnico 5 | 8Al 14Ni 24Co 3Cu* | precipitation hardening, field annealing † | very fine periodic structure of elongated particles in paramagnetic matrix | high remanence (> 12500 Gauss) |
| $A_2$ | alloy, alnico 8 | 7Al 14Ni 34Co 5Ti 5Cu* | precipitation hardening, field annealing | very fine periodic structure of elongated particles in paramagnetic matrix | high coerc. force (~ 1600 oe) |
| $A_3$ | alloy, FeCrCo | 30Cr 12Co* | precipitation hardening (or deformation ageing) | as $A_1$ and $A_2$ but with finer structure and ferromagnetic matrix | equivalent to $A_1$ but is ductile |
| S | superlattice PtCo | 50/50 at.% | precipitation hardening (or powder metallurgy) | ordered precipitate tetragonal phase in disordered matrix | high coerc. force<br>ductile, resistant to corrosion, high cost |
| H | Heusler alloy MnAl | 70Mn 29.5Al 5C* | warm extrusion | texture: fine grains with high density of defects | between $A_2$ and $C_2$<br>cheap raw materials |
| $R_1$ | rare-earth intermetallic, Sm-Co | $SmCo_5$ | sintering with 40Co, 60Sm% (liquid phase) | oriented crystallites<br>high density, single phase | very high coercive force, perfect reversibility; brittle |
| $R_2$ | rare-earth intermetallic, 2-17 phase | $Sm_2(Co,Fe,Cu,Zr)_{17}$ | sintering and precipitation annealing | as $R_1$ but with large grains and finely dispersed second phase | high $BH_{max}$<br>30MGOe but low coercivity |
| $R_3$ | rare-earth intermetallic, Sm-Co with Gd, Dy or Ho substitutions | $Sm_{.6}Gd_{.3}Dy_{.1}Co_5$ | sintering | as $R_1$ | zero temperature coefficient |
| $R_4$ | NdFeB intermetallic, tetragonal | $Nd_2Fe_{14}B$ | sintering in excess of Nd and B ($Nd_{15}Fe_{77}B_8$) | as $R_1$ | very high BHmax and Br, but large temp. coefficient |
| $B_c$ | bonded ferrite or plastoferrite | plastic bonded $BaFe_{12}O_{19}$ | calendering (or extrusion or injection moulding) | fine hexagonal platelets in organic matrix (60% by volume) | easy to use and instal |
| $B_r$ | plastic bonded Re-Co powders | $SmCo_5$ with resins or plastic or rubber | mixing with binder field allignment, die pressing | oriented crystallites in various organic binders | resist fracture, ideal for DC motors but high cost |
| $B_m$ | bonded metal particles LODEX | ESD Fe-Co in metal binder (Pb,Sn,Sb) | electrodeposition in Hg, pressing with magnetic field | ESD Fe-Co particles in metal matrix | important for the understanding of fine particle behaviour, difficult technology |

† A small amount is produced by sintering

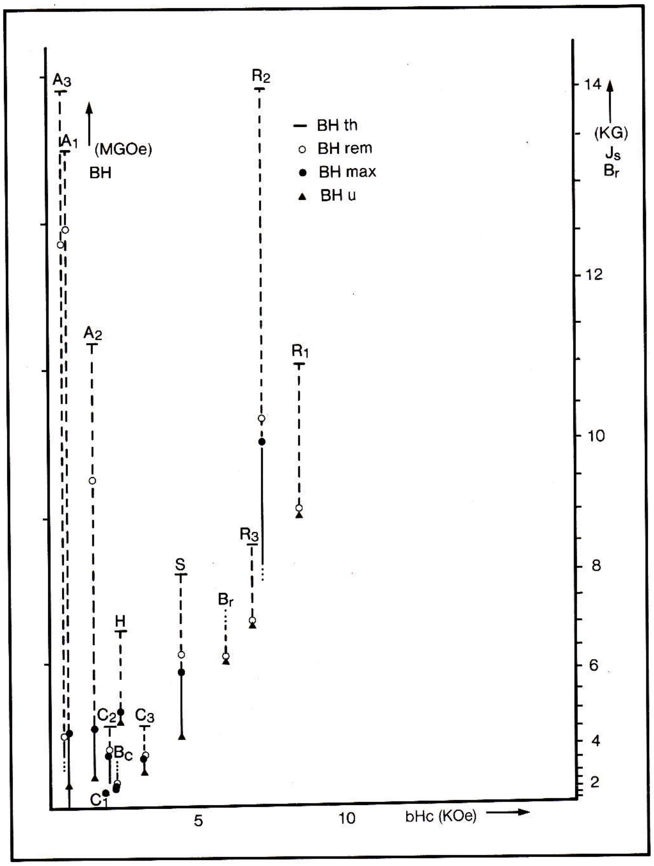
* wt %, Fe. bal.

## TABLE 2 - Typical magnetic parameters of permanent magnets

| | $C_1$ | $C_2$ | $C_3$ | $A_1$ | $A_2$ | $A_3$ | S | H | $R_1$ | $R_2$ | $R_3$ | $R_4$ | $B_c$ | $B_r$ | $B_m$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Remanence Br (KG) | 2.3 | 3.9 | 3.7 | 12.6 | 9 | 12.5 | 6.5 | 5.8 | 9 | 10.3 | 7.1 | 12.5 | 2.4 | 6.4 | 7.3 |
| Intrinsic coercivity jHc (KOe) | 3 | 2.2 | 3.6 | | | | 5.5 | 3.2 | 15 | 7 | 25 | 11.1 | 2.7 | 19 | |
| Coercive force bHc (KOe) | 1.9 | 2 | 3.2 | .65 | 1.5 | .65 | 4.5 | 2.4 | 8.5 | | | 10.9 | 2 | 6 | 1 |
| Energy product (BH)m(MGOe) | 1 | 3.7 | 3.3 | 5.1 | 5.5 | 5 | 9.2 | 6.3 | 20 | 25 | 12.4 | 35 | 1.4 | 10 | 3.4 |
| Max recoil product (BH)u(MGOe) | 1 | 1.7 | 2.5 | 1.5 | 2.1 | | 4.9 | 6 | 20 | | 12.4 | | 1.25 | 10 | 1.2 |
| Recoil permeability $\mu_r$ | 1.2 | 1.05 | 1.05 | 4.1 | 2.3 | | 1.1 | 1.1 | 1 | | | 1.05 | 1.05 | 1.05 | 2.6 |
| $\beta$ Temp, coeff. of jHc(%/C) | +.4 | +.45 | +.45 | | | | | −.2 | | | | 0.6 | | | |
| Range of $\beta$ (°C) | −40<br>200 | −40<br>200 | −40<br>200 | | | | | −20<br>40 | | | | | | | |

magnets. The abscissa gives the value of coercive force bHc and, for each material, the upper theoretical limit of $BH_{max}$, BHth, is also indicated. The scale on the right allows one to read the value of saturation induction $Is = 2(BHth)^{\frac{1}{2}}$ corresponding to BHth; that is, the maximum theoretical value for remanence. At a lower level, another theoretical limit, $BH_r = B_r^2/4$, is indicated, which is correlated with the remanence $B_r$ of the permanent magnet. The difference $BH_r$-$BH_{max}$, in the case of high-coercivity materials, is a measure of the degree of squareness of the intrinsic demagnetization curve M(H), which depends on the degree of orientation of the particles in the magnet and on the homogeneity of the material. From this graph the superiority of rare earth magnets is evident, not merely for the higher $BH_{max}$ value, but also for the higher ratio $BH_u/BH_{max}$. Intrinsic properties are reported in Table 3 for each permanent magnet material. There is some discrepancy among published values of the anisotropy field $H_s$ of high anisotropy materials, i.e. $SmCo_5$ and PtCo. The magnetocrystalline anisotropy of rare-earth intermetallic compounds is difficult to measure by conventional methods. Recent studies in high pulsed magnetic fields, by the SPD technique (Singular Point Detection) (9), on the $PrCo_5$ system, has given for the first time a consistent set of data concerning the magnetic anisotropy of this compound (10). Our understanding of the basic magnetic properties of rare earth-intermetallic compounds has already reached a satisfactory level (11). Other important cases where the

Fig. 3 - $BH_{max}$ vs. bHc for various permanent magnets.



## TABLE 3 - Intrinsic magnetic and physical properties of permanent magnet materials

| | $C_1$ | $C_2$ | $C_3$ | $A_1$ | $A_2$ | $A_3$ | S | H | $R_1$ | $R_2$ | $R_3$ | $R_4$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Saturation magnetization $4\pi Ms$ (KG) | 4.77 | 4.77 | 4.77 | 13.4 | 11.3 | 14 | 8 | 7 | 11 | 14 | 8.5 | 13.5 |
| Type of anisotropy* | mcr | mcr | mcr | sh | sh | sh | mcr | mcr | mcr | mcr | mcr | mcr |
| Anisot. or switching fields Hs (KOe)° | 17 | 17 | 18.8 | 5 | 4 | 6 | 70<br>120 | 40 | 250<br>400 | 70 | | 70 |
| jHc/Hs (%) | 18<br>30 | 13 | 22 | 10 | 40 | 8 | 4<br>7 | 8 | 5<br>13 | 10 | | 16 |
| Coercivity mechanism † | DWnp | DWnp | DWnp | RFC | RCF | DWp | DWp | DWp | DWnp | DWp | DWnp | DWnp |
| α, Reversible temper. coeff. of Ms (%/C) | −.2 | −.2 | −.2 | −.02 | −.01 | | −.015 | .12 | −.04 | −.03 | 0 | 0.126 |
| Range for α (°C) | | | | | 0<br>200 | | | −40<br>80 | −50<br>100 | −50<br>150 | | |
| Curie temperature (°C) | 450 | 450 | 460 | 860 | 850 | 660 | 540 | 300 | 724 | | | 320 |
| Electrical resistivity ($10^{-6}\Omega$.cm) | $10^{12}$ | $10^{12}$ | $10^{12}$ | 50 | 50 | 65 | | 80 | 60 | | | 144 |
| Thermal expans. coeff. (- easy axis) ($10^{-6}$/C) | 10 | 13-8 | 13-8 | 11.5 | 11.5 | 10 | | 18 | 5-13 | | | 4.8-3.4 |
| Density (g/cm$^3$) | 5.28 | 5.28 | 5.11 | 7.3 | 7.3 | 7.6 | 15.7 | 5.1 | 8.6 | | | 7.4 |

* mcr, magnetocristalline; sh, shape anisoptropy

° Hs = $2K_1/Ms$ for mcr anisotropy, NMs for sh anisotropy

† DW, domain wall: n, nucleation, p, pinning; R, rotation; F, fanning, C, curling

use of SPD technique has substantially contributed to the understanding of magnetic anisotropy, are those of PtCo, MnAl and Nd-Fe-B alloys (12-14). In most cases it is possible to obtain specific properties by a proper control of composition parameters, thus leading to the possibility of real material engineering of these compounds. Recent experimental and theoretical investigations have clarified the role of the transition metal and rare earth in determining the high magnetic anisotropy that characterizes these compounds (15, 16). Accurate studies of a variety of pseudobinary compounds have made evident the single-ion nature of rare earth anisotropy (17). A significant contribution to the theory of these materials comes from the canted sub-lattice model (18, 19, 11) that finds quite general application and allows a better insight into the physical phenomena which form the basis of magnetic anisotropy in rare earth-transition metal compounds. An important problem in the case of precipitation hardened alloys is discrimination between the magnetic properties of the two phases. A powerful tool for this kind of investigation is Mössbauer spectroscopy, by which it has been demonstrated that, in alnico type alloys, the matrix after optimum heat treatment is paramagnetic down to temperatures well below room temperature (20). Recently, similar studies in low Co alloys of the Fe-Co-Cr type have shown, somewhat surprisingly, that the magnetizations of the two phases differ by only 10% (6). This result implies a revision of the interpretation of the origin of coercivity in these alloys, and is consistent with recent evidence that domain wall pinning, rather than rotation, is the effective coercivity mechanism. The mechanism of domain wall pinning is also responsible for the coercivity of PtCo and MnAl alloys. The complex microstructure of these materials poses some specific problems that ought to be clarified, especially with regard to the role of the interface and of lattice defects.

### Production and applications

Recent years have also witnessed some important changes in the market for permanent magnets. The production of permanent magnets is continuously increasing and changing in favour of ceramic permanent magnets, due to their good cost/performance ratio. Alnico type alloys are mainly suffering for the recurrent crisis in cobalt supply, and the near future will see an even more drastic reduction in high-Co based materials. The continuous substitution of ceramic for Alnico magnets is accompanied, on the other hand, by a partial substitution for the former by plastoferrite or bonded ferrites. This trend has stimulated a constant improvement in both magnetic and mechanical properties, because the new applications impose more severe working conditions. The price of rare earths has reduced significantly in recent years, so that the incidence of Co is tending, even in Sm-Co magnets, to become preponderant. Figure 4 gives the prices per Kg and per unit of energy (Joule) for the most important permanent magnets materials. The abscissa gives the estimated production in Europe in tons per month. Nd-Fe-B magnets are not included because they are under development. It suffices to say that at present, there are only two producers in the world: the product of Sumitomo Co., "Neomax" has a price that is comparable to that of Sm-Co magnets; "Magnequench", produced by General Motors Co., is much cheaper because it is produced by a rapid cooling method similar to that used for amorphous magnetic materials, but its performance is much inferior. It is worth noting how much the figures are comparatively changed, expressing cost in terms of units of energy: oriented ferrites f.i. become two-three times cheaper than isotropic ferrite. A point of interest is that the largest production is of the lowest

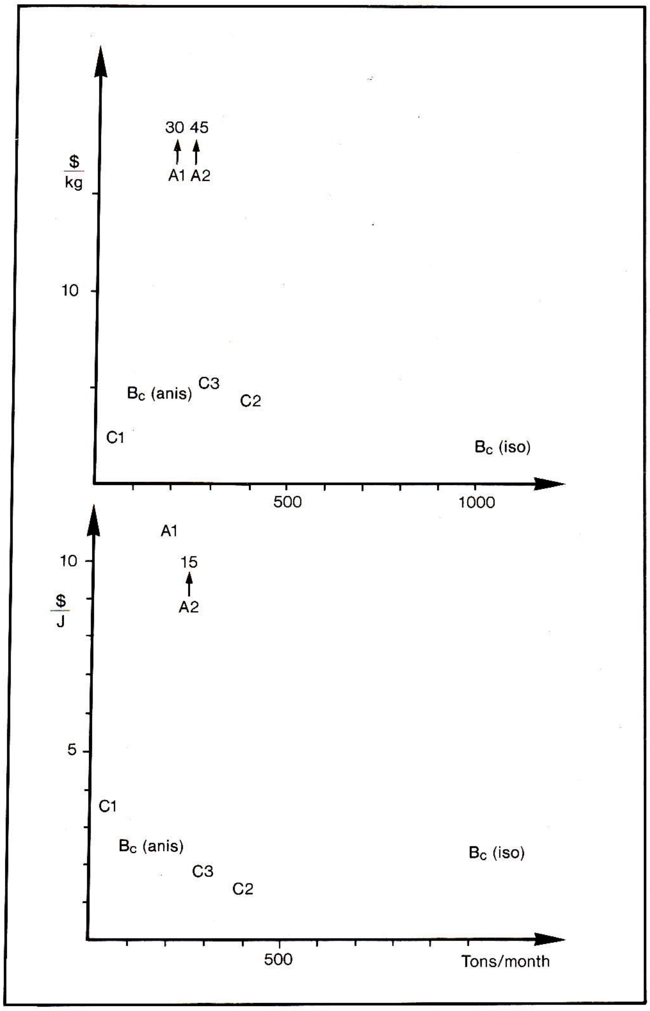


Fig. 4 - Price and production of permanent magnets in $ per unit of weight and per unit of energy.

## TABLE 4 - Prices of raw materials and magnets

| Type of magnet | Raw material | Magnet ($/Kg) |
|---|---|---|
| $C_1$ | 0.2 | 3 |
| $C_2$ | 0.2 | 4 |
| $C_3$ | 0.22 | 4.5 |
| $A_1$ | 20 | 35 |
| $A_2$ | 30 | 45 |
| $R_1$ | 50 | 200-500 |
| $R_4$ | 30 | 200-500 |
| Bc random | 0.5 | 2 |
| Bc oriented | 1.2 | 4.5 |
| Br | 30 | 100-150 |

energy magnet, namely isotropic plastoferrite, which is mostly prepared "in house" by the consumer himself, especially by means of injection moulding and extrusion techniques.

Table 4 gives a comparison between the cost of raw materials and that of the finished magnet. The values given are only indicative, and are subject to large differences depending on supply, especially for $SmCo_5$. About the rate of change, it suffices to mention that alnico prices escalated some 100% in the few years just before 1979,whereas ferrites underwent only very moderate price increases. It is worth noting that, with the exception of $SmCo_5$, the prices in $ have not substantially changed since 1979: only ceramic magnets have slightly reduced their price. The dramatic expansion of the hard ferrite market is estimated at around 800% in the period from 1970 to 1980, the major growth area being in motors, particularly automotive accessory motors. Alnico has been displaced mainly in loudspeakers, the other important growth area. The trend in the car industry is toward further expansion in automotive accessories (mainly in Europe) and in applications to starter motors and alternators. Here part of the potential could be shared with rare-earth cobalt magnets or, most likely, with the new magnets based on Nd-Fe-B. At present these high quality products occupy only a few % of the total market, and there are about 20 companies in the world producing Sm-Co magnets. The general opinion is that most of the usage for these permanent magnets will come from new applications rather than replacement of other magnets, and that this will be impossible unless the knowledge gap existing between produces and potential users is filled.

The applications of permanent magnets are usually classified according to the function they perform in a particular device: i) Conversion of electrical into mechanical energy and vice versa; ii) Force on ferromagnetic soft body; iii) Alignment with respect to field; iiii) Force on moving charge carriers. A complete analysis of modern applications of permanent magnets would require too much space, and it is even difficult to mention all the branches of industrial activity where they are used. An accurate survey is given in the book by Shuler and Brinkmann (21) and recent reviews (22) mention the most recent developments. Besides loudspeakers and motors, other important applications of ferrite magnets occur in magnetos, separators, repulsion devices and couplings. Bonded type ferrites are typically used in refrigerator doors, latches, mechanical switches, television, couplings, advertising signs, toys, small motors, relays. For rare-earth cobalt magnets there has been much discussion about the use of their outstanding properties in DC motors and application at present has been tested in a large variety of devices (23). Interesting areas are in medical aids (24), and in magnetic levitation and bearings.

## Trends

The technological effort is directed toward the use of low-price raw materials. This has promoted the substitution for Sm of mischmetal in Sm-Co type magnets and of Co by Fe, Cu and Mn. At present rare-earth magnets of the 2-17 type are already better than $SmCo_5$, because they offer higher remanence and energy product at a lower price. The recent discovery of Nd-Fe-B magnets opens new possibilities and quite important developments could result if the problem of thermal stability could be solved. Another problem of general importance is that of increasing the coercive force, and this demands a better understanding of the relationship between magnetic hardness and structure-phase state. In the domain of ceramic and plastoferrite magnets, temperature stability is still the main problem. There are indications (25, 26) that W-type ferrites – compounds of the family of hexaferrites, having crystal structure related to that of magnetoplumbite could lead to a higher specific moment or, alternatively, to a lower temperature coefficient by suitable cationic substitutions that give rise to a temperature dependent non-collinear magnetic order.

Phenomena that deserve more attention for the possible development of new permanent magnets materials are exchange anisotropy and metamagnetic transitions (27). Exchange anisotropy has already been considered long ago (28), but very little theoretical and experimental research has been done on it. It seems important to elucidate the phenomena accompanying hysteresis around the transition in metamagnets. These antiferromagnets, having anisotropy stronger than exchange interaction, offer the possibility of ultra-high magnetic energy density. At present this seems possible, in principle at least, at low temperatures with some rare-earth transition metal compounds.

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