

Magnets, Markets, and Magic Cylinders

FEATURE

by Michael Coey and Denis Weaire

New advances may displace iron-core electromagnets

The new rare earth permanent magnets are far superior to any of their predecessors. For example, they may be used to generate a uniform, variable magnetic field with roughly one-tenth the mass of iron-core electromagnets, without requiring special power supplies or cooling water (Figure 1).

Magnetic fields play a key role in a number of industrial processes, including quality control of magnetic materials, the manufacture of magnetic thin-film devices, and the growth of pure semiconductor crystals. Industrial uses typically require fields of 0.02 to 2.0 T. Compact new permanent magnets can generate fields well in excess of 1 T.

Larger fields, in the range of 3 to 16 T, require superconducting electromagnets, which need continuous cooling to a few kelvins. For many companies, therefore, the new generation of permanent magnets offers the compelling advantages of smaller size, lower cost, and ease of operation.

A permanent or "hard" magnet is one whose magnetization remains fixed in magnitude and direction, regardless of magnet shape or the

presence of other magnets in the vicinity. Today's permanent magnet, unlike its steel predecessors, can be formed into any shape without demagnetizing itself. This present generation dates from the early 1980s, when alloys rich in the new $\text{Nd}_2\text{Fe}_{14}\text{B}$ compound were developed independently by Sumitomo Special Metals and General Motors using quite different industrial processes. The Sumitomo magnets, initially composed of $\text{Nd}_{15}\text{Fe}_{77}\text{B}_8$, were manufactured by a powder metallurgy process similar to that used for the earlier generation of samarium-cobalt (Sm-Co) rare-earth permanent magnets. The GM magnets, with approximate composition $\text{Nd}_{13}\text{Fe}_{83}\text{B}_4$, were prepared by a melt-spinning

process which was originally used for amorphous, "soft" magnetic materials.

It was immediately evident that these magnets had clear advantages over their predecessors. As they were iron-based, raw materials were cheap—even the rare-earth metal neodymium is roughly as abundant as cobalt—and the magnetization was 30% greater than for samarium-cobalt. Furthermore, an intensive period of research and development followed to optimize the chemical composition and processing conditions in order to achieve the most desirable combinations of magnetization and coercivity. (In magnets, remanence is a measure of strength; coercivity is a measure of a magnet's ability to maintain its strength in the presence of demagnetizing fields.)

Processing is crucial for magnet development. The new

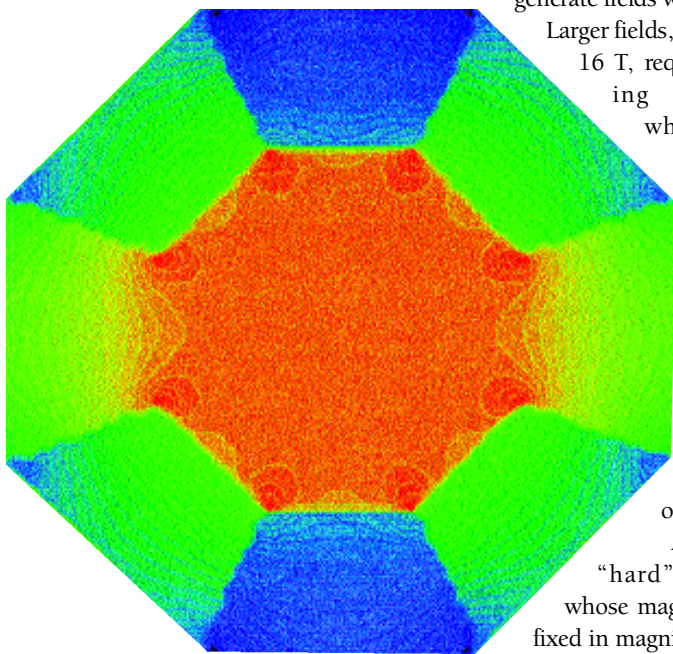


Figure 1. Magic cylinder made of eight segments. Color indicates field strength. The field is uniform in the hollow octagonal core.

Type of magnet	Composition	Total sales
Hard	Ferrite 56%, Sm-Co 10%, Nd-Fe-B 26%, Alnico, etc. 8%	\$5 billion
Semihard	Particulate media 65%, thin films 35%	\$15 billion
Soft	Electrical steels 86%, ferrites 12%, amorphous 2%	\$8 billion

Table 1. Estimate of the world market for magnetic materials in 1997.

permanent magnets require a combination of the right intermetallic compound with excellent intrinsic magnetic properties and a suitable microstructure resulting from bonding or sintering of fine particles. Today, several variants of the manufacturing process are well established, and rare-earth magnets accounted for 36% of all permanent magnet production in 1997 (Table 1).

The 20th century has been the century of permanent magnetism. The energy product—the maximum energy that can be stored in the magnetic field created around a magnet of optimum shape—has doubled, on average, every 12 years since the century began (Figure 2). With the latest Nd-Fe-B magnets, it has attained the value of 440 kJ/m^3 , about twice that of Sm-Co magnets and 10 times that of hard ferrites. This spectacular improvement has yielded new applications, particularly miniature brushless dc motors and actuators, and has led to innovative products ranging from cordless tools to laptop

computers and powerful robots.

Although one can envision further improvement in the energy product, the end is in sight. Fundamental limitations imposed by the electronic structure of the elements in the periodic table rule out any advance beyond $1,000 \text{ kJ/m}^3$. The advances in energy product are due to techniques that have increased coercivity in a series of alloys with improved magnetization. Although rare-earth permanent magnets do not have a magnetization as high as iron itself, they do have enormously greater coercivity.

Rare-earth and ferrite magnets are manufactured worldwide. The production of both is concentrated in Asia, where dominance is shifting from Japan to China.

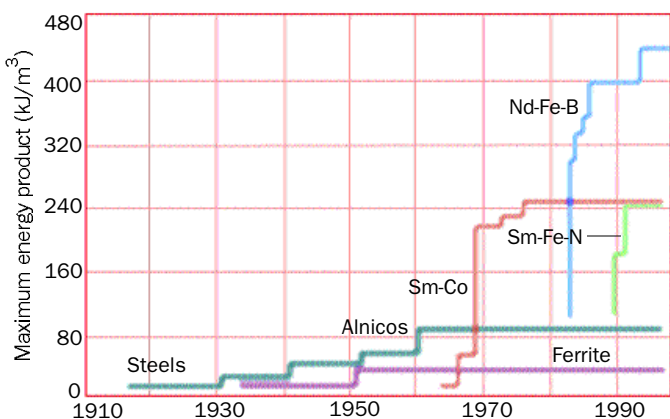


Figure 2. Development of the energy product of permanent magnets during the 20th century.

As the market for rare-earth magnets has grown and diversified, a hierarchy of magnet grades with different properties and prices has emerged. China, with its ancient tradition in magnetism, low costs, and substantial, integrated rare-earth industry, is well placed to supply the market.

Magnet design

Many applications require only small, uniformly magnetized pieces of rare-earth material. A good example is the voice-coil actuator that controls the movement of the read head across the surface of the disk in a hard- or floppy-disk drive. It is astonishing that this single application accounts for more than a quarter of the 10,000 tonnes of Nd-Fe-B produced each year. Much rare-earth

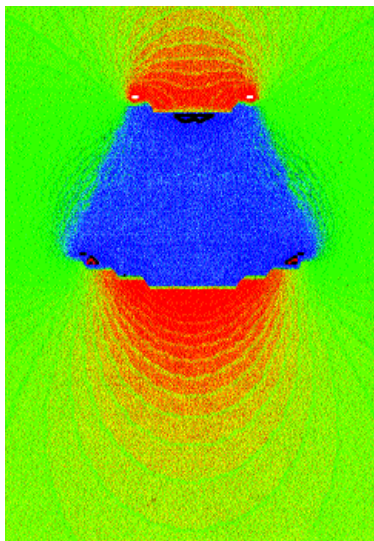


Figure 3. Nonuniform field around a single magnetic segment.

magnet material is also used in dc motors destined for industrial applications or consumer electronics.

In other cases, such as magnetic resonance imaging, a precisely tailored magnetic field is required throughout a large volume. This poses a design problem: how best to

cut and assemble magnet segments to most economically generate the desired field (Figure 3). In many applications, the field must remain uniform, but other uses require rapid spatial variations, such as the focusing magnets on particle beam lines that call for a quadrupole field, or the wiggler magnets on synchrotron light sources that produce a sinusoidally varying field. Long structures of permanent magnets may be the only practical solution in such cases.

Magic cylinders

Modern rare-earth and ferrite magnets actually simplify magnetic circuit design. Unlike their predecessors, the Alnico magnets, the field generated in the circuit is almost independent of the fields generated by the other structural elements. Each magnet is transparent to the flux generated by the others. In *Structures of Permanent Magnets* (Wiley, New York, 1993), Manilo Abele discusses the general problem of designing permanent-magnet structures, concentrating on situations that require a uniform field. He shows how a uniform field may be achieved in a hollow cylinder. Whereas electromagnets generate a field along the axis, these magnetic cylinders produce fields at right angles to the axis. Much of Abele's analysis is based on the idealization of an infinitely long cylinder. He shows that a uniform field can be generated inside the cylinder in a variety of ways. Each involves assembling segments magnetized in different directions (Fig. 4), whose effects combine to make a uniform field inside the cylinder and zero field outside. An elegant but idealized solution has the magnetization direction varying continuously around the cylinder (Figure 4a).

Practical considerations—a cost of \$100 per kilogram for some grades of Nd-Fe-B, for example—dictate that these cylinders be rather short, that is, about as broad as they are long. The designs are conveniently realized with several simple segments of the kinds shown in Figures 4b and 4c. These are sometimes known as magic cylinders, or Halbach cylinders, after Klaus Halbach of Lawrence

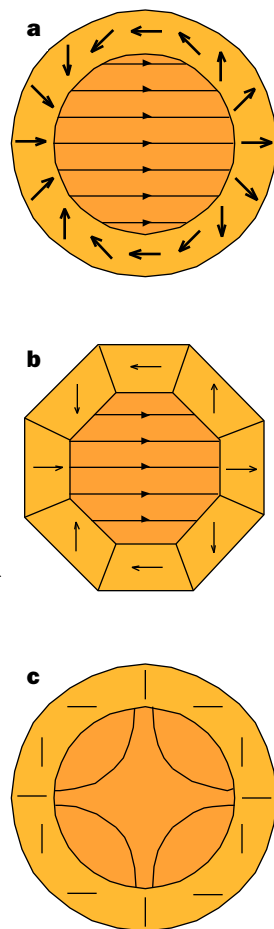
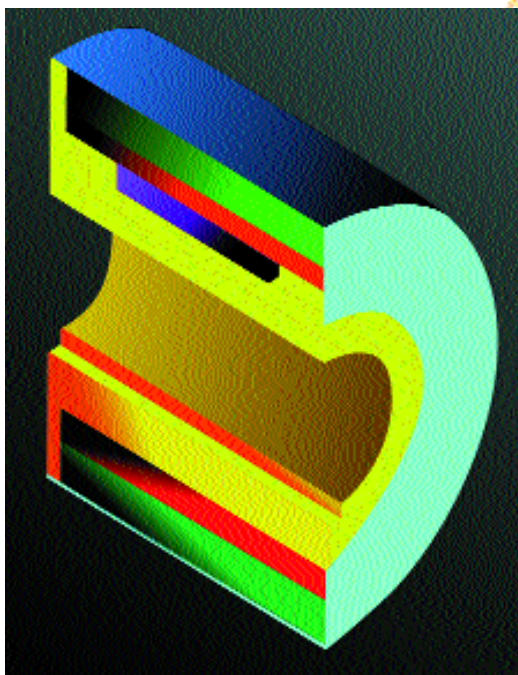


Figure 4. Some magnetic cylinders that generate a uniform field (a, b) or a quadrupole field (c).



Berkeley National Laboratory, who pioneered their use for particle-beam control.

In the ideal case, Figure 4a, the magnitude of the field in the bore is given by $B = B_r \ln(r_o/r_i)$, where B_r is the remanent polarization of the magnet, r_o is the outer radius of the cylinder, and r_i is the inner radius. The field in the bore is proportional to the logarithm of the ratio of the outer radius to the inner radius of the cylinder. A typical value of B_r for Nd-Fe-B is 1.3 T. There are corrections for finite length

Figure 5. A 3D modeling program shows typical industrial use of rare-earth permanent magnets in magnetic torque coupling.

and for the multisegment construction of Figure 4b, but the formula eloquently establishes the practical limitations on permanent-magnet flux sources. Although in principle the field can be increased without limit by increasing the outer radius of the cylinder, it is unreasonable to exceed a radius ratio of about 6. Thus, the maximum field available is less than twice the remanent polarization of the magnets.

As it stands, the Halbach cylinder lacks one important feature of the electromagnet. Although it can be conveniently rotated, the magnitude of the field is fixed. However, a fully variable magnetic field can be provided by nesting one cylinder inside a larger one with the same radius ratio, and allowing independent rotation of the two cylinders. Their fields in the bore add as vectors, so the sum can be adjusted to any value from zero up to the maximum, when the two fields are aligned.

In the ideal design, there is no torque exerted by either cylinder on the other, and the torque is indeed small in actual applications. Only one or two low-power dc motors are required to vary the orientations of the two magnets and complete a variable flux source to rival the electromagnet.

Stability of the new magnets

One obvious doubt about the new magnets concerns their long-term stability. Strictly speaking, any material uniformly magnetized over more than a microscopic region is inherently metastable. Its energy can be lowered by reorganizing the magnetization into domains so that each domain is surrounded by others of opposite magnetization. This tendency can be inhibited by making the magnet from very fine isolated grains, in any one of which it is difficult to reverse the magnetization. This strategy is at the heart of powder processing for rare-earth magnets. It is analogous to arranging the microstructure of large crystals to inhibit their ductility.

There still remains some tendency for the magnetiza-

tion of any permanent magnet to decay slightly over long periods of time. This magnetic viscosity effect is exacerbated at high temperatures and in reverse fields close to the coercivity. In the end, however, the long-term stability of the new permanent magnets will probably be of no more practical concern than the metastability of window glass.

Industrial magnets

For many, the world of magnetism is still represented by the obsolete steel horseshoe magnet and the cumbersome electromagnet. Compared with the glamour of modern microelectronics, magnetism has remained the poor stepchild of electromagnetism. But this is changing. Advanced thin-film fabrication techniques developed for electronic materials have produced spectacular new opportunities for magnetic structures and devices, particularly in information storage. Giant magnetoresistance and spin electronics are buzzwords now making their way from the laboratory to the boardroom, and they will soon have an impact on the balance sheet.

At the same time, new uses are being found for strong magnetic fields. They are, of course, required to magnetize permanent magnets and to measure the remanent magnetization and coercivity of the hard and soft magnetic materials listed in Table 1, whether in bulk or thin-film form. Increasingly, strong magnetic fields are needed in industrial processes, such as thin-film deposition for ion-beam control. Special magnetic annealing furnaces are used in the production of magnetoresistive read heads for hard disks; annual production of these devices is predicted to jump from 300 million today to 1 billion in 2002. Another use of magnetic fields is in growing ultrapure silicon crystals, where the field modifies convection and inhibits the diffusion of impurities.

With countless electromagnetic devices from headphones to small dc motors, which account for much of the 100 g of permanent magnets produced annually for every person on Earth, the future of the magnetics industry is assured (Figure 5). Elsewhere, industry uses magnetic fields in mineral separation, purification of clay, separation of scrap, and the treatment of oil and water. Intriguingly, the effect and potential application of magnetic fields remain controversial and poorly understood in many economically significant areas, such as the suppression of limescale formation in domestic water supplies and of wax formation in oil wells. We still have a great deal to learn about the magic of magnets. □

BIOGRAPHY

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