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Bonded permanent magnets: Current status and future opportunities (invited)

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Permanent magnets play a vital role in modern society as a component in a wide range of devices utilized by many industries and consumers. In 1995, the world production of permanent magnets was estimated to be valued at $3.6 billion and growing at an annual rate of 12%. Bonded permanent magnets are the fastest growing segment of this market. Bonded magnet technology enables a wide variety of magnetic powders to be combined with several polymer and binder systems to produce magnetic components utilizing several processing options. In this article, we review the development of bonded magnet technology. The major classes of magnetic powders, binder systems, and processing technologies are described. Recent developments in magnetic material grades, e.g., anisotropic NdFeB, rare earth lean NdFeB, SmFe(N,C) are outlined. The current status of processing and binder options aimed at increasing the upper application temperature limit of these materials is highlighted. Finally, the improvements and future opportunities for bonded magnets are discussed. © *1997 American Institute of Physics.* [S0021-8979(97)43208-5]

INTRODUCTION

Permanent magnets are ubiquitous in modern societies. Devices which use permanent magnets include motors, sensors, actuators, acoustic transducers, etc. These are used in home appliances, speakers, office automation equipment, medical laboratory diagnostic test equipment, and more. It is estimated, for example, that a typical automobile uses up to 100 permanent magnets in windshield wipers, starter motors, seat adjusters, door lock actuators, fuel pumps, sensors, gauges, etc.

Of the many permanent magnet materials, four are predominant in use: alnico, ferrite, samarium cobalt, and neodymium–iron–boron (NdFeB or ''neo''). Alnico was invented and commercialized in the early 1940's. Ferrite magnets, also called ''ceramic'', were first commercialized in 1952. Samarium–cobalt was introduced in 1961 and an improved composition, Sm_2Co_{17}, provided by the early 1970's. The most recently developed material is neodymium–iron–boron and was first available in 1984. Both these latter materials belong to the family of rare earth magnets.

Each material has unique properties that make it more suitable for selected applications than other magnet options. Selection criteria include: magnetic strength, cost, constancy of magnetic output over temperature extremes, corrosion resistance, resistance to demagnetization, and mechanical properties such as density, physical strength, or flexibility. Ferrite magnets, while providing less magnetic strength than rare earth magnets, cost far less. Therefore, they are still widely used wherever product cost is a major consideration over magnetic performance.

Some examples of applications served primarily by a certain magnet type are: voice coil motors which use NED magnets for positioning read/write heads in computer hard disk drives, high temperature automotive sensors use samarium cobalt, hi–fi speaker magnets use ferrite, and beam focusing devices, such as traveling wave tubes, use alnico, and samarium cobalt. Figure 1 presents a list of common devices and applications.

There are several manufacturing technologies for these materials. Alnico is manufactured by a foundry process of melting alloy and pouring it into molds producing near net shape. These cast magnets are then ground for precise dimension. In order to make parts which are too small for the casting process, cast alnico is pulverized, mixed with additional ingredients, pressed in dies, and sintered. Ferrites and the rare earth magnets are made using powder metallurgy (P/M) processes of milling to fine particle size, pressing, sintering, and cutting/grinding to final dimensions.

Since the 1970's another form of magnet has become commonplace: the bonded magnet. Originally made from ferrite powders and in flexible form, recent developments have been the use of rare earth materials and the technologies of injection molding, compression bonding, and extrusion.

BONDED MAGNET TECHNOLOGY

Bonded magnets, as used here, are mixtures of permanent magnetic powder and a binder. The powder may be ferrite, neodymium–iron–boron, samarium–cobalt, alnico, or mixtures (hybrids). In each case, the powder properties

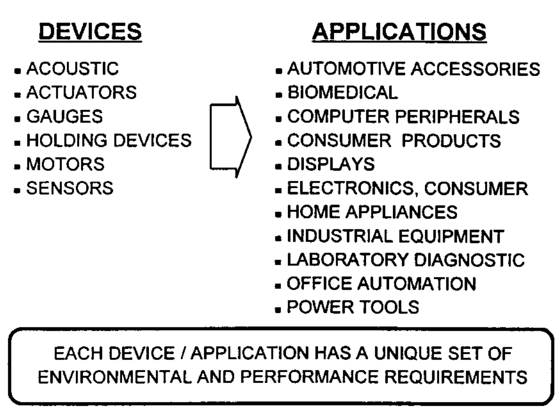

FIG. 1. Permanent magnet opportunities.

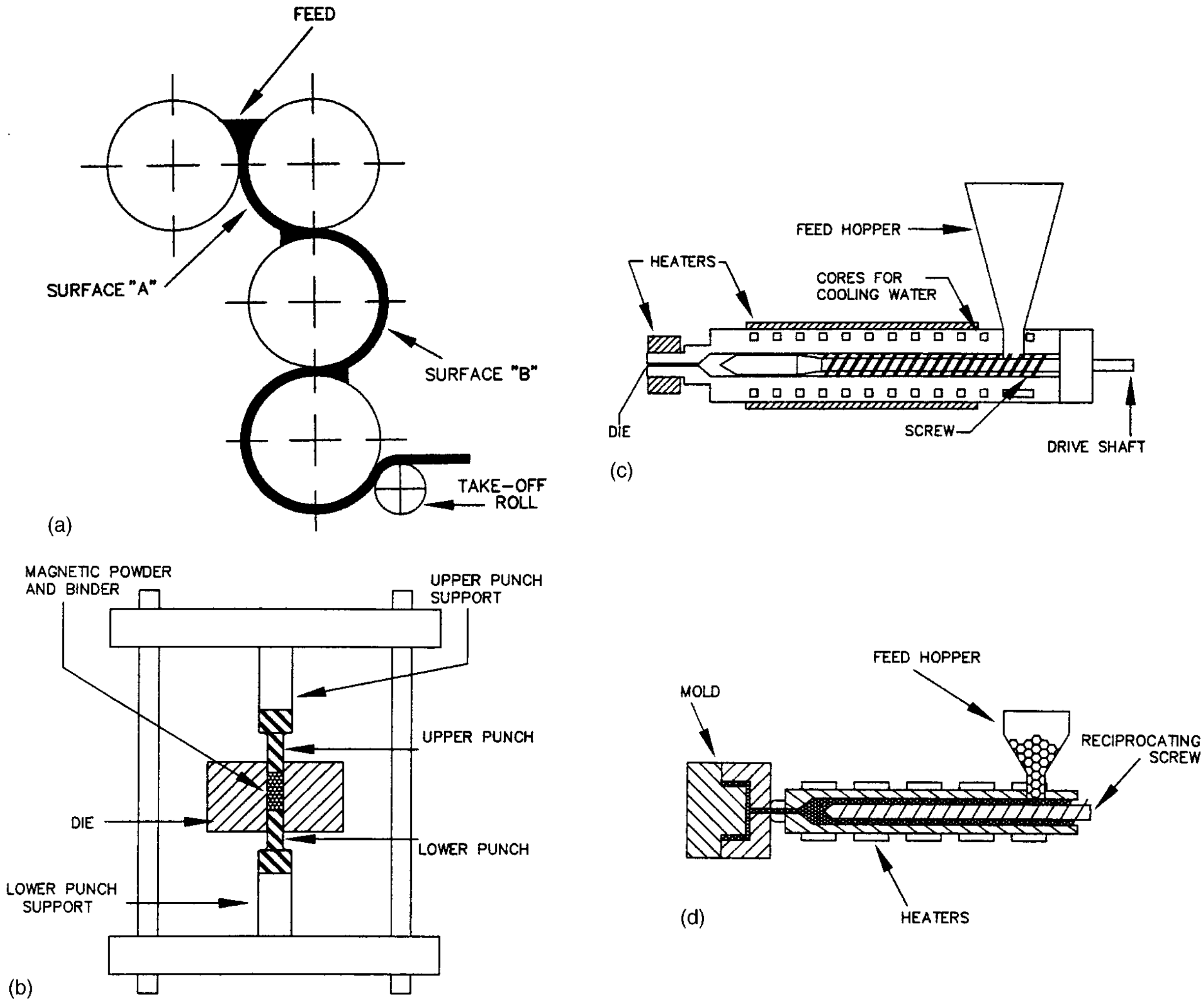

FIG. 2. Bonded magnet mfg methods (a) calendering, (b) compression, (c) extrusion, and (d) injection.

have been improved through process development specifically aimed at the bonded magnet end use. Examples are: melt-spun neodymium–iron–boron, developed by Magnequench, which is almost exclusively used in bonded magnets; special processing of ferrite powders yields clearly defined hexagonal platelets suitable for mechanical alignment during the forming process for flexible magnets, thus maximizing energy output.

The binder that holds the magnetic particles in place may produce either a flexible or rigid magnet. Typical binders for flexible magnets are nitrile rubber and vinyl. Binders for rigid magnets include nylon, PPS (polyphenylene sulfide), polyester, teflon, and thermoset epoxies. The thermoplastic binders may be formed into sheet via a calendering or extrusion process or formed into various complex shapes via injection molding. A major advantage of the bonded process is manufacturing to net shape. If necessary, secondary operations such as drilling, slicing, and gluing can be easily performed. Another advantage of injection molding is the ability to mold onto another object such as a staff or shaft, a hub, or into a can.

There are four processes for manufacturing bonded magnets. Figure 2 schematically describes these processes. Figure 3 shows the commonly manufactured products for each class of binder. These processes are calendering, injection molding, extrusion, and compression bonding. The first three processes use thermoplastic compound which is a mixture of the magnet powder and binder.

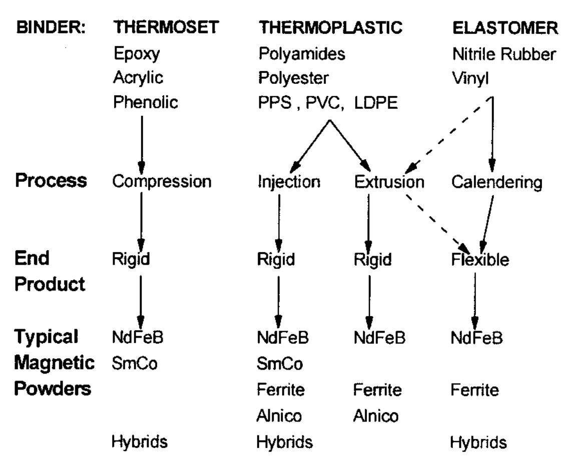

FIG. 3. Bonded magnet types.

TABLE I. Typical maximum energy products of commercially available bonded magnets.

Magnet powder	Mfg method	Magnetic isotropic	Orientation anisotropic
Ferrite	Calendered	0.5–0.7	1.4–1.6
	Extruded	0.4–0.6	1.2–1.5
	Inj molded	0.5–0.8	1.5–1.7
SmCo	Injection molded	(None)	8.5–9.5
	Compression	(None)	13–17
NdFeB	Calendered	4.9–5.1	(None)
	Injection molded	5.0–5.2	9.5–11.0
	Compression	8.0–11.0	14–16

Calendering is forming of a continuous strip by processing of the material between rollers. The strip may be up to several hundred feet long. Typical thicknesses are from 0.012 to 0.250 in. Magnet powders are mostly ferrite though some neo and ferrite/neo hybrids have recently been available. Applications are diverse and include micromotors, printing platens, automotive transmission chip collectors, and a wide range of holding applications.

Injection molding is the process of forcing the heated compound through channels and into mold cavities where it is allowed to cool and harden. The mold is opened and the parts removed. Many magnets can be formed to precise dimension in each machine cycle. Ferrite, neo, and samarium–cobalt are commonly used.

Both calendering and injection molding use magnet powders at up to about 70 volume percent of the part, the remainder being the binder. In calendered product, the high binder content is required for strength and to allow bending/flexibility. In an injection molded product, an adequate binder is required to allow plastic flow through the mold channels and to provide thorough filling of the mold cavity. Magnetic performance is reduced by the dilution effect of the binder.

Extrusion is the squeezing of compound through an orifice while heated and controlling the profile as the compound cools and becomes either firm (flexible end product) or rigid. Magnetic loading in rigid product can be in the 75 volume percent range. Ferrites and rare earth magnetic alloys are very abrasive. One of the challenges for manufacturers of these magnets has been to develop tooling resistant to wear. Inexpensive ferrite extrusions are used for gasketing around doors and for advertising signs typically seen on vehicles. Rare earth extruded magnets are usually rigid and used in motor applications where a long, thin-walled tube is required.

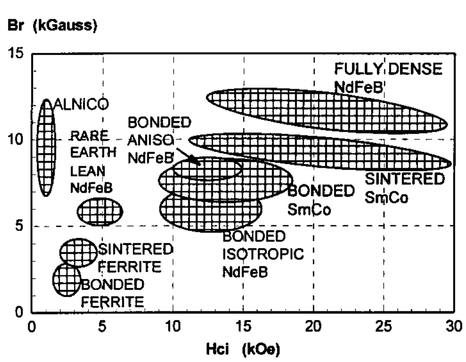

FIG. 4. Typical magnet properties of common permanent magnet materials.

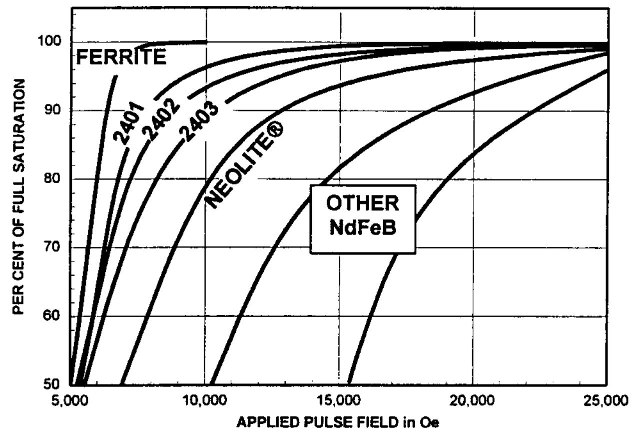

FIG. 5. Saturating field requirement.

The fourth manufacturing process is compression bonding. Magnetic powder is mixed with the binder, usually a thermoset epoxy, flowed into a press cavity and compacted under pressures of about 50 tons per square inch. The compacted magnet is cured at temperatures of about 150–175 °C. One advantage is that the magnetic loading can be as high as 80% by volume, resulting in higher output than calendered, injection molded, and most extruded magnets. Dimensional tolerances are almost as tight as for injection molded products, making secondary operations generally unnecessary. Applications include motor magnets in arc, cylinder, and washer shapes, VCM magnets, and sensors.

Energy products of bonded magnets are presented in Table I. Magnetic properties are compared with traditional, fully dense magnets in Fig. 4.

RECENT DEVELOPMENTS

In the mid 1980's, Philips N. V. developed a neo composition that contained an excess of iron and boron. Melt spun powder magnetic properties included a high B_r, but H_{ci} was lower than other commercially available material. This rare earth lean material exhibited exchange coupling (exchange spring) behavior where the permanent magnetic phase locks the soft magnetic phase. The soft magnetic phase has high magnetic saturation resulting in high B_r.

Recently, Magnequench has made their MQP–Q composition available which has an excess of iron producing a similar effect. An advantage of the rare earth lean materials is excellent corrosion resistance when compared to standard alloys. Second, they reach near saturation with a considerably lower applied field, as shown in Fig. 5.

These alloys may be successfully used alone, but when they are blended with ferrite, synergistic properties of coercivity are obtained. At about 20 weight percent rare earth lean neo, the reversible temperature coefficient of coercivity is approximately zero. Figure 6 compares ferrite to several hybrids and to NdFeB–2401 is the 20% neo hybrid. These

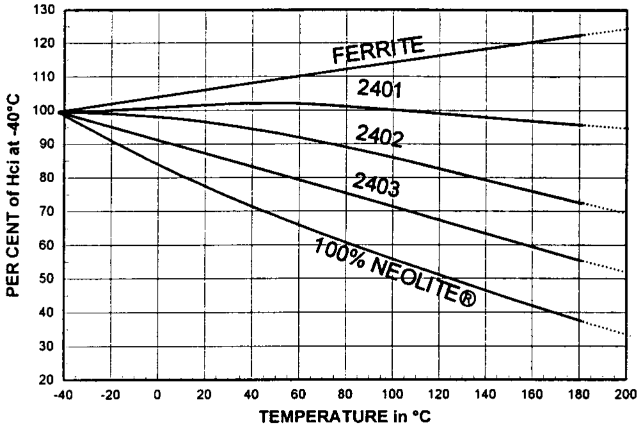

FIG. 6. Coercivity vs temperature.

hybrid magnets have generated much interest in the marketplace. Other hybrids using conventional neo compositions and ferrite, mixtures of neo grades, and even samarium–cobalt with other materials are actively being marketed today.

One major limitation to the use of bonded magnets in ''under the hood'' applications in automobiles is the requirement for stable performance to 180 °C. Standard neo alloys have typically suffered large irreversible loss at these temperatures. About two years ago, Magnequench developed an alloy with a niobium addition. Called MQP–O, it is far more stable at temperatures above 150 °C than its predecessors and with additional protective treatment is advertised for use to 180 °C with no more than 5% irreversible loss over 1000 hours (permeance coefficient=2). An additional benefit is the absence of cobalt in the composition, minimizing price volatility.

High temperature injection molded binders include nylon 6/6 and PPS. Nylon 6/6 suffers less water absorption than nylon 6 and retains full strength even after exposure to 200 °C. PPS has very low water absorption and is very strong. However, it is also quite brittle. Other proprietary compounds and mixtures of thermoplastics are available.

In early 1996, Magnequench made anisotropic neo powder, MQA–T, commercially available. This powder is manufactured by Mitsubishi for Magnequench by the HDDR (hydrogenation, decomposition, dehydrogenation, recombination) process. Structural loss during exposure to elevated temperatures is minimal, but the relatively high reversible temperature coefficient of coercivity, −0.55%/°C, causes substantial irreversible loss above about 100 °C. Typical injection molded properties are a BH_{max} of 10.5 MGOe, compression bonded BH_{max} of 15 MGOe. It has been partially stabilized by blending with other alloys to form hybrids. Both a low saturating field requirement and a high coercivity composition are in development.

Table II summarizes the readily available grades of NdFeB, all manufactured by Magnequench International, Inc., and lists the approximate magnetic properties available from each for injection molded and compression bonded magnets. The MQP–C and D compositions contain 15.5 weight percent cobalt. Cobalt market pricing is quite volatile with prices over the past 6 years ranging from about $11 to over $33 per pound. Pricing of the ''*C*'' and ''*D*'' NdFeB alloys has reflected this. Cobalt improves the temperature stability of the alloy and increases the coercivity thereby satisfying some demanding applications.

TABLE II. World permanent magnet market.

By Material, in $Millions			
Material	1990	1994	A.A.G.%
Bonded NdFeB	$79	$194	25
Fully dense NdFeB	281	603	21
Bonded ferrite	405	673	14
Bonded RE cobalt	20	30	11
Sintered ferrite	835	1244	10
Sintered RE cobalt	211	218	1
Other (incl. Alnico)	239	248	1
Total:	$2070	$3210	11.6%

SmFe(N,C) has been in development since the mid 1980's and is not yet commercially available. Nevertheless, there continues to be interest and progress is occasionally reported. The most promising results are those from Siemens[1] and from Ding, McCormack, and Street[2] via mechanical alloying and those reported by researchers at McGill University utilizing a carbon containing outer skin to stabilize the alloy.[3] According to the Siemens work, bonded SmFeN requires a zinc binder at up to 15% to minimize decomposition. This substantially dilutes the magnetic phase.

Research is proceeding on rare earth lean compositions with additions of gallium, cobalt, molybdenum, and/or niobium.[4,5] These improve Br by squaring the hysteresis loop and result in increased coercivity. Other exchange coupled alloy compositions within the neodymium–iron–boron and samarium–cobalt systems are being investigated.

APPLICATIONS

Bonded magnets are used in numerous new applications as well as supplanting other magnet types in existing ones. The development of compression bonded NdFeB provided maximum energy products of 10 MGOe along with net shape capability. Applications taking advantage of these properties include motor arcs and cylinders which have found use in hand held tools, especially portable drills and screwdrivers. Another example is short axial length, thin wall cylinders which are used in high volume to make spindle motors in floppy and hard drives for the computer industry. Cylindrical magnets can be from two poles to more than 40. They are finding increased usage in electronically commutated (also called brushless DC) and stepper motors.

An advantage of the isotropic neo magnetic alloys is that no aligning field is required during pressing, making fabrication considerably easier and there is no residual magnetization to attract metal particles to the magnets, improving cleanliness during subsequent assembly. And like fully dense magnets, where corrosion might be an issue, bonded magnets can be coated, usually with an epoxy, to improve corrosion resistance. While injection molded NdFeB provides about

TABLE III. Permanent magnet market drivers.

Industry	Drivers
Automotive/transporation	Population growth
Computer and office automation	Democratization/capitalization
Consumer electronics	Information highway
Appliances	Environmental issues
Factory automation	Safety
Medical	Portability
	Energy efficiency

half the energy product of compression bonded neo, it can be molded directly on shafts or in cans simplifying product assembly. It can also be formed into very complex shapes. The thermoplastic binder also provides improved corrosion resistance.

A rapidly growing application for injection molded neo is air core instrumentation gauges. The total, worldwide market for air core gauges is estimated at over 75 million per year. They are used in cars, trucks, ships, and aircraft for speedometers, tachometers, fuel gauges, ammeters, voltmeters, etc. At present, a variety of magnetic materials is used including sintered alnico, sintered NdFeB, injection molded ferrite, sintered ferrite, FeCrCo stamped disks, and molded NdFeB with the latter growing fastest in usage.

Ferrite powders used in injection molding are about 1 to 1.5 micron average particle size permitting molded products to have extremely fine detail, such as gear teeth. Since the ferrite is such an inexpensive material, whole parts can be fabricated using the ferrite-containing compound and only the desired region is then magnetized.

Historic and projected growth of the world magnet industry is presented in Table II. In addition to population growth, numerous social changes are occurring which affect the magnet industry. Several of these growth ''drivers'' are listed in Table III.

Bonded magnets will grow faster than the industry as a whole. Among the reasons for this are: (1) bonded magnets provide an almost infinite variety of combinations of mechanical, physical, and magnetic properties; (2) injection molding enables complex geometries, net shape processing, and magnet assembly by insert or overmolding; (3) compression molding tooling costs are relatively low; (4) handling is relatively easy, and (5) assembly is simple via gluing or press fitting.

SUMMARY

Bonded magnets provide a unique combination of product features. The magnetic and physical characteristics are almost infinitely variable making them a true engineered product. New grades and product enhancements are being introduced frequently. For these reasons, bonded magnets represent the fastest growth segment of the industry. This trend will accelerate with customer awareness and more design ins. Improvement of high temperature capability, increases in maximum energy product, and lowering of selling price of the more expensive rare earth type bonded magnets will extend application opportunities.

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