Journal of Electronic Materials, Vol. 26, No. 5, 1997

Review Paper

Permanent-Magnet Materials: Research Directions and Opportunities

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Permanent magnets are pervasive in modern industrial societies. They enable conversion of electrical energy to mechanical energy, they underlie microwave communications, and they constitute the active material in data-storage devices. To sustain the evolution of new and improved permanent-magnet materials, an active research enterprise is required. In this paper, the status of modern rare earth-transition metal magnets is outlined, contemporary research directions are summarized, and unresolved issues and research opportunities are enumerated.

Key words: Permanent-magnetic materials, rare earth-transition metals

INTRODUCTION

A Committee on Magnetic Materials was established by the National Materials Advisory Board in 1984 to assess the status of research and development in magnetic materials in the United States.[1] Partly in response to that assessment, a workshop was convened by the U.S. Department of Energy (DOE) in 1988 to explore the topic of magnetic materials specifically from the viewpoint of materials science. That workshop was summarized by Thomas, who identified the most important research needs and opportunities.[2] In light of the substantial amount of research and development that has ensued since the DOE workshop, it is appropriate to update the assessment of research trends and to recommend the most fruitful avenues for future work.

In this paper, we summarize the current status of bulk permanent-magnet materials, review contemporary research directions in the science and engineering of permanent-magnet materials, enumerate unresolved issues, and suggest the most promising research opportunities. For economy of space, the fascinating developments associated with magnetic thin films (recording media), magneto-optic materials, and magnets constituted of high-T_c superconductors have been excluded.

A brief overview of the current classes of modern permanent magnets sets the stage for a more detailed examination of current research directions.

MODERN PERMANENT MAGNETS

A magnet of a given volume maintains the highest field in a gap when the product of induced magnetization, B, and applied field, H, is a maximum. $(BH)_{max}$ or maximum energy product can be expressed as either megagauss-oersteds (MGOe) or equivalently as kilojoules per cubic meter (kJ/m^3); 1 kJ/m^3 = $4\pi \times 10^{-2}$ MGOe.

Superior permanent magnets require materials with high magnetization and strong, uniaxial, magnetocrystalline anisotropy. It was first shown in the mid-1960s that certain rare earth-transition metal (RE-TM) compounds could satisfy those conditions.

(Received November 25, 1996; accepted January 28, 1997)

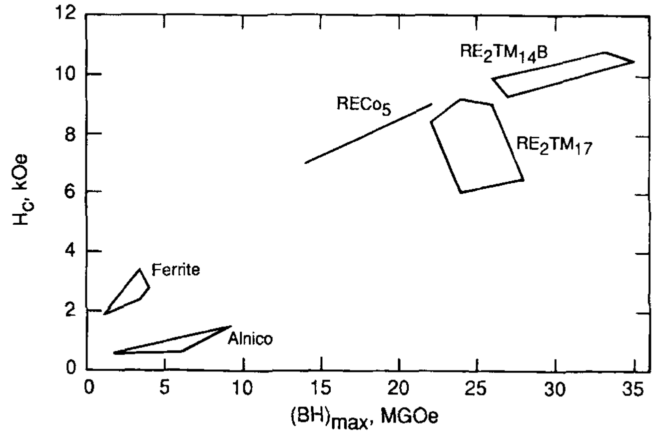

Fig. 1. Regimes of energy product vs coercivity for modern permanent magnets.

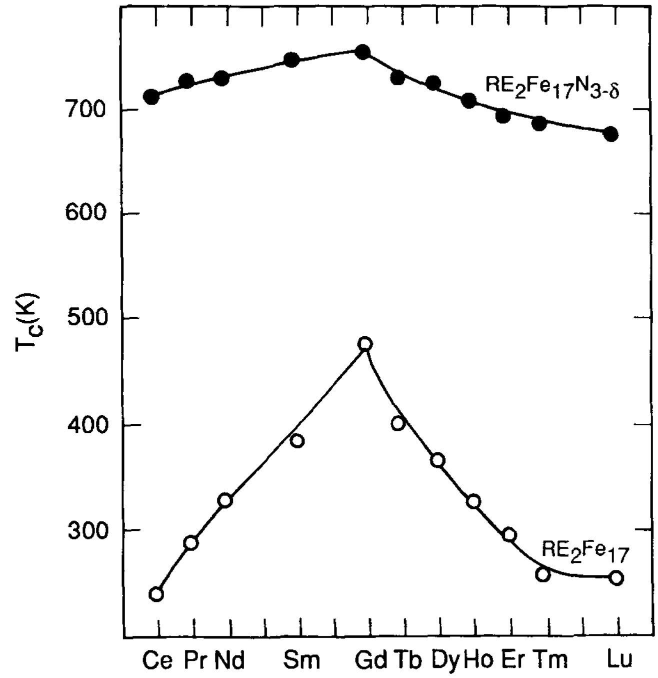

Fig. 2. Curie temperature of RE_2Fe_{17} (open circles) and $RE_2Fe_{17}N_{3-\delta}$ (solid circles). Adapted from Ref. 12.

Initial research centered on the compound $SmCo_5$, which was fabricated by conventional powder-metallurgy methods. $SmCo_5$ magnets with maximum energy products of 16 to 22 MGOe are now produced for the commercial market. For comparison, the best alnico (Fe-Al-Ni-Co alloys) magnets have energy products of about 9 MGOe and best ferrite (iron-strontium oxide or iron-barium oxide) magnets about 4 MGOe.

A second generation of RE-TM magnets with higher magnetizations was based on the compound Sm_2Co_{17}. These magnets contain substantial amounts of iron and copper plus small amounts of zirconium, hafnium, or titanium. They rely on solid-state precipitation reactions for their coercivity. Energy products of 25 to 28 MGOe are typical of the commercial forms of these magnets. All aspects of $RETM_5$ and RE_2TM_{17} magnets are covered in the comprehensive review by Kumar.[3]

The most recent development in RE-TM magnets, and perhaps the most important one in its implications, is based on a neodymium-iron-boron compound. This iron-based material combines high magnetization and high coercivity, and the raw materials are less costly than those for Sm-Co magnets. Energy products of up to 50 MGOe have been reached experimentally and magnets with energy products of 35 MGOe are readily available commercially. The major drawback of Nd-Fe-B magnets is low Curie temperature (585K), which causes the properties to be strongly temperature-dependent at room temperature. Properties and processing of Nd-Fe-B magnets have been reviewed by Herbst[4] and Parker.[5] Fundamental aspects of RE-TM magnets in general are very clearly presented by Gavigan and Givord.[6] Magnetic property comparisons among RE-TM alloys, alnicos, and ferrites are illustrated by Fig. 1.

CONTEMPORARY RESEARCH DIRECTIONS

Discovery of Nd-Fe-B magnets set off a search for other rare-earth compounds, preferably with iron as the main transition metal, that could serve as the bases for improved permanent magnets. In part, this search is motivated by the obvious benefits of higher remanent magnetizations and higher energy products. There is also the motivation to overcome the limitations of Nd-Fe-B magnets: low Curie temperature and chemical instability (high susceptibility to corrosion). The two main thrusts of current enquiry are searches for new, iron-rich compounds, and improvements in processing and manufacturing technologies.[7]

Strategies in the Search for New Compounds

Four strategies for discovering new permanent-magnet compounds are reviewed: systematic variations on known compounds, structure maps, sublattice substitutions, and crystallization of amorphous deposits. Each strategy is based on the recognition that modern permanent-magnet materials are characterized by large exchange interactions, high spontaneous magnetizations, and large magnetic anisotropy. Uniaxial magnetic anisotropy occurs only in low-symmetry crystal structures, typified by $BaCd_{11}$, $ThMn_{12}$, and $NaZn_{13}$. Since there are no *binary* RE-Fe compounds with those structure types, a central issue has been how to choose ternary (or quaternary) elements to stabilize $RE(Fe,X)_n$, where n is 11, 12, or 13.

Systematic Variations on Known Compounds

By far the most common approach to discovering new magnets is the one in which incremental changes are made to well-established compositions, e.g., $Nd_2Fe_{14}B$. A sampling of such research can be found in Refs. 8–10.

Perhaps the most promising development from systematic variation is interstitial modification of RE-Fe compounds. Research has focused on RE_2Fe_{17} compounds (the analogs of $RE_2(Co,Fe)_{17}$ alloys), which are particularly stable and occur across the entire RE series. As binaries, these intermetallics have low

Curie temperatures and do not exhibit easy-axis anisotropy. They crystallize in rhombohedral and hexagonal variants with two kinds of interstitial sites: octahedral sites in the c-planes and sites along the c-axis between two RE ions. Carbon and nitrogen occupy only the octahedral sites.[11]

Interstitial doping of RE_2Fe_{17} powders with nitrogen has thus far produced the most interesting results.[12,13] Crystal structures are unchanged by nitriding, but expansion of the unit cells by 6–7 pct occurs. The most striking effect is elevation of the Curie temperatures, as shown in Fig. 2. Anisotropy fields are high; however, only $Sm_2Fe_{17}N_{3-\delta}$ has easy-axis anisotropy. Magnetization is respectable (16.4 kG) for $Sm_2Fe_{17}N_{3-\delta}$, which equates to an ideal upper limit of 59 MGOe on energy product. Although a practical means of fabricating magnets from nitrided powder has not yet been reported, the prospects for Sm-Fe-N magnets with higher Curie temperatures than Nd-Fe-B are considered to be good.[14]

Structure Maps

A second approach to choices for third (or fourth) elements that stabilize RE-FE compounds is with so-called structure maps. It has been shown that the structures of A_mB_n binary compounds in existing databases can be organized by crystal structure within two dimensions by invoking a coordinate, ***M***, called the Mendeleev number.[15] ***M*** is obtained by running a string through a modified Periodic Table, Fig. 3, and then pulling the string straight to order all the elements along a one-dimensional axis. Note that the string runs from right to left through the rare earths (downward from Sc (19), around Y (25), and thence behind the panel containing the rare earths to enter at Lu (20) on the right-hand side), in order of increasing number of valence d-electrons. The number accompanying each element in Fig. 3 is the Mendeleev number. ***M*** is not based on combinations of physical factors such as electronegativity, atomic size, or average number of valence electrons per atom. Rather, ***M*** is a purely phenomenological coordinate. This simple procedure for obtaining ***M*** turns out to provide good structural separation of binary systems into domains by plotting $\boldsymbol{M}_A$ vs $\boldsymbol{M}_B$. Furthermore, ternary or quaternary compounds with binary structure types A_mB_n can be treated as pseudo-binaries characterized by average Mendeleev numbers, $\bar{\boldsymbol{M}}$; the pseudo-binaries are found to fall into the same structural domains as the pure binaries.[16] Figure 4 is an example of the map for domains with the $ThMn_{12}$ structure, in which binary and pseudo-binary compounds are both represented.

Equivalent maps can be plotted for each A_mB_n structure type, and particularly the $BaCd_{11}$, $NaZn_{13}$, and Th_2Ni_{17} structures that are of most interest for iron-rich permanent magnets. However, it proves more useful to plot more than one domain on a single map by assigning a separate symbol or color to each structure. Then examination of the domains adjacent to, or sometimes overlapping, the structure of interest can suggest how to convert one structure into another by the addition of an appropriate third (or fourth) element. Thus, Pettifor et al. point out that for new compounds in which iron is the majority element, two domains look promising:[17] a $ThMn_{12}$ domain that results from replacing iron with transition metals to the left of iron in the Periodic Table; and a $NaZn_{13}$ domain that incorporates early rare earths and iron replacement with metalloid elements to the right of iron in the Periodic Table. As will be seen in the next subsection, there has been extensive exploration of just those areas.

Sublattice Substitutions

Another approach to new magnet materials is based on binary intermetallic compounds in which at least one constituent element occupies two or more nonequivalent crystallographic sites, as shown in Fig. 5 for $REFe_{12}$ with the $ThMn_{12}$ structure.[18] Preferential occupation of one of those sites by a third element (X) may then lead to a ternary compound. This approach, which is parallel to structure maps, originally identi-

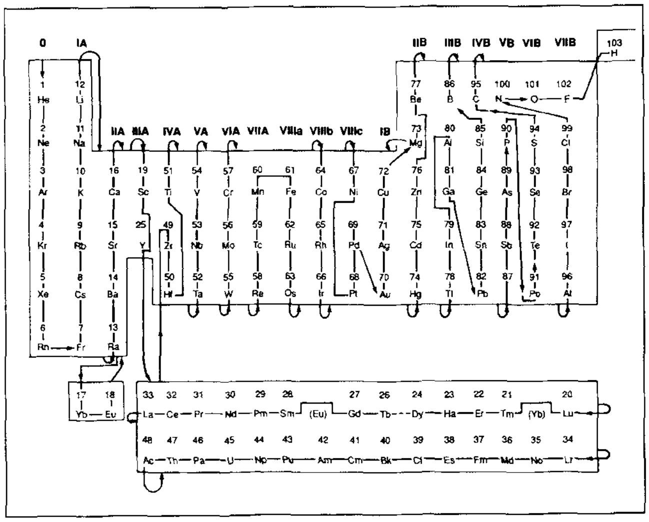

Fig. 3. A string running through a modified Periodic Table puts all the elements in sequential order, given by the Mendeleev number. Group IIA elements Be and Mg are included with group IIB, divalent rare earths are separated from trivalent, and Y is inserted between Tb and Dy. Adapted from Ref. 16.

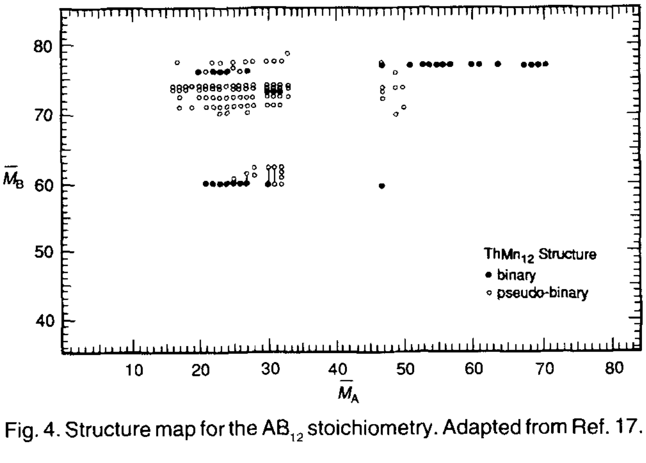

Fig. 4. Structure map for the AB_{12} stoichiometry. Adapted from Ref. 17.

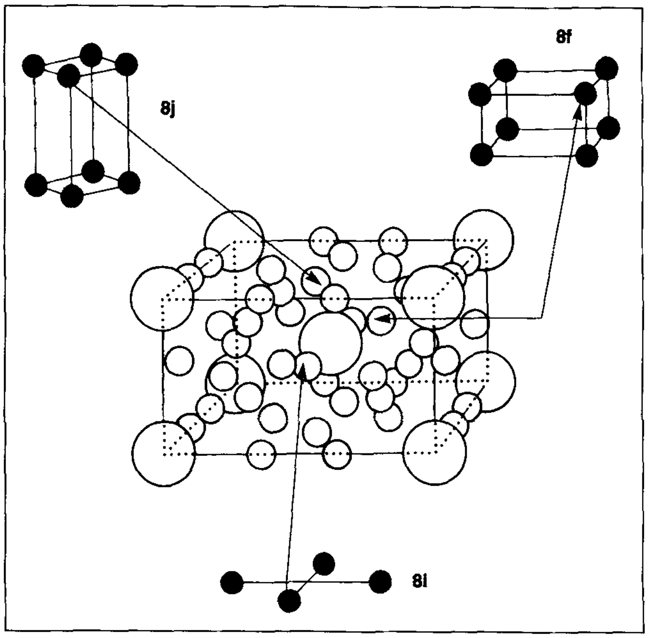

Fig. 5. Schematic of a hypothetical $REFe_{12}$ unit cell with the $ThMn_{12}$ structure, showing the three different Fe positions: large circles are RE atoms; small circles are Fe atoms. Adapted from Ref. 18.

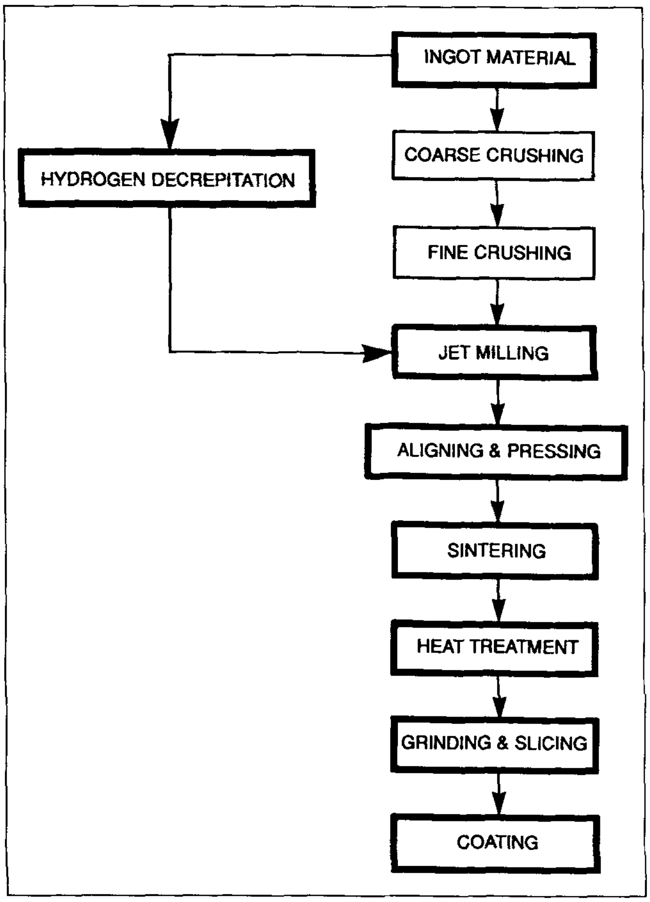

Fig. 6. Production sequence for RE-TM magnets, showing an alternative HD route.[29]

fied five structure types as candidates:[19,20] Th_2Ni_{17}, $SrNi_{12}B_6$, $CeMn_6Ni_5$, $BaCd_{11}$, and $ThMn_{12}$.

Of these candidates, iron-rich compounds that crystallize in the $SrNi_{12}B_6$, $CeMn_6Ni_5$, and $BaCd_{11}$ structures were eliminated either because ternary compounds were few or because Curie temperatures and anisotropies were low and could not be improved enough. In contrast, iron-based compounds with the tetragonal $ThMn_{12}$ and Th_2Ni_{17} structures (e.g., $SmFe_{10}Si_2$ and Dy_2Fe_{17}, respectively) form extensive classes that were investigated in detail. In one study, for example,[20] 80 different compositions of $REFe_{12-x}TM_x$ were prepared by adding Ti, V, Cr, Mo, W, or Si to stabilize the $ThMn_{12}$ structure. Each composition was analyzed by x-ray diffraction and T_c was measured. Compounds in the series $REFe_{10}V$ (Ref. 21) and $YFe_{11}Ti$ (Ref. 22) have also been investigated in comparably detailed studies. Intrinsic properties such as crystalline anisotropies of the RE and Fe sublattices, magnetostriction, etc., were measured and listed in the cited works. Although the research did not result in useful permanent magnets, the compilations should provide an excellent resource for future investigations on materials of these types.

Most recently, research on iron-based compounds with the $ThMn_{12}$ structure has been based on the composition $Sm_{1-x}M_x(Fe,Co)_{12}$, where M is Zr, Hf, or Bi and $0.1<x<0.2$.[23] Coercivities of up to 7200 Oe have been obtained, which suggests that further exploration of this system could result in practical magnets.

Crystallization of Amorphous Deposits

An approach that provides access to metastable compounds that might otherwise be inaccessible involves the preparation of amorphous materials by melt spinning or vapor deposition on cold substrates. The amorphous samples are then heated slowly and monitored continuously by differential scanning calorimetry and magnetic response to a constant magnetic field. This is a quick and powerful method in the search for new phases. Very high magnetic hardness in the Fe-Ti-Sm system was first observed by this method.[24] From a practical point of view, the magnetization of Fe-Ti-Sm alloys is too low (about 3 kG remanence) to be important yet. Other descriptions of this approach can be found in Refs. 25–28.

Processing and Manufacturing

The discovery of Nd-Fe-B magnets, and the possibility of their widespread usage in industrial motors and other large devices, has motivated research into new processes for mass manufacture. In this section, the following topics in process research are surveyed briefly: small-particle production, sintering, and deformation shaping.

Small-Particle Production

Coarse-grained, randomly oriented, cast ingots of RE-TM alloys must be converted to fine-grained, highly oriented, sintered magnets. Usually this is accomplished by the process sequence of crushing and grinding shown in the right-hand column of Fig. 6. An alternative route is to break down the ingot material by hydrogen decrepitation[29] (HD) shown in the left-side loop of Fig. 6.

HD is the conversion of bulk material into small particles (through pervasive intergranular and transgranular cracking) solely by dissolving hydrogen in the material. The process depends on the ready absorption of hydrogen at room temperature by Sm-Co and Nd-Fe-B, and the fact that the powders produced by decrepitation are extremely friable and easily pulverized (by jet or attritor mills) to the 2 μm size required to make sintered magnets.[30] The powder, still in the hydrided condition after milling, can be aligned in a magnetic field, although the unsintered compacts do not have any coercivity (a feature that facilitates handling). Sintering temperatures and oxygen contents of magnets made from HD powder are lower than those of magnets made by the standard route.

A useful discovery was that small additions of Zr, Hf, or Ga are very effective in promoting anisotropy in HD powders.[31] The reasons for this additive effect are still a matter of speculation; it is suspected that hydrogen absorption is diminished or blocked in the very local regions where additive concentration is relatively high.[10]

Decrepitation is not the only intriguing aspect of hydrogen processing. When coarse-grained Nd-Fe-B alloys are heated to 700–800°C in hydrogen and held at temperature in vacuum for about one hour, the $Nd_2Fe_{14}B$ phase appears first to disproportionate to $2NdH_{2.9} + Fe_2B + 12Fe$ and then to recombine to a fine-grained microstructure.[32] Exposure of $Nd_2Fe_{14}B$ powders to hydrogen, in similar experiments,[33] converted the original particles into aggregates of smaller crystallites (about 0.3 μm) in which the small crystallites were not surrounded by a nonferromagnetic Nd-rich phase. Yet at certain stages of dehydrogenation, the powders exhibited high coercivity, which calls into question the conventional view of magnetic isolation for high coercivity.

Sintering

Liquid-phase sintering, one of the two most-used processing routes for Nd-Fe-B magnets, is based on the occurrence of a low-melting, Nd-rich phase for densification and for a grain-boundary layer between $Nd_2Fe_{14}B$ particles. Since the Nd-rich phase is nonferromagnetic, it dilutes the remanent magnetization of sintered bodies. Attempts to lower the Nd content of sintered magnets have been rewarded mostly by unacceptably low coercivity or by low mechanical integrity.

A novel approach devised by Otsuki et al.[34] was to cast an ingot of stoichiometric $Nd_2Fe_{14}B$ and crush it. Since solid shapes with good magnetic and mechanical properties cannot be produced from $Nd_2Fe_{14}B$ powders alone, a melt with the composition of the liquid phase during sintering was solidified into flakes by melt spinning, and the flakes were crushed. Crushed $Nd_2Fe_{14}B$ and melt-spun flakes were combined in the desired proportions, pulverized, and sintered in the usual way. More uniform microstructures, lower oxygen contents, and superior magnetic properties (energy products of more than 50 MGOe) resulted. Similar procedures have been employed to effect small composition changes that improve magnetic isolation of the $Nd_2Fe_{14}B$ grains without reducing the saturation magnetization.[10] Thus, "powder mixing" offers a flexible basis for process experiments.

Deformation Processing

In contrast to the "standard" method of milling ingot material to a particle size of about 10 μm, anisotropic Nd-Fe-B magnets can be prepared by consolidating and orienting melt-spun ribbon by hot deformation.[35] Additions of Co and Ga together with control of grain growth during densification and die upsetting[36] have resulted in maximum energy products of 48 MGOe. Scaling up the deformation processing of melt-spin ribbon has been explored for hot rolling and hot extrusion. Hot rolling required subsequent pulverization, alignment, and rapid electrosintering;[37] hot extrusion produced fully dense shapes without the intermediate steps,[38] although magnetic alignment was not as well developed.

Significant steps toward industrial-scale manufacturing were taken in investigations of hot rolling and hot upset forging of Pr-Fe-B-Cu ingots[39,40] and hot rolling of Nd-Fe-B ingots.[41] High strain rates were achieved (up to 10/s for rolling, upsetting in 20s for forging), which enabled the processing of sizable ingots in short times. Energy products of 29 MGOe for forging and 33.8 MGOe for hot rolling were obtained after post-deformation heat treatments.

A few fundamental studies of deformation mechanisms and texture development for rapidly quenched and hot-deformed Nd-Fe-B have been undertaken, most notably by Graham and coworkers.[42,43] Such information will undoubtedly be useful for the development of innovative processmg schemes.

UNRESOLVED ISSUES AND RESEARCH OPPORTUNITIES

Research and development on new permanent-magnet materials and their applications continue at an intense pace throughout the industrialized world. In spite of these widespread activities, it should come as no surprise that there is still much room for improvement. Some of these improvements will come from research already underway along well-mapped routes. Others await answers to issues that are currently unresolved. In this section, we describe very briefly several unresolved questions and research opportunities that were identified in the study.

Physics and Chemistry of Permanent-Magnet Materials

Coercivity Issues

Questions about the temperature dependence and mechanisms of coercivity in RE-TM compounds are of considerable theoretical and practical interest. We cannot now explain why intrinsic coercivity (H_{ci}) has greater variation with temperature than does the anisotropy field. Magnetostatic interactions,[44,45] crystal defects that control the nucleation field,[46,47] and thermal activation[48–50] have been proposed as explanations; the community remains unconvinced, however, that an unequivocal answer has been found. This is an active topic of research in many laboratories.

High coercivities of certain Nd-Fe-B materials in which there is little or no isolation of the ferromagnetic grains[33,43] cannot be accounted for either. These observations are inconsistent with the conventional view of magnetic isolation and domain-wall pinning at grain boundaries

Shortcomings of Nd-Fe-B Magnets

A low Curie temperature (585K) is the main technical impediment to wider application of Nd-Fe-B magnets. Solutions to this problem, primarily by composition adjustments[51,52] and partial substitutions of cobalt[53] or heavy rare earths[10,45] are also being sought by many investigators. Although improvements have been made, the gains have been modest and further progress is still needed.

Magnetism in Heavy Rare-Earth Elements

Several heavy rare-earths (HREs) have very high magnetizations at low temperatures, and some intermetallic compounds between HREs and nonferromagnetic partners have noteworthy hard magnetic properties at liquid helium temperatures.[54] Routes to achieving such properties at practical temperatures are unknown and it is possible that none exist. However, a possible first step in an approach to heavy rare-earth magnets can be glimpsed in research on $DyFe_6Al_6$, which indicates that the compound is a ferrimagnet with a Curie temperature of 316K and relatively strong magnetocrystalline anisotropy.[55] This is not presently a popular topic of research. Nevertheless, it is conceivable that the situation is similar to the status of superconducting materials just a few years ago, before the copper-oxide-based superconductors were discovered.

Manganese-Based Magnets

Manganese has an electronic structure that corresponds to the maximum possible moment, 5 μ_B, in the first transition series of elements. The interaction between neighboring ions in manganese is antiparallel, however. For decades a "dream" of researchers was to discover a manganese-based alloy or compound that exhibits parallel (ferromagnetic) coupling of all moment-bearing ions and thus provides high saturation magnetization and high Curie temperature. The search for manganese-based materials peaked with the development of extruded Mn-Al-C[56]and then declined with the advent of RE-TM magnets. If the low costs forecast for RE-TM magnets at the time Nd-Fe-B magnets were discovered cannot be achieved (see below), it could be worthwhile to reassess past investigations of, and future prospects for, manganese-based materials, especially in the light of current understanding of RE effects, interstitial effects, nonequilibrium phases by melt spinning, etc. Careful analysis may still reaffirm the impossibility of manganese alloys with high Curie temperatures and high magnetizations, but the potential rewards would seem to favor one more critical evaluation.

Processing

Fabrication of RE-TM-N Compositions

Gas-phase interstitial modification of RE-TM compounds is of much current interest. To date, only $Sm_2Fe_{17}N_3$ appears to have a chance of rivaling Nd-Fe-B in permanent-magnet applications,[14,57] but the possibilities of other useful substances are far from exhausted. These materials cannot be consolidated by conventional methods, since they decompose at temperatures (~650°C) much below the usual sintering temperatures. Therefore, measurements and demonstrations have been conducted with powders or bonded (by resin or zinc) magnets. Making bulk magnets from nitrogen-modified powders should not be an insuperable challenge. Possible processes include shock consolidation, plasma-assisted sintering, and plasma-enhanced chemical vapor deposition.

Arc-Plasma Spraying and Melt Spinning

Arc-plasma spraying has produced near-net shape $RECo_5$ magnets with small grain size and low oxygen content.[58] The main disadvantage of thermal-spray methods is that the deposits are close to isotropic, and consequently remanences are low (about 7.4 kG) and energy products are limited to about 9 MGOe. This is also true of melt-spun Nd-Fe-B ribbons if they are not aligned by subsequent unidirectional plastic deformation at high temperature. Excellent alignment of plasma-sprayed $SmCo_5$ has been achieved by deposition on hot steel substrates (966–1127°C);[59] however, Sm evaporation at these temperatures spoiled the magnetic properties. Are there process variations that can get around this difficulty?

One possibility is magnetic annealing. Both arc-plasma spraying and melt spinning can produce amorphous or mostly amorphous deposits of RE-TM alloys. It would be worthwhile to know if imposition of a strong magnetic field during slow heating of amorphous RE-TM deposits can influence the nucleation of microcrystals.

Cost of Raw Materials

Permanent-magnet materials based on rare-earth elements have found extensive and essential use in many commercial products. Continued penetration of these materials into new markets and wider application will depend critically on the cost of raw materials. Most of the so-called rare earths are not rare; they are about as abundant as zinc, nickel, copper, lead, and cobalt,[60] and much more abundant than cadmium, silver, mercury, and gold. It is the reduction of rare earths to pure metals that is costly.[61] The necessity for two solvent-extraction cuts to isolate a single rare earth (typically Nd, Pr, or Sm), followed by a conversion step to the appropriate combined form (typically a fluoride), and then a reduction step (calciothermic or electrolytic), makes it hard to imagine that rare-earth metals will ever be inexpensive. Although costs will undoubtedly decrease as production capacity rises to meet demand, will they ever decrease enough to make economically attractive the use of RE-TM materials for multi-kilogram-size magnets in products with markets potentially as big as that for large electric motors?[7] This question is at the root of which direction to choose for research: discovery and development of other permanent-magnet materials not based on rare earths vs research on discovering and improving RE-based permanent-magnet materials and applications.

CONCLUSIONS

There is an intensive, continuing search for new permanent-magnet materials with superior properties at many institutes and laboratories throughout the world. This search is motivated mainly by the central role of permanent-magnet materials in converting electrical energy to mechanical energy.

Most of the ongoing research is aimed at RE-TM alloys, which are the dominant permanent-magnet materials by virtue of their high remanences, coercivities, and maximum energy products. The principal, new, permanent-magnet materials that are offered commercially are based on $SmCo_5$, $Sm_2(Co,Fe,Cu)_{17}$, and $Nd_2Fe_{14}B$.

Discovery of the iron-based Nd-Fe-B magnets triggered much of the current research activity because iron and neodymium are more plentiful and less costly than cobalt and samarium. However, Nd-Fe-B magnets suffer from a low Curie temperature, which limits their usefulness. Many research projects are directed at alloying or processing variations to rectify that shortcoming or to discover other compounds of iron that could be developed as good, cheap, permanent magnets.

Despite recent progress, there are a number of unresolved issues in the materials science and engineering of permanent-magnet materials. Issues that are being actively researched in the global community include explanation of the temperature dependence of coercivity in RE-TM magnets, coercivity mechanisms in real magnets, and the low Curie temperature (and associated temperature-sensitive magnetic properties) of Nd-Fe-B magnets.

Although there are relatively few gaps in the current spectrum of research activities worldwide, unresolved issues that may not be adequately addressed include magnetism in heavy rare-earth elements and compounds, manganese-based magnets, near-net shape fabrication of RE-TM magnets (e.g., by thermal-spray methods), consolidation and magnetic alignment of nitrided RE-TM compositions, and future costs of pure rare-earth metals for magnets.

For a number of major market segments, such as the application of permanent magnets in large electric motors, a critical assessment of future prices for RE-TM magnets would seem to be especially important in deciding about directions for research on permanent-magnet materials.

ACKNOWLEDGMENT

This study was conducted for the Electric Power Research Institute under contract RP2426-32. We thank Dr. John Stringer, the EPRI project manager, for discussions and support.

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