What are we going to make magnets from?

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The market for permanent magnets is dominated by ferrites at the low end of the performance spectrum and rare earths at the high end. When the rare earth elements became the poster-children for critical materials in around 2010 [1], concerns grew about supplies of the elements that go into high-strength magnets based on the $Nd_2Fe_{14}B$ formula – in which some of the neodymium can be replaced with praseodymium, dysprosium and/or terbium, depending on the intended applications of the magnets. All of those elements, however, are rare earths and rare earths are mined extracted from ores in which they co-exist, so a shortage of one tends to predict a shortage for others. Much effort has gone into finding replacements for Nd-Fe-B, in response to the rare earth supply-chain uncertainties.

In 2008, 98% of the world's supply of rare earths came from China, and it was reducing its exports. The Chinese government had begun imposing annual export quotas on rare earths in 2005, and it sharply reduced the quota in 2010, as its domestic industries increased their utilisation of these materials. Anxieties rose further in September of 2010, when it was reported that China had cut off all rare earth shipments to Japan in response to a collision between a Japanese Coast Guard vessel and a Chinese fishing boat in waters near a disputed group of islands in the East China Sea, known as Senkaku in Japan, and Diaoyu in China. Concerns about access to rare earths were aroused in governments and industries around the world, and prices spiked sharply in 2011, with neodymium peaking at around ten times its pre-crisis price and dysprosium up by a factor of 25. Prices fell back almost as fast as they had risen, however, and within three years most were within a factor of two to four of their pre-crisis levels, with europium notably falling to only a quarter of its 2008 value.

The price spike or the "rare earth crisis," as it is frequently known, caused some short- and long-term changes in the market. Price increases destroy demand; and while global production of the rare earths had been growing steadily at around 13% per year from 1950 to 2010, it dropped by 17% in 2011.

In Figure 1, we show that the global per capita global consumption of rare earths grew steadily from 1950 until about 1984 as a variety of different applications emerged and grew. On average, every man, woman and child in the world's middle and wealthy classes created a demand for about 14 g of rare earth oxide (REO) in 1965 and this figure grew by about 0.3 g per year until 1984. Over the next two decades, demand grew at a rate exceeding 2 g per consumer per year and this sudden increase in the growth rate coincided with the introduction of $Nd_2Fe_{14}B$: over this period, neodymium magnets found their way into many different aspects of our lives.

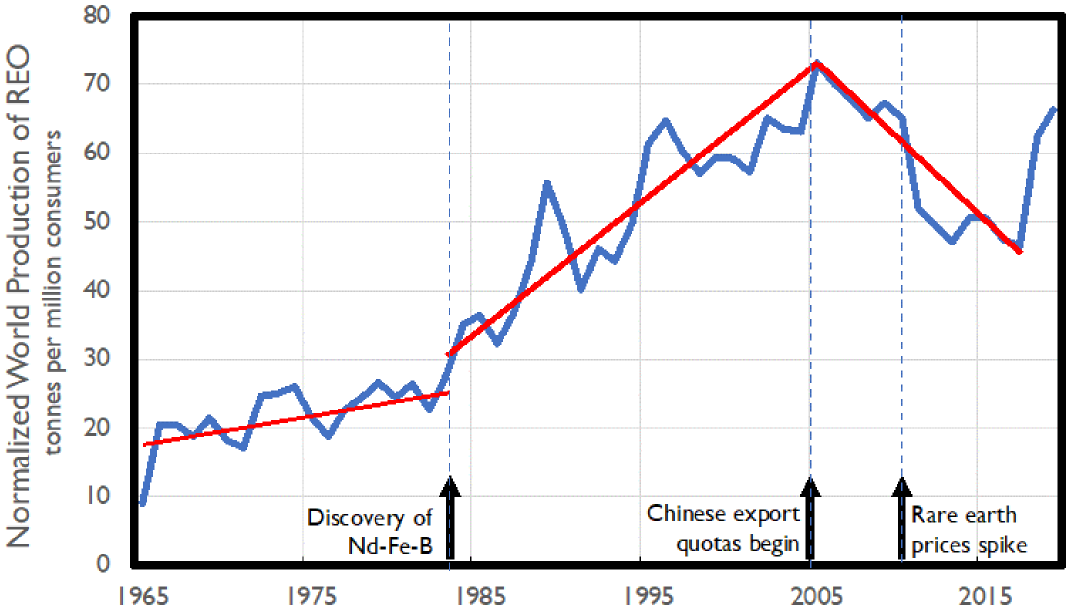

Figure 1: Global production of rare earths normalised by the estimated numbers of consumers, from 1965 to 2017. The production figures are tonnes of total rare earth oxide (REO) taken from the US Geological Survey's annual Mineral Commodity Summaries. The numbers of consumers include all members of the world's wealthy and middle classes (who are considered to have disposable income) taken from World Bank statistics.

The global per capita production of rare earths peaked in 2005 – the year when the Chinese government first imposed export quotas – but total production continued to grow until the price spike occurred in 2010, because the number of consumers was also growing rapidly. By 2014, three years after the price spike, production had fallen to about 47 g of REO per consumer per year. So how did the usage drop?

One answer comes from studies of the feasibility of recycling rare earths from scrapped vehicles. Conventional internal combustion-engined (ICE) cars and light trucks contain several electric motors and actuators to drive their starters, pumps, windshield wipers, air conditioners, fans, windows and rear-view door-mirror adjustments, along with other amenities such as power steering, seat adjusters, and door and trunk openers, depending on the vehicle's level of luxury. A modern passenger vehicle can contain more than 30 electric motors and a dozen loudspeakers. Rare earth permanent magnet (REPM) motors are generally smaller, lighter and more efficient than motors based on other kinds of permanent magnet and these gradually became the preferred components after the introduction of neodymium magnets in 1986.

A 2012 study of pre-crisis vehicles found that a single ICE car or truck might contain up to 1.3 kg of rare earth magnets (containing about 350 g of REEs) in its various electric motors and loudspeakers [2]. A tear-down of light vehicles manufactured after the rare earth crisis showed that the use of these magnets had become restricted to door-mounted loudspeakers where they still provide a necessary size advantage, and the amount of REE per vehicle was then only about 40 g [3]. The shift away from REEs in vehicles' electrical components is a clear example of demand destruction in the wake of a price spike. It caused the motors and actuators to be a little larger, heavier and less efficient than they would have been if they used REE permanent magnets, but the overall impact on vehicle performance was small, and rare earth magnets had been replaced by ferrite in nearly all of the electric motors and actuators in light vehicles.

Magnets represent a small fraction of the cost of a car, but they are a large fraction of the cost of raw materials for individual loudspeakers or small motors and there were large financial incentives for the component manufacturers to replace REPMs when the price spike occurred.

In other areas, particularly for applications that use larger magnets, performance considerations have driven the market in the direction of REPMs. Tesla Motors used induction motors as traction sources to maximise performance measures like acceleration in its early electric vehicle models, but started to use REPM motors to improve efficiency and range with the introduction of its Model 3, in 2017. Wind energy saw a major uptick in the rate of installations in around 2008 but, with Chinese export limits in place, almost all of the turbines that now dot the landscape in Europe and North America use magnet-free induction generators. With the shift to larger off-shore units, starting in the middle of the 2010s, the trend has been toward direct-drive REPM-based generators which offer higher efficiency and lower maintenance requirements because they do not rely on failure-prone gearboxes. The magnets in vehicles and wind turbines have undergone intense development, too: although most of them are still based on variants of $Nd_2Fe_{14}B$, the materials have been improved and the systems have been designed to allow them to be smaller, and operate at lower temperatures, reducing or avoiding the need for dysprosium or terbium, which are especially expensive.

The rare earth crisis clearly impacted the utilisation of rare earth magnets. Where they were once used almost anywhere that a high-performance magnet was an attractive option, they are increasingly reserved for cases where they are a true necessity. Even so, with the rare earth supply crisis seemingly abating, their use is growing once again as new technologies emerge.

The rare earth supply-chain is perhaps a little more robust than it was in 2011 but it still has several vulnerabilities, and if a new crisis emerges we will face a situation in which the easy options for replacing REPMs have already been taken, and the current uses are much harder to work around. Rare earths have grown more critical rather than less, at least in the context of permanent magnets.

So, what options exist for permanent magnets in the coming years?

We should first recognise two trends. Small magnets are getting smaller, and big magnets are getting bigger. The first one is a result of shrinking electronic devices and the second is an outcome of growing wind turbines. The two ends of the size spectrum also represent cases in which the strength of a magnet is an important consideration: higher strength allows for smaller sizes, in both cases.

The magnets that are used in these cases are made from sintered $Nd_2Fe_{14}B$-based materials, and the sintering process creates some significant challenges because it has a size range of its own, that does not encompass the entire size spectrum of magnet usage.

It is not efficient to sinter very small magnets to final size and may not even be possible in some cases. Most of our small magnets are machined from larger sintered blocks and this allows for greater uniformity of the magnet performance, but it comes at a price.

As we cut smaller and smaller magnets we convert a larger fraction of a sintered block into swarf, which can be recycled at some cost. There is also a reduction of the magnetic flux emitted by these magnets because of surface damage caused by the cutting process and/or coating the magnets for oxidation protection. As the magnets are cut smaller, the impact of this flux reduction increases, and the available performance declines.

At all sizes, the optimal magnet shape for any application is frequently approximated using blocks cut from sintered blanks into simple shapes. This results in less-than-optimal performance because of flux loss at the cut surfaces, mass reduction resulting from the need to coat the individual blocks, and flux leakage where blocks do not meet perfectly.

When we make larger magnets, we also run into the limitations of sintering presses. The largest sintered magnets available today are around 2 kg, and where larger magnets are needed they are constructed from individual blocks, often by hand. Larger and larger magnets will have more and more flux losses where the individual blocks meet.

So where are we heading?

Neodymium and ferrite magnets will continue to be important, because they have significant price advantages in their respective performance ranges. However, I believe that new magnet materials will emerge and become the preferred choices for different parts of the magnet size spectrum, particularly for high-performance magnets where neodymium currently dominates. The age of “one material for all applications” is going to pass.

Small Magnets

At the small end of the size spectrum, with dimensions of a millimetre or less, the problems associated with cutting magnets from sintered blocks push up the price per unit of performance and make it hard to optimise magnet shapes to their applications. Maintaining the magnet strength is also a major consideration: we all want miniature devices that deliver big performance.

The tiniest magnets have to be strong, so they must be made from materials with large energy products and/or large coercivities but they may not need to be able to operate at temperatures significantly above ambient, because their small size makes them easy to cool. Most importantly, however, they will need to be compatible with some variant of net-shape manufacturing, allowing them to be formed into complex shapes, without the need to machine them to size. Of these requirements, formability may be the most important: a material that exceeds the performance of the highest grades of Nd-Fe-B will not help if it cannot be made into the right shape and optimally magnetised without machining, but a material that only meets the same magnetic specification will be adopted if it can be directly formed into a preferred shape. There are many methods for net-shape forming, but the ones that work well for sub-millimetre length-scales differ from those that are applicable to larger magnets, and they impact performance in different ways that can either be beneficial or detrimental. The development of new high-strength magnet materials for these applications must consider the processing method as well as the intrinsic and extrinsic magnetic properties.

New materials that meet these needs will enjoy some economic benefits as they seek their niche in the marketplace. The total material demand will be relatively low, which is a two-edged sword: the cost to start up production will be modest because of the small volumes needed, but the total revenue that could be generated is also correspondingly small. The magnets, however, will go into high-priced devices like computers, smart phones and earbuds with large profit-margins so there may be some flexibility on price if the materials enable features that are attractive to their consumers.

Larger Magnets

There are different opportunities at length scales of a centimetre or more. A particular target occurs where we currently assemble individual permanent magnets into arrangements designed to concentrate and localise magnetic fields. This is often achieved with simply-shaped magnets in the form of bricks, cylinders or discs that have been cut from sintered blocks of material. As the magnets get larger, the fractional performance losses caused by cutting and coating are reduced but flux leakage where the magnets meet at an angle tends to increase.

Researchers in the US Department of Energy's Critical Materials Institute, led by the Ames Laboratory at Iowa State University, have shown that ideally-shaped magnets can outperform current magnet assemblages in motors and generators, even when they are made from materials that have smaller energy products [4]. The lower magnetic strength is offset by the ability to form the magnet into its optimal shape in a single piece: better formability beats better magnetic properties when the key metric is device performance. 3D printable magnets are being developed with a variety of different magnetic powder materials, which can include powders sourced from recycled magnets, embedded in polymer matrices [5, 6], and these have the advantage that they can be made as large as necessary for almost any application [7].

Ideally-shaped magnets have some significant economic advantages, too. They contain smaller amounts of the critical rare earth elements than the magnets that they will eventually replace, they do not need to be sintered at high temperatures and pressures, they minimise the need for machining to shape, and they do not have to be coated.

The Role of Magnetic Properties

While formability is emerging as an important consideration in the selection of permanent magnet materials, magnetic strength is still a vital concern.

Figure 2 shows the performance ranges of different classes of magnetic materials available today, in terms of their room-temperature energy products. The strongest magnets belong to the class of sintered Nd-Fe-B, with energy products ranging from about 24 to 55 MGOe for different grades. Much research goes into extending the top of this range or finding new materials with even higher energy products, which are shown here as "unobtainium" because they are not yet available. A variety of candidates show some promise, including iron-nitrogen, samarium-iron-nitrogen and ordered iron-nickel (tetrataenite) alloys, along with various kinds of exchange-coupled nanocomposite "spring magnets," but in all of these cases the biggest challenge is processing the material. If we could only make it, we are pretty sure that it will work. Breakthroughs in this end of the performance spectrum will

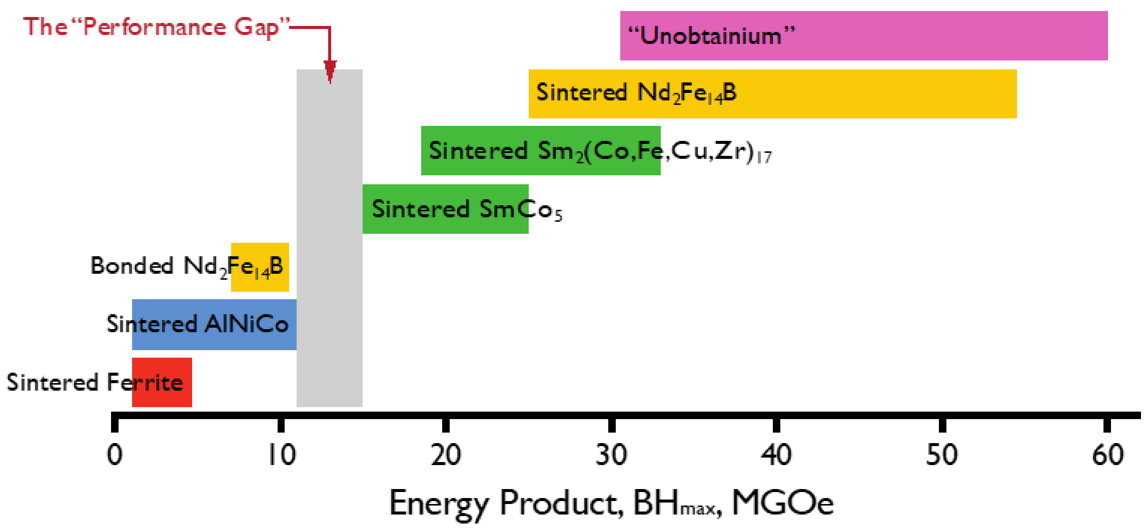

Figure 2: The performance ranges of existing and aspirational magnet materials, in terms of the energy product – which may not be the most important metric for all applications.

doubtless gain attention in the research community, but if they are to be adopted for real applications they must offer a price / performance ratio that compares well with Nd-Fe-B, and they must be easily processed and formed into the required shapes. The highest magnetic strengths are likely to be more important for small magnets than for large magnets and the manufacturing methods for small magnets can differ significantly from the ones that would be needed at larger scales. It is probably more fruitful to concentrate on processing methods that are appropriate to small length-scales for most of the various unobtainium candidates.

The spectrum of magnetic strength reveals a second area of opportunity. No commercially available magnet material has an energy product in the range of about 11 to 15 MGOe. We refer to this region of the spectrum as the "magnetic performance gap." If a design requires a magnet in this range, then a higher strength magnet has to be used and for various reasons, including cost and manufacturability, those tend to be sintered Nd-Fe-B magnets. And if Sm-Co cannot be used because of its higher price and poorer manufacturability, the performance gap extends all the way up to the low end of the Nd-F-B performance range. Gap-range applications are a drain on the supply of the rare earth elements that are needed where higher strength is actually required. New permanent magnet materials that offer energy products between 11 and 24 MGOe will have significant impact on the availability of critical rare earths for higher-strength applications, provided that they are made from readily available ingredients and they have a price-performance ratio that is comparable with that of Nd-Fe-B. They will reduce the overall demand for the rare earths, allowing them to be used where they are absolutely necessary. “Gap magnets” will be particularly attractive if they can be formed into complex final shapes more easily than is possible with sintered Nd-Fe-B. Printable bonded magnet materials show great promise among the various possibilities, because of their formability advantages and adaptability to making large magnets, but they are not the only candidates. The performance of AlNiCo is being extended into the gap range, and additive manufacturing methods are being developed to make net-shape manufacturing possible [8]. Finally, some “failed” attempts to create supermagnets, e.g. [9, 10] may also have second lives as gap magnets if they have other attributes such as formability or highly available ingredients, and researchers should be aware of their potential value.

Summary

- Discovering the next super-magnet material is a worthy scientific pursuit, but there are other opportunities, too.
- High magnetic strength has the greatest value for applications that call for the smallest magnet sizes, so new super-materials must be compatible with net-shape manufacturing processes that are appropriate for those length-scales.
- Mid-strength “gap magnets” have greater potential value than is commonly recognised, as they can reduce the demand for Nd-Fe-B, but they must be cost-competitive with Nd-Fe-B.
- Net-shape manufacturability and magnetic alignment control provide advantages that can offset poorer magnetic performance, at all length scales.

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