Stronger, Lighter, and More Energy Efficient: Challenges of Magnetic Material Development for Vehicle Electrification

Matthew A. Willard, U.S. Naval Research Laboratory, Washington, DC

ABSTRACT

Magnetic materials have a fundamental role in the operation of electric and hybrid electric vehicles. Advances in magnetic materials will enable higher efficiency and greater stored energy for important EV/HEV technologies, including: generators, motors, inverters, and power electronics. This article will describe state-of-the-art magnetic materials for switching (i.e. soft magnetic) and non-switching (i.e. permanent magnetic) applications, their role in EV/HEV applications, and outlook for future performance improvements.

INTRODUCTION

A fundamental transformation of the transportation sector in the United States is underway. In parallel with advances in renewable energy resources for power generation, the rising use of electric and hybrid electric vehicles (EV/HEV) is transforming the future of civilian transportation. Similar efforts are moving forward for 'more-electric' ships, aircraft, and other military technologies. When we think of EV/HEVs we don't typically think of magnetic materials, but we should. Due to their prevalence, magnetic materials play an important role in improving the efficiency and performance of devices in electric power generation, conditioning, and conversion. We have become accustom to many modern vehicle features that would not be possible without advanced magnetic materials. From magnetic sensors used for safety, engines, controls, breaking, and amenities to motors and actuators used for fans, pumps, wipers, and locks, magnetic materials are ubiquitous.

Despite the vast array of vehicle technologies using magnets, the most noteworthy challenges for magnet designers surrounds the unique power systems used to supplement (or replace) the internal combustion engine. Significant challenges exist for magnetic materials especially when used for transportation technologies, where enhanced reliability, power density, and overall energy capacity are increasingly important. Specifically, the challenges of improving the permanent magnet materials for motors and generators and soft magnetic materials for inverters and power electronics require special attention. In addition to performance metrics, the availability of critical materials for permanent magnets is becoming increasingly important. The following sections will address the state-of-the-art magnetic materials, figures of merit for these materials, and where researchers are working to improve their performance.

MAGNETIC MATERIALS IN THE ELECTRIC VEHICLE

Two magnetic parameters are defining characteristics for magnetic performance, the saturation magnetization (or simply magnetization) and the coercivity. The magnetization is the density of magnetic moments within a ferromagnetic material. A material with higher magnetization can produce larger external magnetic fields than a same-sized material with lower magnetization. Alternatively, a material with higher magnetization requires less material to achieve the same magnetic field. Some magnetic materials require a magnetic field to be applied to align the magnetic moments throughout the whole material (we call these soft magnets) and others produce significant magnetic field without an applied field (we call these hard magnets). The defining characteristic between these classes of materials is the coercivity.

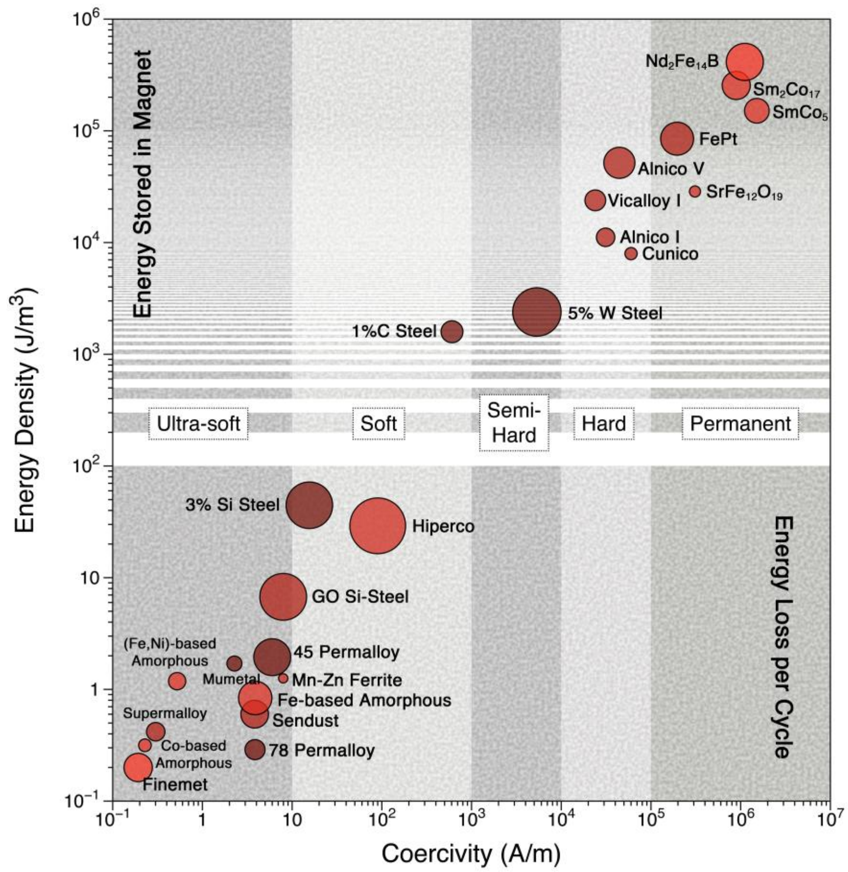

FIGURE 1: Energy density plotted against coercivity for state-of-the-art magnetic materials. The materials in the top part of the figure are used in applications where the magnetization is fixed in the material, resulting in energy storage in the magnet (i.e. permanent magnet). The materials in the bottom part of the figure are used in applications where the magnetization is switched frequently, resulting in an energy loss per cycle (i.e. soft magnets). Desirable characteristics are maximum energy storage or minimum energy loss per cycle. The circle size is proportional to the size of the material's magnetization.

These two varieties of magnetic materials have been refined over the course of the twentieth century to provide optimal performance for: (1) applications where the magnetization is very reluctant to switching when a magnetic field is applied (e.g. hard or permanent magnets) or (2) applications where the magnetization is very easily switched when a magnetic field is applied. Hard magnetic materials possess large coercivities (more than ~10 kA/m), resulting in greater energy storage making them useful for motor and generator applications. Soft magnetic materials are used in applications where switching occurs easily and therefore a low value of coercivity (less than ~400 A/m) is desirable. The coercivities available today span eight orders of magnitude between the softest and hardest magnetic materials (see Figure 1). Progress in the development of magnetic materials has been accomplished with jumps in the performance when new materials are introduced, followed by incremental steps as compositions and processing steps are refined to provide the best microstructures and phase combinations. In the following sections, we will discuss each class of magnetic materials and some of the current technological issues being addressed by researchers.

Permanent Magnets

The modern high performance permanent magnets that are typically used in EV/HEVs are made up of rare earth elements (largely Nd & Dy), the magnetic transition metal element, iron (Fe), and the metalloid element, boron (B). The rare earth elements provide a large magnetocrystalline anisotropy and are responsible for the large energy storage capacity of these alloys and Fe provides a relatively large magnetization. These alloys have been refined over the past 30 years into the premier permanent magnet materials, with the largest energy storage capability (see Figure 1 (top)). However, the growing market and in some cases real scarcity of some rare earth elements has driven recent research efforts to consider alternative materials or ways of reducing the amount of rare earth elements in permanent magnets.

Light rare earth elements (e.g. Nd, Pr, La) are not exactly rare, having natural abundances similar to the industrial metals Cu and Ni. So why are rare earths such a problem? First of all, rare earths are difficult to separate from each other, due to their bonding occurring through the 4-d electrons, which are the same for the whole series of rare earth elements. Secondly, they are also very reactive with oxygen adding to the difficulties in refining them as metals. Additionally, the heavy rare earths (e.g. Dy, Tb, etc.) are essential to extend use to the 200°C required for EV/HEV operation and are scarcer than the light rare earths. Finally, Chinese companies dominate mining for all rare earths and exports are expected to decline in the coming years as these resources are used entirely for Chinese domestic products. For these reasons, alternative, rare earth-free materials have been a recent topic of intense research.

Theoretically, nanocomposite magnetic materials with finely divided regions of soft and hard magnetic phases mixed together can provide improved energy storage while reducing the rare earth content of the alloy. However, simply mixing the typically available powders of hard and soft magnetic materials and pressing them together to full density will not produce the desired improvement. Rather, the powders would necessarily be nanoparticles with sizes no larger than 15 nm in order to achieve the required microstructure and concomitant improvement in energy storage. If a nanocomposite microstructure can be produced, these new permanent magnets could provide energy storage of ~1.1 MJ/m^3 (nearly a factor of 3 larger than available today) and at 10% of the required amount of rare earths! That being said, since the hypothesis of this type of alloy in 1995, it has not yet been demonstrated in the bulk form necessary for motors and generators. Other more radical ideas have proposed complete elimination of rare earths, considering a variety of unusual substitute materials including: manganese aluminide (MnAl), manganese bismuthide (MnBi), iron nitride ($Fe_{16}N_2$), and cobalt carbides (Co_3C/Co_2C) (see Figure 2 for comparison with other materials).

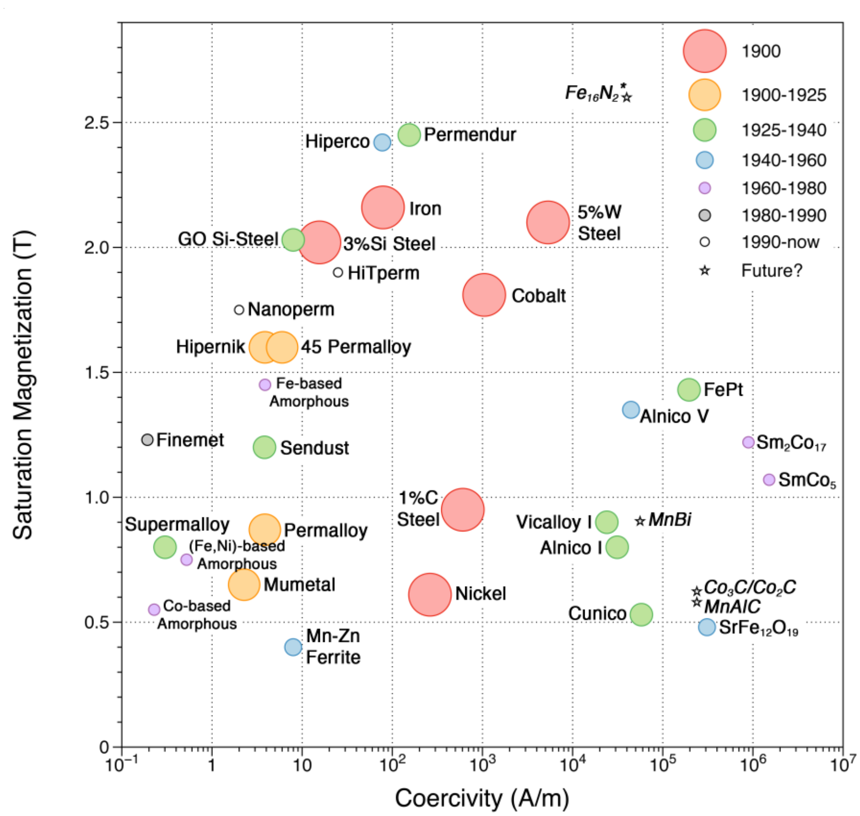

FIGURE 2 Saturation magnetization plotted against coercivity for state-of-the-art magnetic materials. Symbol size and color identify discovery date. Magnetic softness improves to the right and magnetic hardness improves to the left.

Soft Magnets

Soft magnetic alloys do not suffer from the same critical materials problem that plagues rare earth permanent magnets. However, the trend to miniaturization of soft magnetic components while maintaining excellent energy efficiency is important as the electrical generation and conversion technologies require more power demand. Miniaturization of magnetic components can be achieved by increasing the magnetization of the magnetic materials and/or by increasing the operation frequency. Of these, the most significant reduction can be achieved by increase of operation frequency, however the materials lose some energy as heat during each switching cycle (i.e. core losses) resulting in energy inefficiency (see Figure 1 (bottom)). These core losses appreciably increase with increasing operation frequency, so conventional materials do not perform well under these conditions. Amorphous and nanocrystalline alloys possess low coercivity and high electrical resistivity, making them suitable candidates for high frequency use. Higher switching frequencies are of increasing importance for vehicle electrification when power electronics are considered for power conditioning and conversion.

Recent advances in nanocrystalline soft magnetic alloys provide materials that are energy efficient to 100s of kHz, with larger magnetization than comparable amorphous alloys, and have good thermal stability (to 500°C in some cases). However, the mechanical brittleness and difficulties with processing in ambient air have limited the widespread use of these materials.

OUTLOOK AND CHALLENGES

Improvements in soft magnetic properties through continued development in processing-microstructure-property relationships will provide the premiere materials of the future. For nanocrystalline soft magnetic alloys, refinement of compositions to provide improvements to the energy efficiency (i.e. reduction of core losses), mechanical performance (i.e. reduction of brittleness), and air-processability are expected to advance this technology in the next five to ten years. For permanent magnets, near-term improvements in nanostructured composite materials, produced in the bulk with crystallographic texture (i.e. preferred orientation), will show the most near-term technology improvement. With new, rare earth free options being explored extensively, the future of magnetic materials for vehicle electrification can be viewed optimistically. This is especially true with current research interests in low cost $Fe_{16}N_2$ and high anisotropy MnAl compounds. Given a similar, considerable investment, as was made for rare earth permanent magnets over the past 30 years, a rare earth free material capable of operating at temperatures to 200°C is certainly possible in the next ten to fifteen years.

ADDITIONAL READING

E. Alonso, A. M. Sherman, T. J. Wallington, M. P. Everson, F. R. Field, R. Roth, and R. E. Kirchain, “Evaluating rare earth element availability: A case with revolutionary demand from clean technologies”, *Environmental Science and Technology* **46** (2012) pp. 3406-3414.

K. T. Chau and C. C. Chan, “Emerging Energy-Efficient Technologies for Hybrid Electric Vehicles” *Proceedings of the IEEE* **95(4)** (2007) 821-835.

Electrification Roadmap: Revolutionizing Transportation and Achieving Energy Security, Electrification Coalition, November 2009

A. Emadi, Y. J. Lee, and K. Rajashekara, “Power electronics and motor drives in electric, hybrid electric, and plug-in hybrid electric vehicles”, *IEEE Transactions on Industrial Electronics* **55(6)** (2008) 2237-2245.

O. Gutfleisch, M. A. Willard, E. Brück, C. H. Chen, S. G. Sankar, and J. P. Liu, “Magnetic Materials and Devices for the 21st Century: Stronger, Lighter, and More Energy Efficient”, *Advanced Materials* **23** (2011) 821-824.

S. Sugimoto, “Current status and recent topics of rare-earth permanent magnets”, *Journal of Physics D: Applied Physics* **44** (2011) 064001.

M. A. Willard, M. Daniil, and K. E. Knipling, “Nanocrystalline Soft Magnetic Materials at High Temperatures: A Perspective”, *Scripta Materialia*, 2012, in press (doi:10.1016/j.scriptamat.2011.12.043).

M. A. Willard and M. Daniil, “Nanocrystalline Soft Magnetic Alloys: Two Decades of Progress”, *Handbook of Magnetic Materials*, 2012, submitted.