Prospects for permanent magnets with non-critical rare earth elements in traction drive motors

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It has been over a decade since the first crisis in the rare earth elements (REEs) supply chain [1]. While significant investments in exploring and developing new sources for REEs, alternatives to REE-based permanent magnets (PM), and new processing methods to reduce the more critical heavy REEs, much still needs to be done. Concern for climate change has accelerated regulations on internal combustion engines (ICE) and even planning outright bans of ICEs in many localities. Nd-Fe-B based PMs still provide the highest energy density in the temperature range (< 150°C) for most consumer and industrial applications. While current proven reserves for light REEs are sufficient in the near-term outlook for PM applications [2, 3], the supply chain for manufactures outside of China remains vulnerable. The heavy REE (Dy, Tb, Ho) needed for improved high temperature PM operations are scarce and getting scarcer [4] resulting in more uncertainty in price and availability. While there are many alternatives to the current Nd-Fe-B based PM alloys and some of these compounds can be utilized in PM-type traction motors, there is a penalty to the overall system performance. Substituting with these lower energy density alternative PMs will result in higher fossil fuel consumption in hybrid vehicles and lower driving range in all-electric vehicles for the same vehicle size. For all electric vehicles (AEV), loss in PM performance will require additional battery capacity. A 5% increase in battery capacity will cost nearly US$300, which is almost double the cost of the materials that goes into PM motors. Switching to lower performing PMs or to induction motors will greatly increase AEV [5]. This also means that the demand for the critical materials such as graphite, Li, Ni, Mn, Co will increase more rapidly.

The solutions are 1) develop a new PM without critical elements with performance matching Nd-Fe-B based PM, 2) develop new motor topologies that utilized characteristics of current non-critical PMs more efficiently, and/or 3) find ways to maintain the operating temperature performance of the Nd-Fe-B based PM without critical elements. The first scenario is unlikely in the near term because many significant large-scale research efforts, conducted since 2012, have yet to discover such new, powerful PM materials. While there have been some intriguing PM discoveries, many of these materials are far from commercial applications or even full lab demonstrations. There has also been considerable effort in new topologies for PM based motors that have been promising [6]. In fact, better integration between PM materials research and motor design is needed to foster advances in both arenas.

Most of the success has been in more efficient use of heavy REE, such as diffusing Dy only into the near surfaces of the Nd-Fe-B PMs that experiences the highest demagnetization fields [7]. Another promising route is to reduce the grain size (< 5 µm) of the Nd-Fe-B PMs to produce higher coercivity (H_{ci}) and operating temperature without heavy REE additions [8, 9]. The smaller grains are more resistant to field reversals and having more grains in a given volume hardens the overall magnet. However, reducing the grain size doesn't improve the slope of the temperature dependence of the coercivity, it simply shifts up the whole H_{ci} (T) curve. Our initial investigations on grain size effects on the properties of heavy REE free sintered PMs has shown that even modest reductions in the grain size can result in significant improvements in H_{ci} (Figure 1). However, this work has revealed that the mode of milling, their energy inputs and mechanism for commutating particles affects particle shape and size distribution. Also critical is powder handling since particle surfaces make up a much higher fraction of the volume. Special care in handling the powders is required to keep the uncontrolled surface oxidation at a minimum.

To address this, Ames Laboratory has developed a Controlled Atmosphere Materials Processing System (CAMPS). CAMPS provides a solution for synthesis of high quality magnets in an environment that limits potential for oxidation and moisture contamination. It enables multiple complex materials synthesis operations to be performed in inert atmosphere. Within the same inert atmosphere, materials can be milled, magnetized, compacted and heat-treated. An optical microscope in the CAMPS allows for the imaging of particles during processing. One of the key enabling features of CAMPS is that the tools for the operations are in inert chambers while most of the control of the operations are performed outside of the chamber.

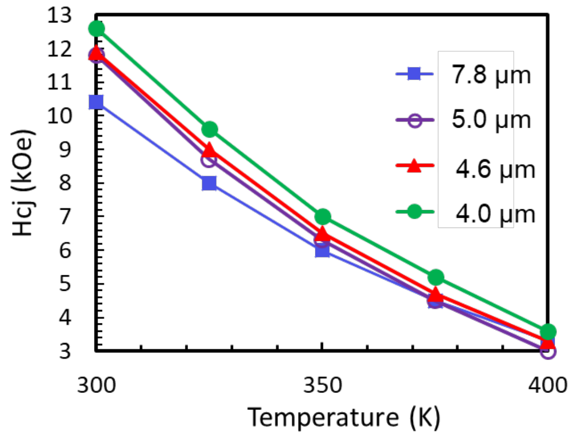

Figure 1. Effect of average grain size on the temperature dependence of the corecivity. The energy product also increased from 34.8 to 43.6 MGOe at room temperature with decreasing grain size.

The other challenge is to limit the grain growth during sintering of the superfine feedstock powder. We are investigating lower sintering temperatures, using excess REE as well as other external transient liquid phase to further reduce sintering temperature while achieving full magnet densification. Adding a grain boundary pinner may also be necessary to prevent grain growth. The extra effort in grain size reduction will be for naught if a fully dense; oxide free part that maintains the small grain size cannot be fabricated.

Non-rare earth magnets can be used for EV traction motor if the strict requirement of high power density and low cost can be met. One approach to mitigate the impact of weaker magnet on the motor density is to increase motor excitation frequency. However, this also creates other challenges. For example, at higher frequency, the hoop stress will be higher and eddy losses will be much higher in both soft and hard magnetic materials. We will present results on a recently completed project demonstrating that a 10 KW motor with power density of 1.2 KW/kg and 4.3 KW/L using MnBi PM. The motor run at 400 Hz. Its stator is made of 6.5%Si steel, which has 50% higher electrical resistivity comparing the common 3.2%Si steel. The motor maintained 90% efficiency when running at full power.

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