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Permanent Magnets Beyond Nd-Dy-Fe-B

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Permanent magnets are one of the key parts in energy conversion devices to realize the utmost efficiency. DC motors up to the 100-kW class are used in some "strong" hybrid electric vehicles (HEV), in which the top-grade Nd-Dy-Fe-B-type permanent magnets are required. Such motors have inner permanent magnet (IPM) rotors with which the combination of magnet torque and reluctance torque is optimized. For such an optimized design, permanent magnets are shaped in thin plate-like blocks with a thickness of about 5 mm, inserted into slots in a laminated rotor core, and magnetized perpendicularly to the largest surfaces of the block. The weight of the magnets may amount to about 2 kg or less per vehicle. The reason why Nd-Dy-Fe-B permanent magnets are used is simply because the highest performance of this class of material in terms of residual flux density, B_r, can be generated with them. These magnets have high intrinsic coercivity, H_{cJ}, typically about 2.0–2.4 MA/m. Such high H_{cJ} values are certainly not necessary at room temperature, but the magnet temperature can rise to about 200°C at which H_{cJ} is only about 0.6–0.8 MA/m, being marginally enough to withstand the armature magnetic fields generated by driving current. Dysprosium (Dy) or terbium (Tb) is used in the magnet in order just to obtain such high H_{cJ} but have been indispensable in the permanent magnets. Since Dy and Tb can be mined industrially only in a southern province of China in a limited quantity, Dy and Tb are now typical critical elements, overreliance on these elements should be avoided. For this very reason, permanent magnets beyond Nd-Dy-Fe-B are now extensively sought.

Development of permanent magnets beyond the Nd-Dy-Fe-B is a challenge because $Nd_2Fe_{14}B$, the main hard magnetic phase of the magnet, is the compound that has the largest magnetization at room temperature among all existing hard magnetic compounds, and that, in terms of elemental abundance, already consists mainly of Fe and Nd, both of which are the most abundant elements carrying magnetic moments in the 3d and 4f transition metal series, respectively. One of the approaches is to reduce the overall average Dy content over the entire commercial grades down to a sustainable level, which may be about 1–1.5 mass percent in the magnets, even if the crustal abundance ratio with Nd is considered. Another approach is to seek for an entirely new material with or without rare earth elements.

In advanced economic blocks that have benefitted from functional critical elements, governments have taken strategic actions to promote developments in technologies that will lead to reduced society's dependence upon those elements. In Japan, well ahead of the crisis of rare earth supply and a sudden surge of prices of rare earth elements that took place in 2011, there were government-funded projects in the development of high-performance permanent magnets free from critical elements. In Europe, the United States, and Korea, similar projects have been called for. As a result, academic activities in the field of hard magnetic materials and magnetism have been reactivated after a long, gray period between ca. 2000 and ca. 2010. The Japanese projects on permanent magnets include the Elements Strategy Initiative by MEXT which is now in the second stage of a research center formation started in 2012 after the first stage of academy-industry cooperative stage in 2007–2011 fiscal years. These projects have been carried out in parallel with consortiums organized by NEDO under METI sponsorship in Japan. Moreover, there are two projects on permanent magnets in CREST and Collaborative Research Based on Industrial Demand, programs funded by the Japan Science and Technology Agency (JST). In the United States, projects on permanent magnets include ARPA-E REACT, which stands for "Rare Earth Alternatives in Critical Technologies", including a project on permanent magnets free from critical elements starting from 2012, while the Critical Materials

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Institute (CMI) also includes activities on permanent magnets. In Europe, ROMEO (Replacement and Original Magnet Engineering Options) was organized and started its activity in December, 2012, focusing on the dramatic reduction of critical elements in high-performance permanent magnets. Besides these, G8 Research Council is supporting a Europe–Japan–USA consortium, "High Performance Permanent Magnets sustainable for Next Generation" on rare earth-free permanent magnets on Mn-based alloy systems since 2012. There are other projects in Europe, REFREEPERMAG (Rare-Earth Free Permanent Magnets) and NANOPYME (nanocrystalline permanent magnets based on hybrid metal-ferrites), both of which also started in 2012, as far as I am aware.

The blossom of funded projects has naturally produced new results and understandings. It seems, therefore, to be the right time to collect some information about recent progress in these projects. In addition, outside of such projects, there are stimulated individual researchers who have produced very interesting results. Not to collect exhaustively but to obtain a perspective of activities with totally different characteristics and approaches, I have contacted only a few people and tried to collect manuscripts from the activities in which they are involved.

The overview paper by P. McGuiness et al. on the ROMEO project depicts the current achievements as of a middle point of the project. The overview paper by D. Niarchos et al. on REFREEMAG, describes different approaches of another large EU project. Besides these overviews on two EU projects, the readers will find reviews on specific subjects. The first one is on the mechano-chemical synthesis of hard magnetic nanoparticles by A.M. Gabay and G.C. Hadjipanayis. The particles are building blocks of composite permanent magnets and have recently been intensively studied by many groups. Synthesis of hard magnetic nanoparticles is still a challenging subject. The article by D. Goll illustrates an innovative, efficient, experimental approach to search for new thermodynamically stable multi-component compounds or alloys suitable for further investigations. The overview on $NdFe_{12}N$ compound by Y. Hirayama et al. provides an update of this newly synthesized material which is reported to have outstanding magnetic properties, surpassing those of $Nd_2Fe_{14}B$ in terms of saturation magnetization, magnetocrystalline anisotropy, and Curie temperature. The article by S. Baunce et al. is on a micromagnetic approach to calculate activation energy in the thermal activation phenomena involved in the magnetization reversal in permanent magnets, which is always the central issue in hard magnetism at elevated temperatures.

These are only a small portion of recent vast investigations in the field of permanent magnetism and hard magnetic materials. I hope that the papers collected in this topic will help readers grasp some aspects of the current situation.

The following papers being published under the topic of Permanent Magnets Beyond Nd-Dy-Fe-B provide excellent details and research on the subject. To download any of the papers, follow the url http://link.springer.com/journal/11837/67/6/page/1 to the table of contents page for the June 2015 issue (vol. 67, no. 6).

- "Replacement and Original Magnet Engineering Options (ROMEO): A European 7th Framework Project to Develop Advanced Permanent Magnets without, or with Reduced Use of, Critical Raw Materials" P. McGuiness, O. Akdogan, A. Asali. S. Bance. F. Bittner, J.M.D. Coey, N.M. Dempsey, J. Fidler, D. Givord, O. Gutfleisch, M. Katter.D. Le Roy, S. Sanvito, T. Schrefl, L. Schultz, C. Schwöbl, M Soderžnik, S. Šturm, P. Tozman, K. Üstüner, M. Venkatesan. T.G. Woodcock, K. Žagar, and S. Kobe
- "Towards Rare Earth Free Permanent Magnets: A Combinatorial Approach Exploiting the Possibilities of Modelling, Shape Anisotropy in Elongated Nanoparticles and Combinatorial Thin-Film Approach" D. Niarchos, G. Giannopoulos, M. Gjoka, C. Sarafidis, V. Psycharis, J. Rusz, A. Edström, O. Eriksson, Peter Toson, Josef Fidler, E. Anagnostopoulou, U. Sanyal, F. Ott, L.-M. Lacroix, G. Viau, Cristina Bran, Manuel Vazquez, L. Reichel, L. Schultz, and S. Fähler
- "Application of Mechanochemical Synthesis to Manufacturing of Permanent Magnets" A.M. Gabay and G.C. Hadjipanayis
- "Novel Permanent Magnets by High-Throughput Experiments" Dagmar Goll, Ralf Loeffler, Johannes Herbst, Roman Karimi, Ulrich Pflanz, Roland Stein, and Gerhard Schneider
- "Rare Earth Lean Hard Magnet Compound $NdFe_{12}N$" Yusuke Hirayama, Takashi Miyake, and Kazuhiro Hono
- "Thermal Activation in Permanent Magnets" S. Bance, J. Fischbachger, A. Kovacs, H. Oezelt, F. Reichel, and T. Schrefl