A Demystification of HREE-Free NdFeB Magnets

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Since the announcement of the 2025 Chinese export restrictions on Heavy Rare Earth Elements (HREEs), HREE-free Neodymium-Iron-Boron (NdFeB) magnet materials have become a focal point of interest. The potential supply disruption due to these export controls has generated much interest in HREE-free magnet grades. This article will explain how alloy composition impacts the performance of NdFeB permanent magnets, how the manufacturing of these magnets has evolved over time, and which grades can be produced without HREEs.

Background

Neodymium-Iron-Boron (NdFeB) permanent magnets are the highest strength magnets commercially available. The NdFeB material was discovered in mid 1980s, and has undergone numerous compositional, microstructural, and process improvements since then.

Fundamentally, NdFeB magnets are composed of approximately 30 wt% of Nd, 1 wt.% of B and the balance wt% of Fe. This composition is optimized by the addition of small amounts of other metals, including other Rare Earth elements (REEs), which modify the microstructure or intrinsic properties, for higher magnetic performance.

NdFeB permanent magnets have facilitated the development of advanced technologies across many industries, having a profound effect on the performance of complex engineered

Figure 1. Typical forms of NdFeB magnets

systems, such as high torque density electric motors and highly efficient power generators. Demand for these high energy magnets has continued to grow and is now expanding the capabilities of the green energy transition, electric mobility, medical technology, defense and aerospace, electronics and computing, industrial automation, and robotics.

Rare Earth Elements (REEs)

On the Periodic Table of elements, the Rare Earths are a group of elements that exhibit special electronic, magnetic, catalytic, and optical properties. As illustrated in Fig. 2, the REEs are commonly categorized into two groups:

- Light REEs (LREEs): the lanthanide elements with atomic numbers 57 to 64;
- Heavy REEs (HREEs): the lanthanide elements with atomic numbers 65 to 71, plus Y;
    - (Y is not a lanthanoid but exhibits certain properties similar to other HREEs and is generally found in ores with them)
- Sc has been historically classified as an REE and is not categorized in either of the LREE or HREE groups.

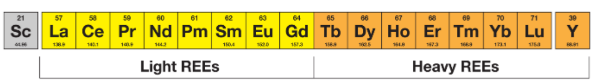

Figure 2. The Lanthanide series of elements from the Periodic Table [1]

The Role of HREEs in NdFeB Magnet Grades

NdFeB magnets are produced with two principal phases: the $Nd_2Fe_{14}B$ matrix phase and a Nd-rich grain boundary phase. The matrix phase represents over 90% of the magnet and provides the hard magnetic characteristics. The grain boundary phase is strongly linked to the coercivity of the magnet (resistance to demagnetization) and typically represents 6-8 volume percent of the bulk magnet. However, as noted before, alloy additions and RE-substitutions are common and help control the magnetic properties and thermal stability. Thus, Nd can be substituted by other LREEs such as Pr, Ce, Gd, or by HREEs such as Dy and Tb.

Compositions containing Nd and Pr provide the highest saturation magnetization among the REEs and give the NdFeB magnets their exceptional energy density and $(BH)_{max}$, at and around room temperature.

Dy and Tb provide higher magnetocrystalline anisotropy within the magnet, which is the primary source of intrinsic coercivity, H_{ci} – a measure of the resistance to demagnetizing fields [2]. These HREE were originally added to the composition to increase the thermal stability and enable use at higher temperatures (up to 220-240°C).

Historically, NdFeB magnets have been marketed in well-defined grades based on their magnetic performance [3] determined mostly by these substitutions and additions. The same grade produced by different manufacturers will have similar magnetic property ranges for specific maximum operating temperatures.

HREE-Free and HREE-Less NdFeB Magnets

The HREEs are less abundant and more costly than LREEs. Currently, most HREEs are produced in Myanmar and are subject to serious geopolitical risks, supply chain disruptions, and price volatility. Also, the extraction and purification of these HREEs tend to take a higher toll on the environment [4]. An estimated 99% of global Dy and Tb supply is refined in China.

Another challenge that comes with the use of HREEs in direct substitution for Nd or Pr is that they exhibit an antiferromagnetic coupling with the Fe atoms in the $Nd_2Fe_{14}B$ lattice. This means that the magnetic remanence, B_r, of the magnet will be compromised by using HREEs to improve thermal stability. Therefore, it has been a long-term goal of the industry to reduce the dependance of NdFeB magnets on HREE components and look for alternatives for high coercivity and thermal stability.

One of the most successful technologies that has minimized the need for HREEs in recent years has been the **Grain Boundary Diffusion** (GBD) process [5]. This process effectively concentrates the HREEs at the grain boundaries of magnets rather than alloying them throughout the whole microstructure. This means that modern UH and EH grade NdFeB magnets will now have less than 2 wt.% Dy or Tb content, compared to greater than 10 wt.% with the conventional alloying manufacturing process used in the past. Fig. 3 illustrates the GBD process of modifying the grain boundaries of NdFeB magnets, selectively distributing the HREEs at the grain boundaries [6].

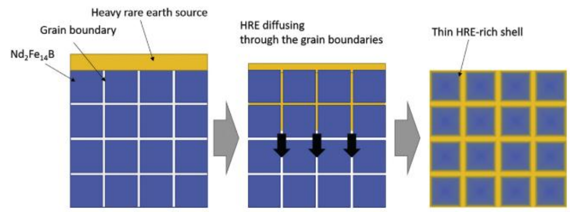

Figure 3. Grain Boundary Diffusion (GBD) process [6]

Other process modifications have happened in parallel with GBD-type developments: finer grain structures and lower oxygen levels both enable NdFeB magnets to achieve higher magnetic performance [7, 8].

Figure 4 illustrates the status of HREE and HREE-free sintered NdFeB magnet grades that are achievable nowadays. For specific material properties, please reach out to Permag's technical team for in-depth information.

HREE - free Process | Traditional Process (contains HREE) | GBD Process (HREE-less, limited dimensions)

Grade	Intrinsic Coercivity H_{ci} (kA/m)	(kOe)	28	30	33	35	38	40	42	45	48	50	52	54	56	Max Op Temp (°C) (PC=2 or L/D=0.66)
AH	2628/2787	33/35	N28AH	N30AH	N33AH	N35AH	N38AH	N40AH	N42AH	N45AH						220
EH	2388	30	N28EH	N30EH	N33EH	N35EH	N38EH	N40EH	N42EH	N45EH	N48EH	N50EH				200
UH	1990	25	N28UH	N30UH	N33UH	N35UH	N38UH	N40UH	N42UH	N45UH	N48UH	N50UH	N52UH	N54UH		180
SH	1592	20	N28SH	N30SH	N33SH	N35SH	N38SH	N40SH	N42SH	N45SH	N48SH	N50SH	N52SH	N54SH	N56SH	150
H	1353	17		N30H	N33H	N35H	N38H	N40H	N42H	N45H	N48H	N50H	N52H	N54H	N56H	120
M	1114	14			N33M	N35M	N38M	N40M	N42M	N45M	N48M	N50M	N52M	N54M		100
N	955	12				N35	N38	N40	N42	N45	N48	N50	N52	N54	N56	80
			28	30	33	35	38	40	42	45	48	50	52	54	56	(MGOe)
			223	239	263	279	302	318	334	358	382	398	414	430	446	(kJ/m^3)

Maximum Engergy Product, $(BH)_{max}$

Figure 4. Sintered NdFeB magnet material grades

Composition

Historically, there have been significant variations in the composition and microstructure of each NdFeB magnet grade. For example, an N42SH grade in the 1990s would have had between 3 and 5 wt.% Dy. Now, in 2025, with improvements in the microstructure and manufacturing process, the N42SH grade may contain no HREEs.

ASTM standard A1101-23 [3] calls for specifying NdFeB magnets primarily by magnetic performance. Alloy compositions should only be specified when magnetic and physical characteristics are insufficient to meet user requirements. It is notable that the specific elements in the chemical composition are usually given a permissible range; from one supplier to another, or even from one batch to the next with the same supplier, the composition of a given grade in the magnet industry is likely to have differences. There is no "gold standard" to define the exact chemical composition for each NdFeB grade. Instead, ASTM A1101-23 presents a rather wide compositional range (Table I).

Table I. NdFeB Magnet Material Typical Composition Range ([3], adapted)

Element	Weight %	Comments
Total Rare Earth Content (TRE)	29 - 33	Required for magnetic phase formation, liquid phase sintering and coercivity mechanism
Nd	22 - 29	Required for magnetic phase formation, liquid phase sintering and coercivity mechanism
Pr	0 - 8	Can substitute for Nd to form the magnetic phase, promote liquid phase sintering and coercivity mechanism
Dy and /or Tb	0 - 10	Dysprosium (or terbium, or both) is substituted for neodymium to increase intrinsic coercivity (resistance to demagnetization) and allows NdFeB magnets to be used at higher temperature.
Ce and/or La	0 - 15	Low cost, more abundant rare earth element substitute for Nd in cost-sensitive application Harmful for magnetic properties and thermal stability
Fe	Balance	Fe content is usually expressed as the "balance" of the composition after all other content i added up and it is generally in the range of 61 to 67 weight percent. It is required to form the magnetic phase Nd2Fe14B
Co	0 - 5	Substituting Fe with Co raises the Curie temperature. Other advantages of cobalt include reducing the reversible temperature coefficient of induction and the grain boundary phase melting temperature.
B	0.9 - 1.1	Boron is the key to obtaining the Nd2Fe14B tetragonal crystal structure of Neo magnets. The boron level is controlled within narrow limits for sintered magnets.
Al	< 0.5	Grain boundary modifier
Cu	< 0.5	Grain boundary modifier
Ga	< 0.5	Grain boundary modifier
Sm, Gd, Ca, Mg, Si, Mn, Zr, Cr	<0.1	Other minor/contaminant elements to be controlled

For general users, the goal of pursuing a fixed chemical composition is neither practical nor enforceable. Such practice also runs the risk of falling behind technological and manufacturing development curves or even rendering the specified magnet material unavailable as time goes by.

HREE-Free Material Physical Properties

Compared to the conventionally processed NdFeB material, the HREE-free magnets exhibit no difference in mechanical properties, corrosion resistance, and coating/plating adhesion. However, subtle differences exist in the reversible temperature coefficients (RTC) of remanence (α) and intrinsic coercivity (β). Test data indicates that the absolute difference in RTC (α) and RTC (β) between HREE-free and conventionally processed (with Dy) materials is around 0.01%, as illustrated in Table II.

Table II. Comparison of Magnetic Properties between HREE and HREE-Free Grades N42SH and N48H

Grades	20℃				120℃				RTC of Br, α	RTC of Hci, β
	Br (kG)	Hc (kOe)	Hci (kOe)	BHmax (MGOe)	Br (kG)	Hc (kOe)	Hci (kOe)	BHmax (MGOe)	(%/℃)	(%/℃)
N42SH (HREE-free)	13.02	12.52	20.10	40.7	11.45	8.25	8.36	30.8	-0.121	-0.585
N42SH (Dy)	13.27	12.75	20.22	42.2	11.78	8.32	8.65	32.5	-0.112	-0.572
N48H (HREE-free)	13.90	13.25	17.43	46.1	12.30	6.97	7.11	35.2	-0.115	-0.592
N48H (Dy)	13.87	13.26	17.65	46.0	12.40	7.35	7.45	35.8	-0.106	-0.578

In practice, the difference in RTCs means there will be a very small reduction in the maximum operating temperature of the magnet. It should be advised, however, that the generally marketed "Maximum Operating Temperature" of a NdFeB grade is dependent on the permeance coefficient (PC) – relevant to the magnet geometry and the magnetic circuit condition – of the magnet, and therefore manageable through design. Most of the magnet applications are not sensitive to this 0.01% difference in RTC, but in special cases, when needed, the magnet users can also overcome this factor by adding cooling features to their system.

Dy / Tb Content Found in N, M, H, SH Grades

As previously pointed out, the array of N, M, H grades and several of the SH grades can be made using the HREE-free process. Yet the alloy composition reported by the magnet suppliers can at times be found to include HREEs. The reason can be attributed to the rare-earth magnet recycling programs across countries and regions [9]. In a typical NdFeB supplier factory setup in China, as much as 10% of feedstock comes from recycled feedstock. The recycled feedstock brings HREEs (mostly Dy) along to the new NdFeB magnet batches, mostly for the low to middle H_{ci} grades. On the other hand, a primary material batch (with no recycled feedstock) of low to middle H_{ci} grade material would not contain Dy. These variations in composition, between batches, have always existed and have no impact on the performance of the magnet in question, as the magnet manufacturers design the mix to ensure the magnetic specifications of the grade are met.

How Permag can help

Whether your focus is magnet material selection, manufacturing process control, magnetic design optimization, or magnetic performance inspection, Permag is here to support you at every step in the process with its industry leading engineering team. HREE-free NdFeB magnet material has been in existence for over a decade; in the backdrop of recent REE export controls by China, Permag can help you identify export-ready NdFeB material to reduce lead times and safeguard your intellectual property.

As the only domestic SmCo magnet producer in the USA, and localized supply-chain, Permag is also your reliable source for DFARS-compliant Rare-Earth permanent magnets.

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