$Fe_{16}N_2$: Hype, hope, or heavy hitter? A critical review

Imants Dirba, TU Darmstadt, & John Ormerod, JOC LLC

Introduction

The increasing emphasis on green energy technologies such as wind turbines and electric vehicles require a sustainable, resource- and cost-efficient supply of high-performance permanent magnets. NdFeB magnets possess the highest energy product BH_{max} at room temperature, making them the preferred material for various applications essential to the clean energy transition. These magnets are widely used in hard disk drives, microphones, speakers, sensors, permanent magnet motors, and electric generators. Future demand is expected to rise sharply, particularly in the fields of mobility and sustainable energy technologies, as well as in automation-related electronics.

Reliance on, and supply of, rare earth (RE) elements raise environmental, economic and geopolitical concerns. Recent history from the Chinese restrictions on RE exports around 2012 through to US tariffs in 2025 causing China to respond with export controls on key RE has demonstrated the fragility of the RE magnet supply chain due to total reliance on a single supplier. In this light, the search for permanent magnet materials with competitive performance containing no RE elements is perfectly reasonable and necessary.

The iron nitride α''-$Fe_{16}N_2$ phase has been suggested as a possible RE-free permanent magnet candidate. Considering the recent interest in this material triggered by large-scale investments and public forward-looking statements regarding its possible alternative to NdFeB magnets, we thought it necessary to communicate a neutral overview and data-based analysis of the current situation and future potential of α''-$Fe_{16}N_2$.

In this article we therefore aim to provide a concise review on the most important characteristics of the α''-$Fe_{16}N_2$ material, describing the potential benefits as well as shortcomings, examining the best to-date reported performance, and assessing the potential for future development into a RE-free permanent magnet.

The iron nitride α''-$Fe_{16}N_2$ phase

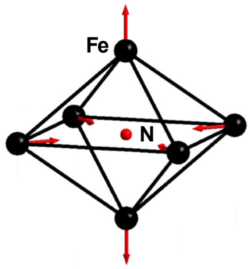

Figure 1:Fe lattice distortion due to an interstitial N atom

Extensive studies on iron-nitrogen system have been done in mid-20th century with the Fe-N phase diagram summarised by Jack[1]. The various iron nitrides, Fe_8N, Fe_4N and Fe_3N are interstitial alloys of nitrogen atoms distributed in an ordered or disordered manner in polymorphs of iron (bcc α-Fe, fcc γ-Fe and hcp ε-Fe respectively). The nitrogen atoms are incorporated in the empty voids between the host metal Fe atoms. Depending on the size of the interstitial atom and the corresponding geometry, this leads to a distortion of the parent phase lattice. This is shown in Figure 1 where the N atom in bcc Fe is pushing the Fe atoms above and below axially apart, which leads to a local

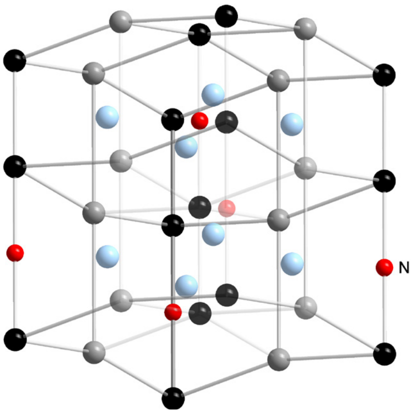

Figure 2: Unit cell of α''-$Fe_{16}N_2$ consists of 2x2x2 units of α'-Fe_8N.

lattice expansion along z direction and a small contraction within the x y plane resulting in a local tetragonal distortion. The crystal symmetry then is being altered from α-Fe body-centred cubic (bcc) to body-centred tetragonal (bct). This is the so-called primary martensite or α′-Fe_8N_x which can be defined as an interstitial solution of atomic nitrogen in α-Fe, where N atoms occupy with respect to the principal crystal axis similar octahedral sites in a random manner. It has a solubility region of roughly 0-11 at.% N, the lattice parameters vary linearly with the N atom concentration and a c/a ratio of about 1.1 is reached at 11 at.% N corresponding to Fe_8N_1 composition. Importantly, absorption of nitrogen atoms in the iron host lattice has profound impact on magnetic properties as well as phase stability. For example, the fcc γ-Fe and hcp ε-Fe are not stable at ambient conditions whereas their respective nitrides are. Furthermore, the fcc γ-Fe is nonmagnetic while γ′-Fe_4N is ferromagnet with high magnetisation and Curie temperature[2].

The secondary martensite or α"-$Fe_{16}N_2$ which is the focus of this article was first described by Jack in 1951[3]. It is a superstructure of the original α′-Fe_8N_x martensite with Fe_8N_1 chemical composition as shown in Figure 2. The $Fe_{16}N_2$ unit cell consists of 2x2x2 unit cells of Fe_8N_1, has a body-centred-tetragonal crystal structure as such having twice the lattice parameters, a = b = 5.72 Å, c = 6.29 Å and the c/a = 1.1. The nitrogen atoms occupy octahedral interstitial sites in a completely ordered manner.

This leads to the first important conclusion regarding the potential hard magnetic properties of the α"-$Fe_{16}N_2$. **It is slightly strained soft magnetic iron where the tetragonal lattice distortion is stabilised by the nitrogen atoms.** Therefore, it can be expected that the resultant magnetic properties will resemble those of bcc iron with additional hardening effect resulting from the induced tetragonality. As will be seen in the next sections, this largely happens to be the case.

‘Extraordinary’ magnetic properties?

Saturation magnetisation

After two decades of silence, the story of fame for the α"-$Fe_{16}N_2$ started in 1972 when Kim and Takahashi investigated Fe thin films with added nitrogen gas during deposition and reported “a new magnetic material which has the highest saturation magnetisation at room temperature among all the magnetic materials”[4]. An ultrahigh magnetic moment up to 3.0 μB per Fe atom was attributed to formation of $Fe_{16}N_2$ which would be even higher than $Fe_{65}Co_{35}$ - the highest magnetisation material at room temperature among all the magnetic materials known so far. However, ever since there have been many discussions and controversy concerning reproducibility and magnetic properties of a $Fe_{16}N_2$ resulting in phrases like "the magnetism of $Fe_{16}N_2$ has been a mystery for 40 years"[5] and *Magic moments in magnetism* by J. M. D. Coey[6] in the scientific literature.

In principle, the enhancement in magnetic moment is consistent with the magnetovolume effect resulting from the iron lattice expansion as discussed above and later works have shown that indeed the average iron moment does not exceed 2.6 μB from both experimental and theoretical point of view[7, 8], which results in a moderate increase in saturation magnetisation M_s due to the accompanied unit cell volume expansion (magnetisation is the magnetic moment per unit volume).

Coercivity

However, for the purpose of this article, the discussion regarding enhanced or not magnetic moment is misleading and frankly speaking completely irrelevant. Even if the magnetisation remains unchanged and equal to that of the parent bcc α-Fe with 2.15 T it would significantly exceed 1.61 T of $Nd_2Fe_{14}B$ (magnetic properties of several relevant materials are compared in Table 1). And this is where the first misunderstanding regarding $Fe_{16}N_2$ comes from. Statements like, “rare-earth-free iron nitride magnet with performance and thermal stability that rivals or exceeds today’s leading neodymium-based magnets”, can be found in media communications. This is based on a maximum energy product $BH_{max} = \frac{\mu_0 M_s^2}{4}$ estimation, where M_s is saturation magnetisation and μ_0 vacuum permeability.

As illustrated in Table 1, **using this metric (which obviously considers only the saturation magnetisation M_s) any soft magnetic material with high magnetisation such as a simple iron will ‘rival or exceed today’s leading neodymium-based magnets’**. Which obviously doesn’t make sense because a useful permanent magnet needs high coercivity to be able to withstand demagnetisation (either self-demagnetisation or via an applied external magnetic field) and this is the biggest shortcoming of the $Fe_{16}N_2$.

Figure 3 gives a summary of coercivities reported within the last two decades on lab-scale $Fe_{16}N_2$ samples. The

Material	$\mu_0 M_s$ (T)	$\mu_0 M_r$ (T)	H_a (kOe)	H_c (kOe)	H_c/H_a (%)	T_c (°C)	κ	BH_{max_theor} (MGOe)
$Nd_2Fe_{14}B$	1.61	1.49[1]	76	1.1[1]	14	315	1.5	64.8
Fe	2.15	-	0.6	-	-	770	0.1	115.6
$Fe_{16}N_2$	2.39	0.5[2]	10	2.2-3.3[2]	25	361-540[3]	0.5	143
$SrFe_{12}O_{19}$	0.47	0.42[4]	18	3.8[4]	21	473	1.4	5.7

1 N55 grade

2 Lab-scale isotropic nanoparticles samples

3 Difficulties in exact Curie temperature determination due to the phase decomposition at ~200 °C

4 TDK grade FB6B

Table 1: Summary of magnetic properties for various materials: saturation magnetisation $\mu_0 M_s$, remanent magnetisation $\mu_0 M_r$, anisotropy filed H_a, coercivity H_c, H_c % of H_a, Curie temperature T_c, hardness parameter κ, theoretical BH_{max}.

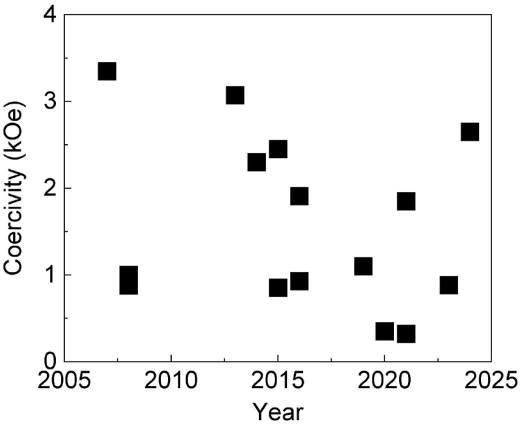

Figure 3: Coercivity values reported for $Fe_{16}N_2$ within the last two decades.

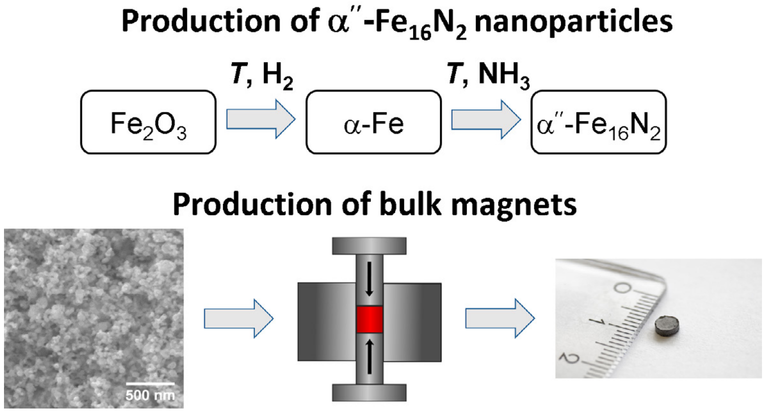

Figure 4: Production of $Fe_{16}N_2$ nanoparticles and bulk magnets.

highest reported coercivities are in fine nanoparticles reaching 3.35 kOe at room temperature[9]. This is comparable to low-grade hexagonal ferrites and considering that there is no upwards trend, a significant improvement anytime soon is unlikely.

To understand the fundamental reason for this, it is important to look at the theoretical physical as well as practically achievable limits of various magnetic materials. The theoretical upper limit for coercivity is set by the anisotropy field H_a. In reality however, the measured coercivities reach only about 25% of the theoretical H_a which is known as the Brown's paradox. For example, the anisotropy field of the $Nd_2Fe_{14}B$ phase is 76 kOe, whereas coercivities of nanocrystalline NdFeB magnets (HRE-free) reach only about 20% with even lower values in the case of sintered magnets. This is a general rule-of-thumb from decades of permanent magnet research (see Table 1). The α"-$Fe_{16}N_2$ phase has an anisotropy field of about 10 kOe. By applying the same rule, **the expected coercivities are around 2.5 kOe which is about 25% of the H_a** and therefore a significant further enhancement will be difficult to achieve.

Hardness

This is also evident when considering the magnetic hardness parameter $\kappa = \sqrt{H_a/2M_s}$. For a permanent magnet κ should be larger than 1 and as shown in Table 1, this requirement is certainly fulfilled for known permanent magnets such as $Nd_2Fe_{14}B$ or $SrFe_{12}O_{19}$ whereas **hardness parameter for the α"-$Fe_{16}N_2$ reaches only about κ≈0.5 and therefore it must be considered a semi-hard magnetic material**.

Thermal stability

Regarding the statement claiming superior thermal stability. Two distinct phenomena need to be distinguished here. First, the thermodynamic stability of the phase. As will be discussed later, $Fe_{16}N_2$ is far inferior to NdFeB or ferrite magnets due to its decomposition/oxidation at comparably low temperatures <200 °C. Second consideration is the decrease in magnetic properties with temperature (the well-known temperature coefficients for remanence and coercivity α and β).

The claim that $Fe_{16}N_2$ is superior to leading neodymium-based magnets comes from **normalised** temperature-dependent measurements where remanence and coercivity of both $Fe_{16}N_2$ and NdFeB were normalised to unity[10]. This is misleading and a similar trend would obviously be obtained for pure soft magnetic iron since the Curie temperature of iron and iron nitride are much higher than that of $Nd_2Fe_{14}B$ (see Table 1). However, if we look at the absolute value of coercivity reported, a completely different picture arises – in NdFeB magnets coercivities easily exceed 10 kOe, whereas $Fe_{16}N_2$ reached only 1.1 kOe in the above cited work, which is clearly insufficient for a permanent magnet.

Bulk magnet production

A large number works have been published on $Fe_{16}N_2$ in the form of thin films. However, it seems the only publicly known viable way to produce bulk magnets so far is via nanoparticles. The typical synthesis route is illustrated in Figure 4.

First, iron oxide (Fe_3O_4 or Fe_2O_3) nanoparticles are reduced to iron using hydrogen at temperatures of about 390-450 °C for several hours. It is possible to lower the temperature of the reduction step to about 210 °C by using hydrogen at high pressures[11] which minimises particle coarsening and thus improves $Fe_{16}N_2$ phase formation[12] as well as the final coercivity. Next, the iron nanoparticles are nitrogenated in an ammonia flow at temperatures of about 130 – 170 °C to obtain the $Fe_{16}N_2$ phase. During this step,

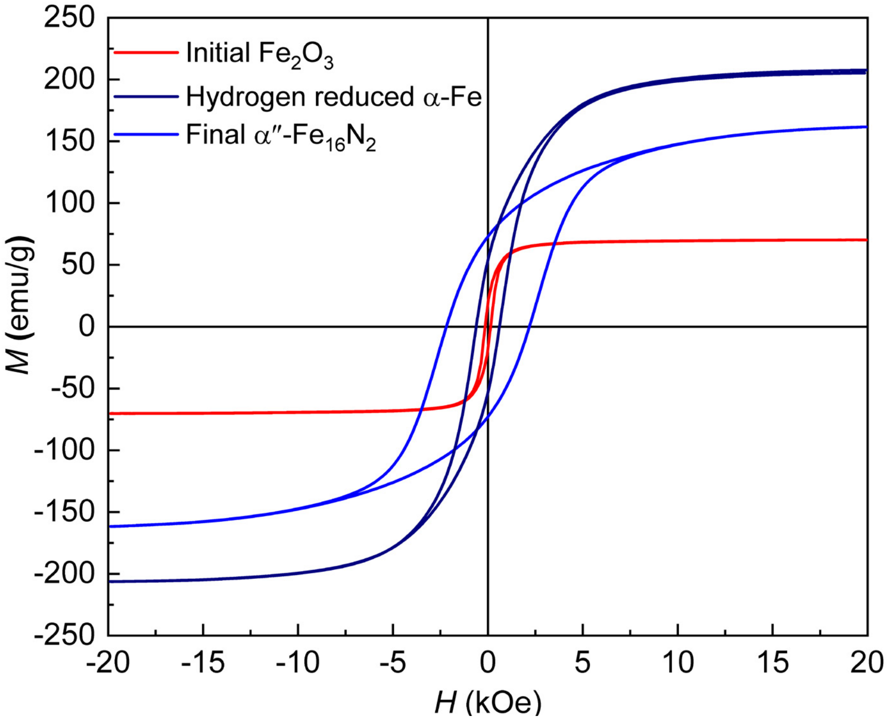

Figure 5: Hysteresis loops of the initial iron oxide, intermediate hydrogen reduced iron and final nitrided $Fe_{16}N_2$ nanoparticles.

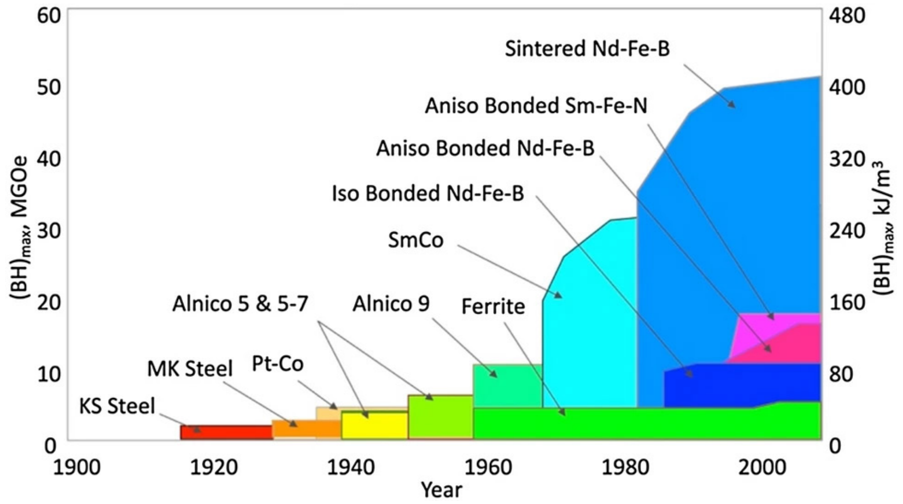

Figure 6: Historical trend of the improvement in the maximum energy product for commercially produced permanent magnets

saturation magnetisation decreases and coercivity increases. Hysteresis loops of the initial Fe_2O_3, intermediate hydrogen reduced α-Fe, and final nitrided $Fe_{16}N_2$ nanoparticles are summarised in Figure 5.

The big challenges in production of bulk magnets currently are thermal and chemical stability of the reactive nanoparticles. It has been shown by using systematic temperature-dependent in situ X-ray diffraction experiments that the $Fe_{16}N_2$ phase decomposes into α-Fe and γ'-Fe_4N below 200 °C in inert atmosphere. The situation becomes even worse in air where the $Fe_{16}N_2$ nanoparticles already begin to oxidise around 160 °C. This makes production of bulk magnets more complicated since compared to other stable permanent magnet materials such as NdFeB or ferrites, low temperatures need to be used as well as particle coating strategies with for example SiO_2 or Al_2O_3[13] to prevent oxidation.

There are currently two possibilities for obtaining bulk magnets from the synthesised $Fe_{16}N_2$ nanoscale powders. First, mixing with a polymer for production of polymer-bonded magnets. The advantages are temperatures below the decomposition of the $Fe_{16}N_2$ phase (~200 °C) and flexibility with the shape. The obvious disadvantage is dilution of magnetisation due to the nonmagnetic polymer. Second, production of bulk magnets using high-pressure/low-temperature consolidation as illustrated in Figure 4. The process is similar to conventional hot pressing of NdFeB [14], yet at lower temperatures to avoid phase decomposition. In this case, the nanopowder is filled in a die that is heated to temperatures < 200 °C and high pressure is applied resulting in densification. Small lab-scale samples have been prepared in this way[15, 16]. Unfortunately, at such low temperatures it is not possible to obtain fully-dense bulk samples with good mechanical integrity and at higher temperatures coercivity decreases significantly. Furthermore, it is not possible to align the nanoscale powders to produce anisotropic magnets. For this reason, remanence values in these isotropic nanoparticles samples are typically around 0.5 - 0.6 T, which is only slightly higher than that of ferrite magnets. For example, a high-grade LaCo-free ferrite magnets can reach remanence of 0.45 T.

Commerciality?

History of permanent magnet development

Several comprehensive reviews exist which extensively cover the development of RE magnets and the factors determining their coercivity [17]. Figure 6 shows the historical development and commercialisation of permanent magnets based on their BH_{max}. It is noteworthy that the main discoveries of new commercial hard magnetic materials and the advancement in BH_{max} have occurred exclusively during the twentieth century. No major new magnetic material has been introduced since NdFeB in the early 1980s; in fact, it is now more than 40 years since the announcement of NdFeB magnets at the 29th MMM Conference held in Pittsburgh, PA, in November 1983.

Permanent magnet market

As can be seen in Figure 6, hard ferrite magnets were commercialised about 60 years ago; NdFeB magnets about 40 years ago. So how has the market for these materials developed?

Figure 7 shows the change in the mix of

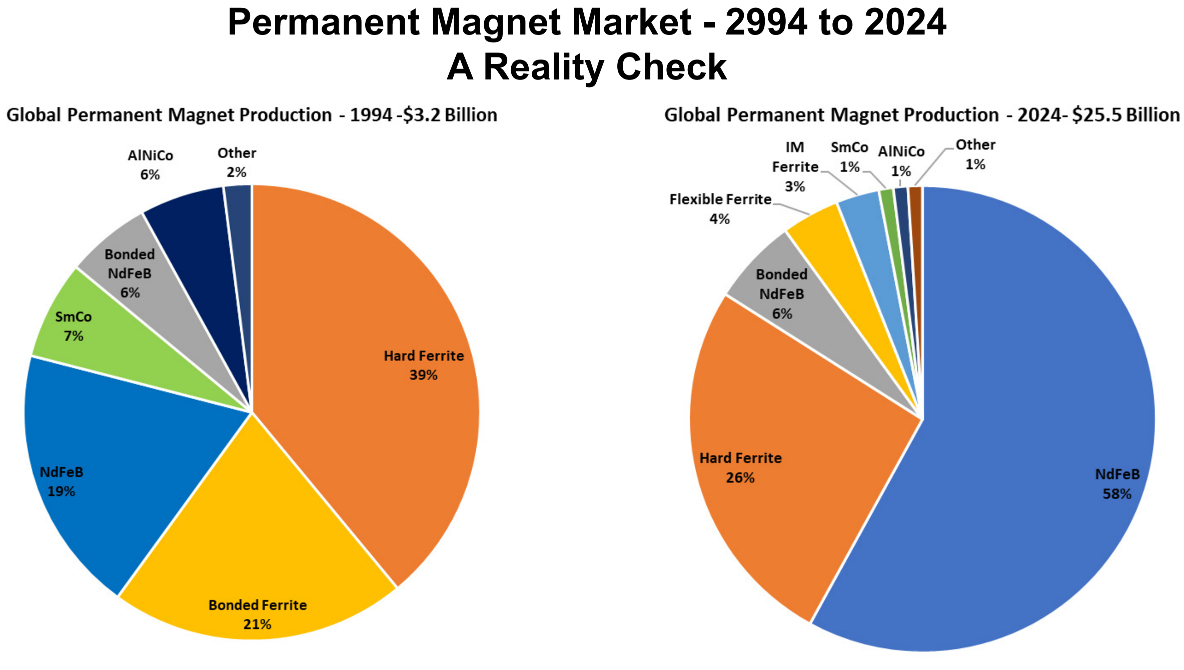

Figure 7: Permanent magnet market – 1994 to 2024

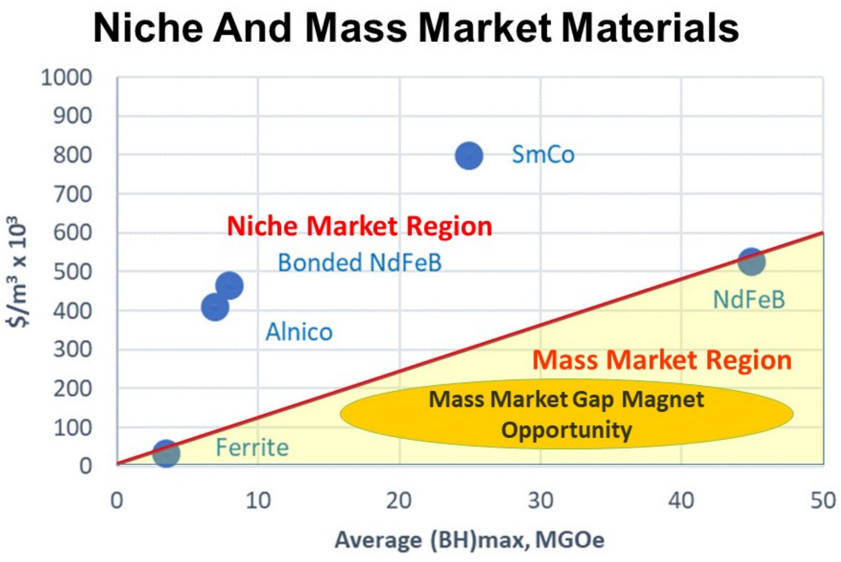

Figure 8: Niche and mass market magnet materials

magnet types over the last 30 years, based on some estimates of the permanent magnet market in 1994[18] and 2024.

Some observations:

- NdFeB market has grown from \$800 million to over \$15 billion.
- Hard ferrite market has grown from \$1.9 billion to \$8.4 billion.
- Everything else (Alnico, SmCo etc.) declined from 15% to 3% share.
- **NdFeB and Ferrite magnets of all types make up 97% of the 2024 permanent magnet market**

Now, Ferrite and NdFeB are not perfect magnet materials; ferrite has low temperature demagnetisation problems while NdFeB has high temperature operating limitations. However, they both have compelling price : performance characteristics[19] as shown in Figure 8, but critically **device designers have figured out how to overcome their performance limitations**.

Commercial opportunity for FeN magnets

Despite the major limitations mentioned earlier in this paper (e.g. low coercivity, thermal stability, fabrication), non-RE magnets based on iron nitride have received a lot of attention in the non-technical press. One of the leaders in attempting to commercialise the technology is Niron Magnetics, Inc. Their Iron Nitride technology was conceived at the University of Minnesota and is being developed in their commercial pilot plant.

One of the challenges being faced by the magnet community is the lack of data being shared by FeN commercialisation operations. This has led to speculation and conjecture regarding the performance of FeN magnet prototypes. However, at the 2025 MDSM conference[20], Frank Johnson of Niron presented a hint of what could be their current magnet material, when he provided 2 data points: B_r of 1 T and a BH_{max} of 10 MGOe.

Based on these, Figure 9 shows the estimated Niron characteristics vs an $AlNiCo_9$ and a N48SH NdFeB grade [21]. All are normal demagnetisation curves with an intrinsic curve included for the NdFeB grade. As can be seen the estimated Niron properties are much closer to the AlNiCo magnet than the NdFeB characteristics; it is more a super-AlNiCo albeit with a much lower maximum operating temperature.

Based on these properties, what is the potential commercial significance of FeN magnets? The probability of a magnet becoming a commercial success was presented at the 2024 Magnetics Show conference[22]. The Probability of Commercial Success index (Pcs) incorporates H_c/B_r ratio,

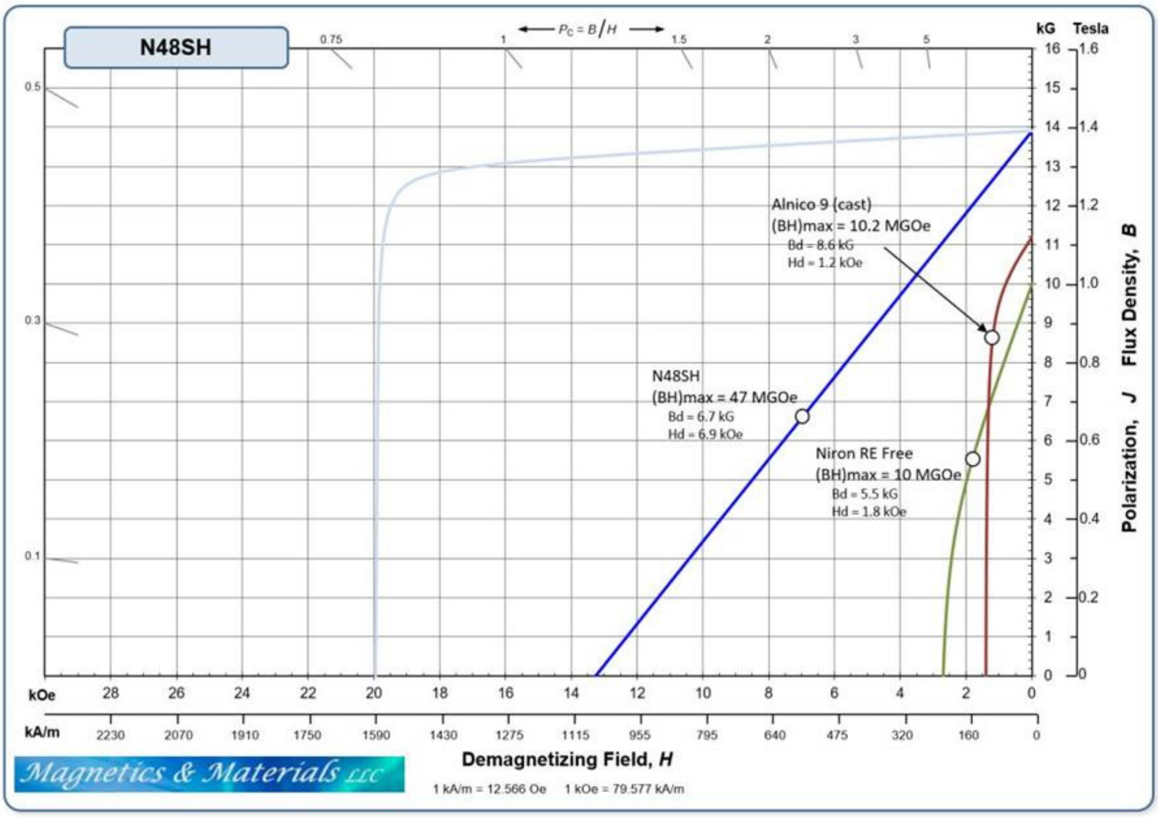

Figure 9: Comparison of 2nd quadrant demagnetisation characteristics

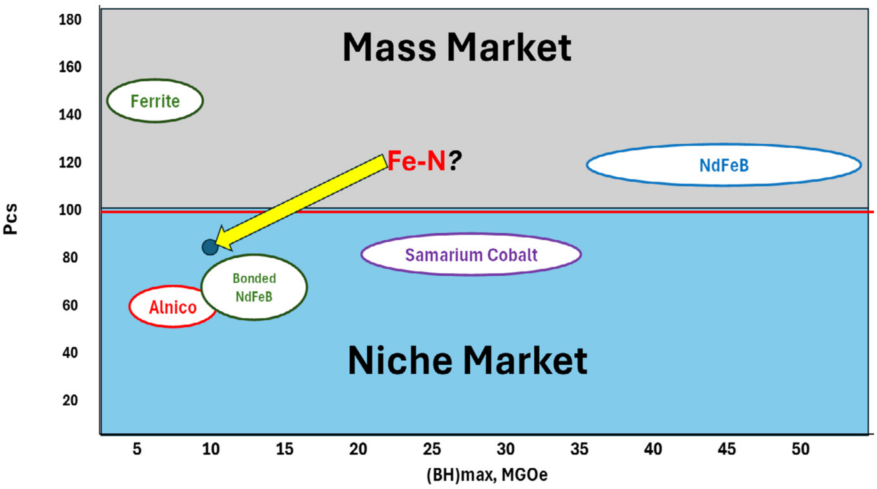

Figure 10: Probability (Pcs) of a permanent magnet being a commercial success

price : performance, BH_{max}, maximum operating temperature, recyclability, and supply chain resilience. Figure 10 gives a plot of estimated Pcs' for current commercially important magnet types and FeN. One can arbitrarily take an index of 100 for the demarcation between a mass market and niche product. The estimated Pcs for FeN is on the high side of the Niche market region but below 100. Not a big surprise given the similarity of its magnetic properties to AlNiCo.

Summary

In this article we have reviewed the most important characteristics of the α''-$Fe_{16}N_2$ material, assessing its potential for future development into a commercially feasible RE-free permanent magnet. By looking at the best achieved coercivities within the last decades and the intrinsic magnetic properties, we conclude that $Fe_{16}N_2$ can be considered a semi-hard magnetic material. Its poor thermal and chemical stability are likely to make production of fully-dense bulk magnets challenging since processing temperatures need to be kept < 200 °C. The only publicly known to date viable production route for bulk FeN magnets is through reduction of iron oxide nanoparticles with subsequent ammonia nitriding, which results in isotropic samples, thus sacrificing the remanence.

If the costs of the production can be reduced, and magnetic properties and thermal and chemical stabilities optimised, it is possible that $Fe_{16}N_2$ can compete with hexagonal ferrites and AlNiCo magnets in the future.

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