Rare earth free permanent magnets

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Properties of common commercial PMs

Material Families	Remanence, B_r (G)	Coercivity, H_{ci} (Oe)	Energy product, BHmax (MGOe)	Maximum Operating Temp. (°C)	Density, (g/cm^3)
NdDyFeB	10,000 – 15,000	11,000-42,000	28-56	70-220	7.4-7.5
SmCo	8,000-12,100	6,200-35,000	16-34	250-350	8.1-8.5
AlNiCo (cast)	6,000-13,900	500-1,550	1.2-7.2	450-550	6.9-7.3
Ferrites	2,100-4,700	1,750-5,150	0.7-5.4	350	4.8-5.2

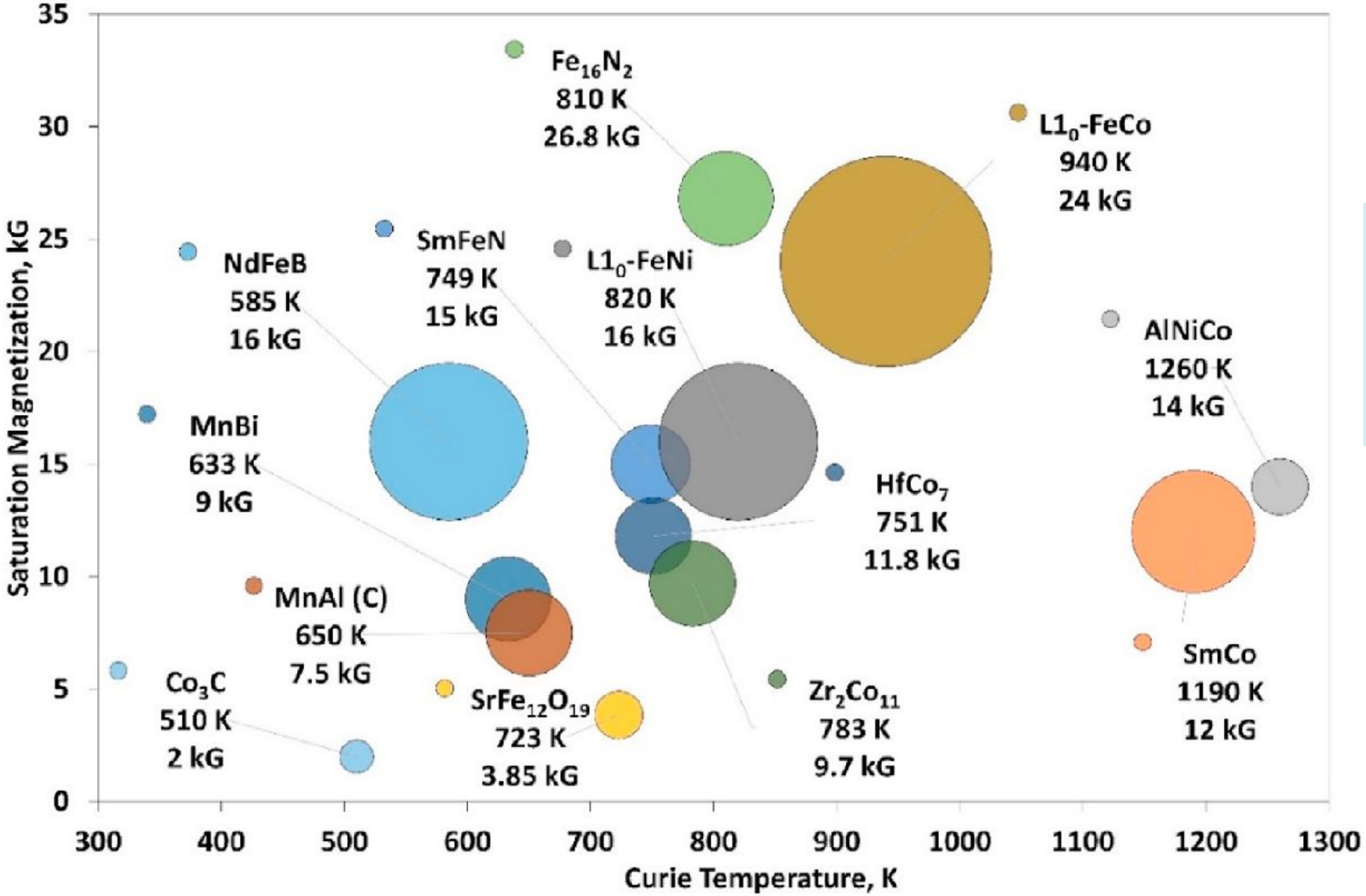
H_{ci}, intrinsic coercivity (the ability to resist demagnetization)

B_r, remanence (residual magnetization with the removal of magnetic field)

BH_{max}, energy product (the maximum energy a magnet can store)

H. Wang, T. Lamichhane, M. P. Paranthaman Materials Today Physics, 24, 100675 (2022); https://doi.org/10.1016/j.mtphys.2022.100675

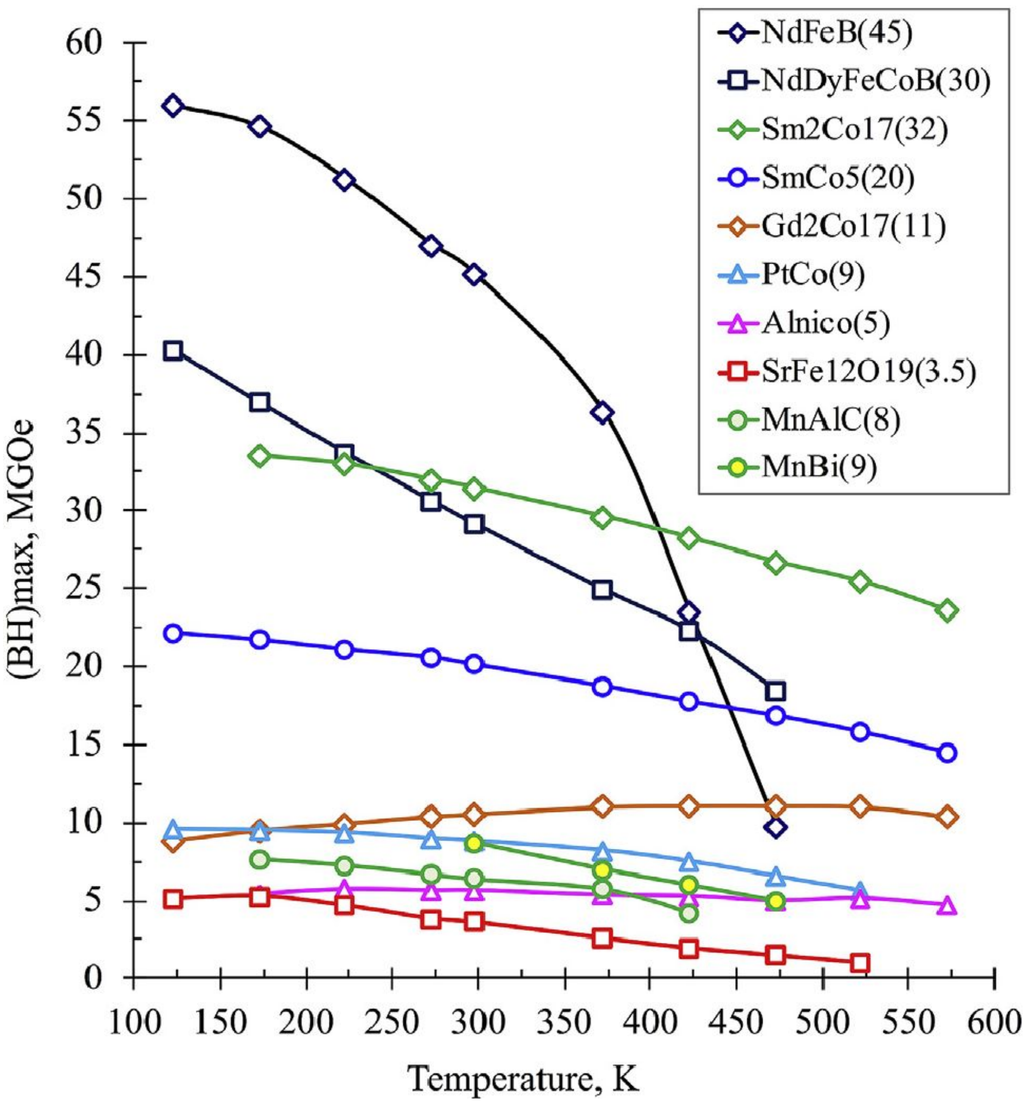
Magnetic properties of permanent magnets at room temp



Curie Temperature Tc, Saturation Magnetization Ms, Energy Product (BH)max. Circle size represents magnitude of Energy Product

H. Wang, T. Lamichhane, M. P. Paranthaman Materials Today Physics, 24, 100675 (2022); https://doi.org/10.1016/j.mtphys.2022.100675

MnBi are alternates to NdFeB (non rare earth PM)



MnBi-based motors are a promising option for reducing costs and eliminating rare earth dependencies.

Pros:

- **Cost**: MnBi-based motors can reduce magnet costs by up to 50% compared to NdFeB and ferrite materials.
- **Earth abundance**: MnBi is made of earth-abundant materials.
- **High energy density**: MnBi-based magnets have a high energy density, which makes them suitable for electric motors in electric vehicles, wind turbines, and flying rovers.

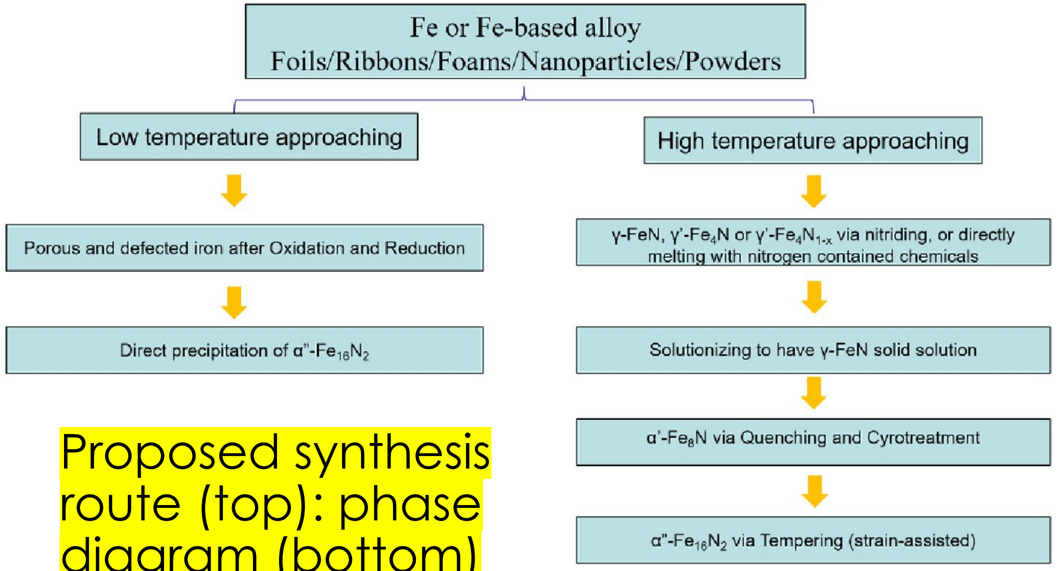
Cons:

- **Low remanent flux density:** MnBi has a lower remanent flux density than NdFeB, which can lead to a lower constant power speed ratio.
- **Demagnetization:** MnBi is more susceptible to irreversible demagnetization at low temperatures.

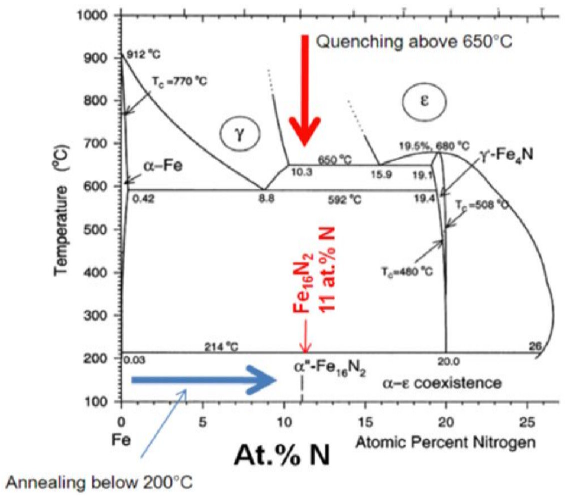
- **Research** on MnBi-based motors are in progress.

Jun Cui, Matthew Kramer, Lin Zhou, Fei Liu, Alexander Gabay, George Hadjipanayis, Balamurugan Balasubramanian, David Sellmyer, Acta Materialia, 158, 118 (2018).
doi.org/10.1016/j.actamat.2018.07.049

$Fe_{16}N_2$ are alternates to NdFeB (non rare earth PM)



Proposed synthesis route (top): phase diagram (bottom)



BHmax: 20 MGOe (ion implantation); BHmax: 9 MGOe (bulk)

FeN are a promising option for reducing costs and eliminating rare earth dependencies. It has a high intrinsic saturation magnetization.

Pros:

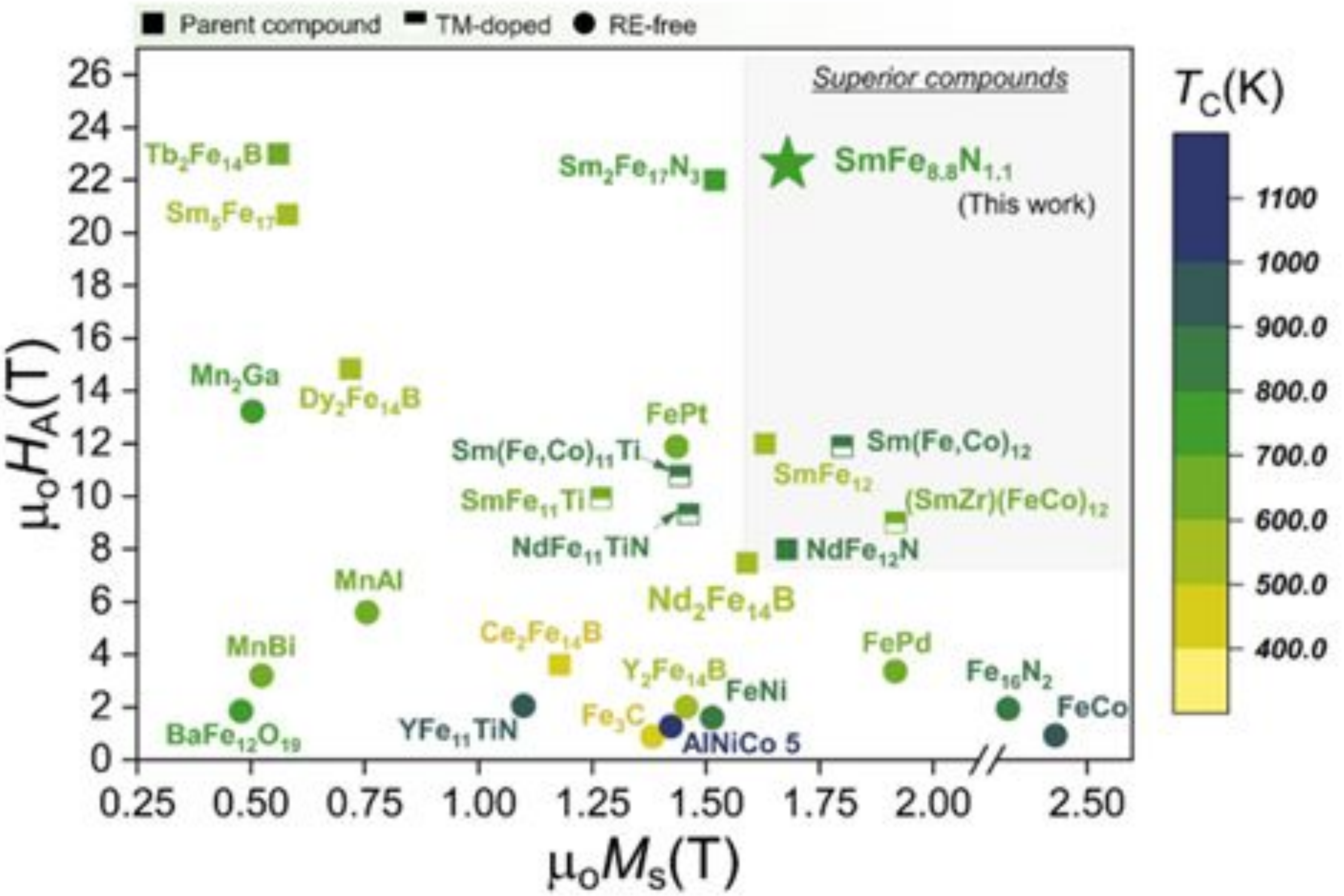
- **Cost**: FeN magnets are less expensive than NdFeB
- **Sustainability**: FeN magnets are made of inexpensive materials.
- **Temperature stability**: FeN magnets perform well at speaker operating temperatures.
- **Applications**: FeN magnets are suitable for applications that work at relatively low temperatures and don't require high coercivity.

Cons:

- **Low coercivity and energy products**
- **Scale up research** on FeN magnets is in progress.

Jian-Ping Wang, J MMM 497, 165962 (2020). https://doi.org/10.1016/j.jmmm.2019.165962

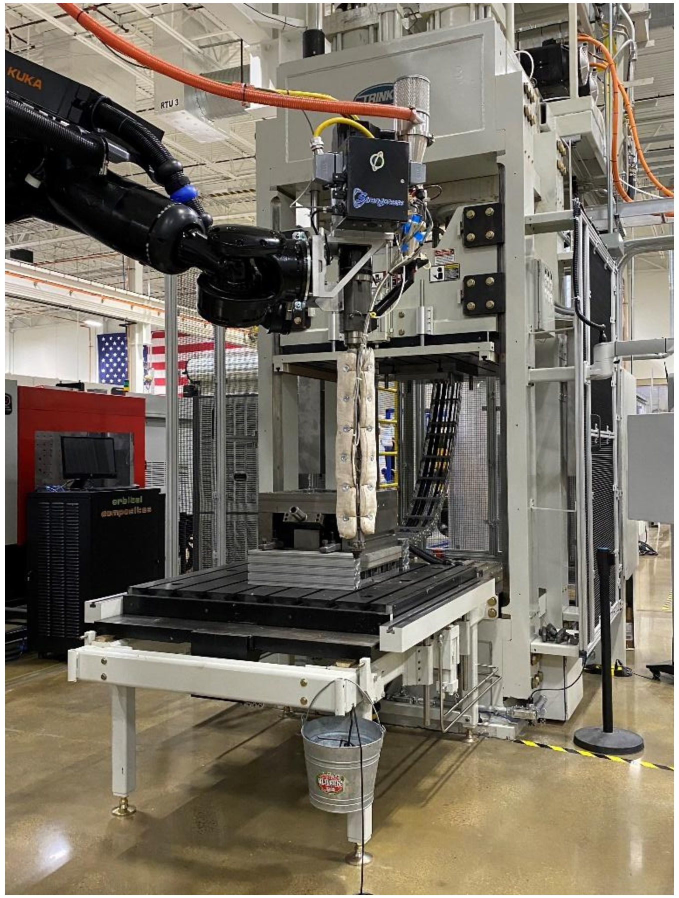
$TbCu_7$ type Sm-Fe-N are alternates to NdFeB (non heavy PM)



- **$SmFe_9N_\delta$ - Ms 1.64 T (thin films) compared to $Sm_2Fe_{17}N_3$ (1.57 T) and NdFeB (1.61 T)**
- **1:12 compounds: (Sm, Zr)(Fe,Co)$_{12}$) have better intrinsic properties compared to NdFeB; it is unstable in bulk; however, with Ti and V stabilization reduced magnetic properties**
- **$Sm_2Fe_{17}N_3$ and $SmFe_9N$ have been commercialized by Daido Steel for bonded magnet fabrication. Nichia and Sumitomo made anisotropic SmFeN powders for injection molded magnets**

A.R. Dilipan, D. Ogawa, H. Sepehri-Amin, P. Tozman, T. Hiroto, K. Hono, Y. K. Takahashi, Acta Materials, 274, 119996 (2024). https://doi.org/10.1016/j.actamat.2024.119996

BAAM (Big Area Additive Manufacturing)



Polymer additive BAAM
Cincinnati (250x250x350 mm)
(96x9.8x13.8 in);
Build rate: >80lbs/hour

Additive Manufacturing – Compression Molding (AM-CM)

Compression followed by printing improves the density by 5-7%
(reduces the porosity between the layers)

3D Printing and Additive Manufacturing – Global state of the industry is growing exponentially…….
http://web.ornl.gov/sci/manufacturing/mdf/

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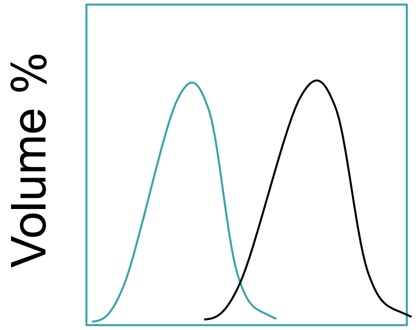
Reaching full density avoiding shrinkage requires higher packing factor, which could be as simple as tailoring PSD (non heavy rare earth)

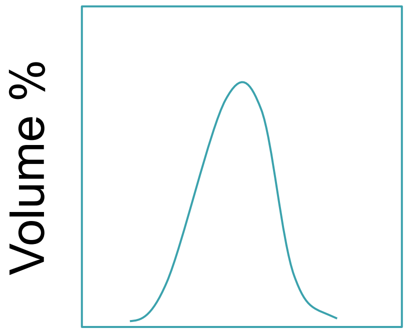
- Typical powder feedstocks have gaussian distribution, which has a packing factor of around 0.6-0.7
- Bimodal Distributions have a maximum packing factor of *0.868*
- *To HIP/compression, a density of ~0.9 is achieved*

Bimodal

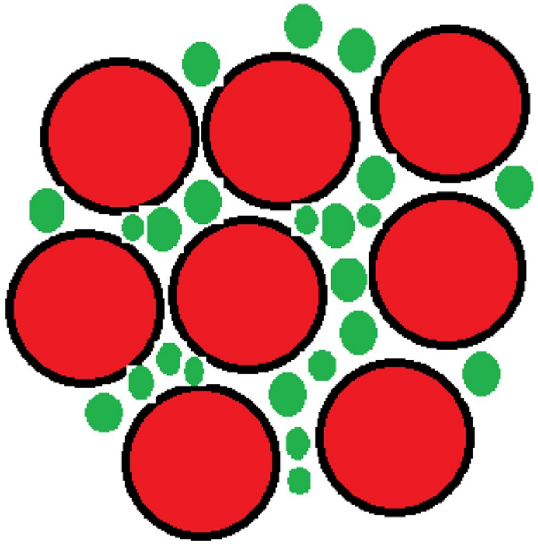


Diameter

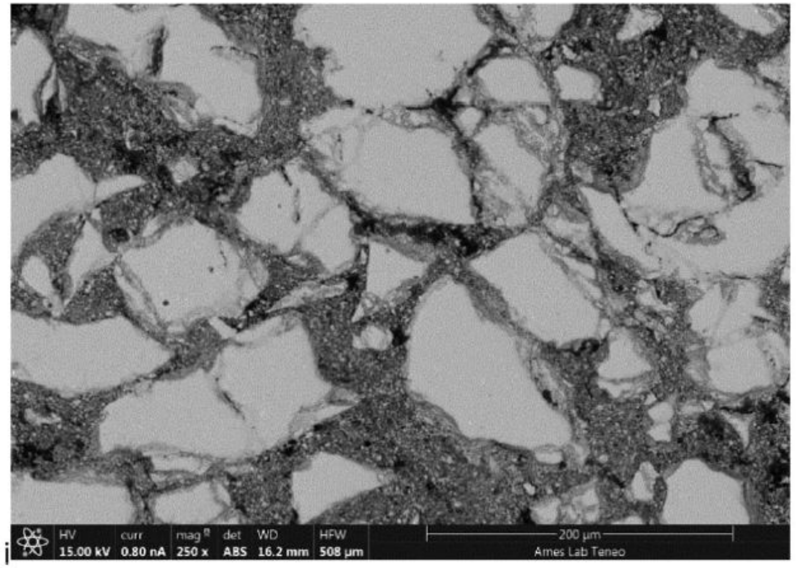
Monosize



Diameter



Monodispersed Particle Size Distribution



60% Dy-free NdFeB (100 µm) and 40% SmFeN (3-5 µm) packing in 10% PPS yielded an energy product, $(BH)_{max}$ of 20 MGOe at 300 K

X. B. Liu, K. Gandha, H. Wang, K. Mungale, U. K. Vaidya, I. C. Nlebedim, and M. P. Paranthaman, RSC Advances 13 (25), 17097-17101 (2023). DOI 10.1039/d3ra02349d

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Non heavy Dy-free NdFeB SmFeN PPS Bonded Magnets

Target: Gap magnets with energy product, (BH)max: 20-25 MGOe and higher.

- Successfully fabricated high performance anisotropic MF15 NdFeB SmFeN PPS composite magnets with 96 wt.% (~ 80 vol%) (density: 6.15 g/cm^3) and (BH)max of 20.0 MGOe at 300 K

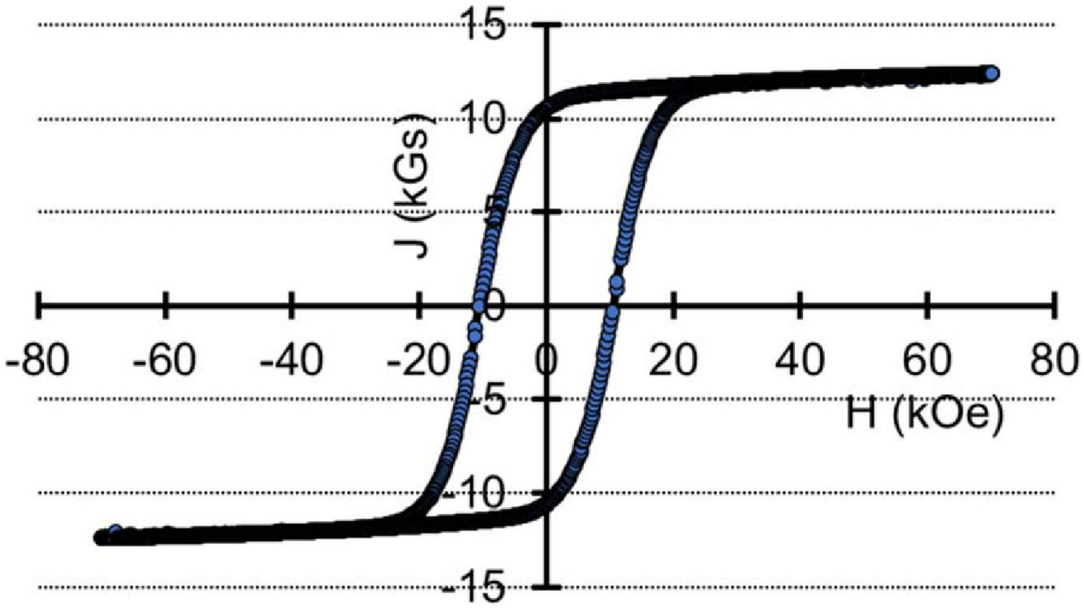
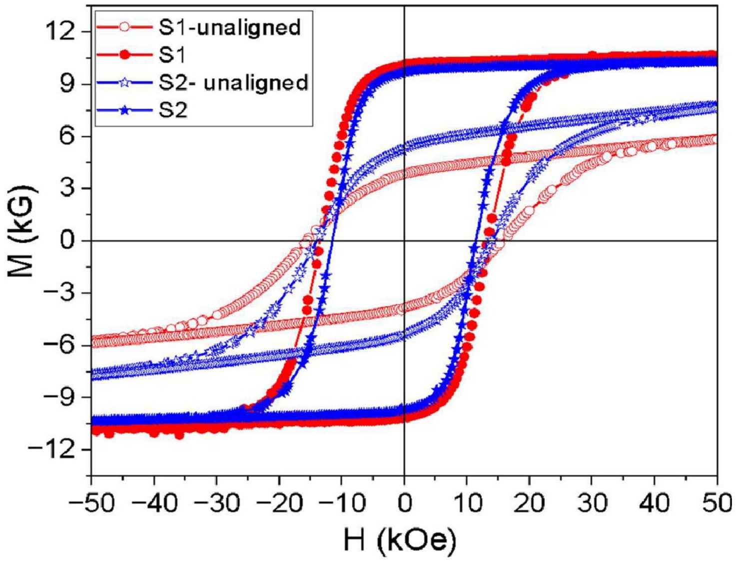


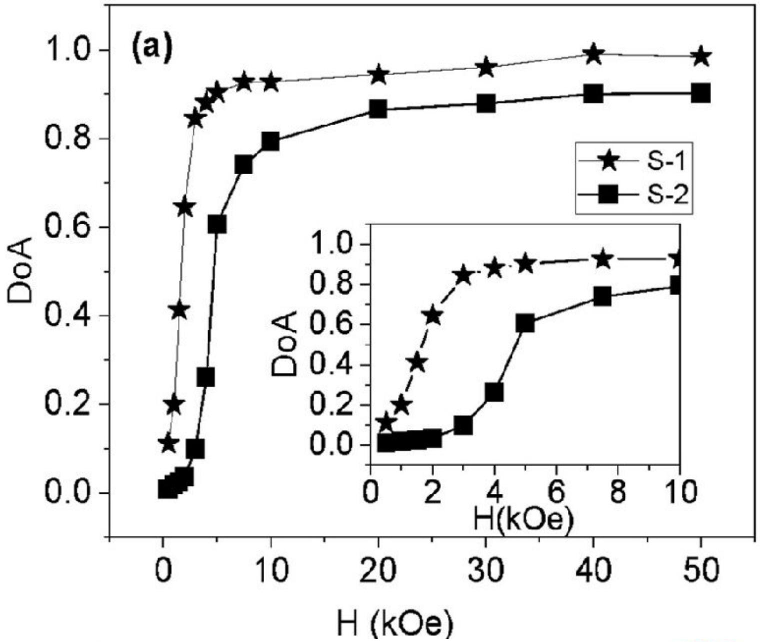
Table: Magnetic properties of Dy-free NdFeB (non heavy): SmFeN PPS composite magnets

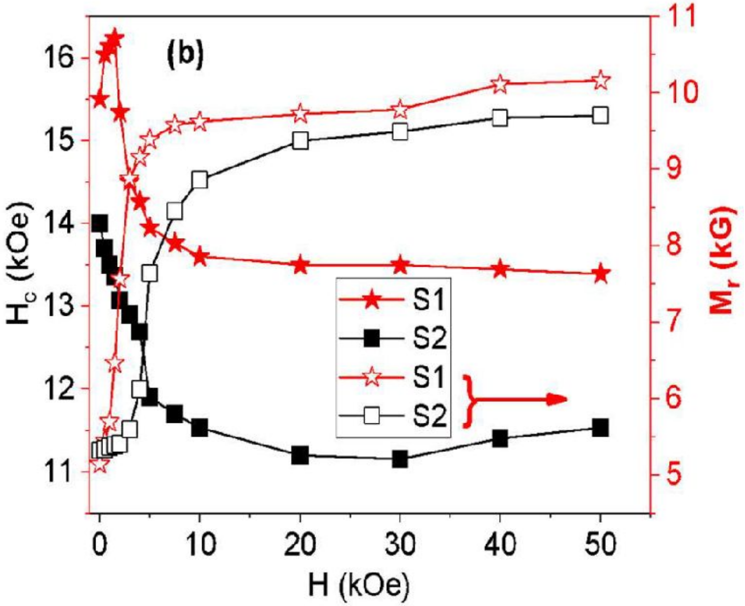
Sample ID	Remanence B_r (kGs)	Coercivity H_{ci} (kOe)	Maximum energy Product $(BH)_m$ (MGOe)
1	10.4	10.80	20.0
2	10.5	10.82	20.0
3	10.2	10.76	19.5

X. B. Liu, K. Gandha, H. Wang, K. Mungale, U. K. Vaidya, I. C. Nlebedim, and M. P. Paranthaman, RSC Advances 13 (25), 17097-17101 (2023). DOI 10.1039/d3ra02349d

SmFeN-nylon bonded magnets – extrusion compression molding (non heavy rare earths)

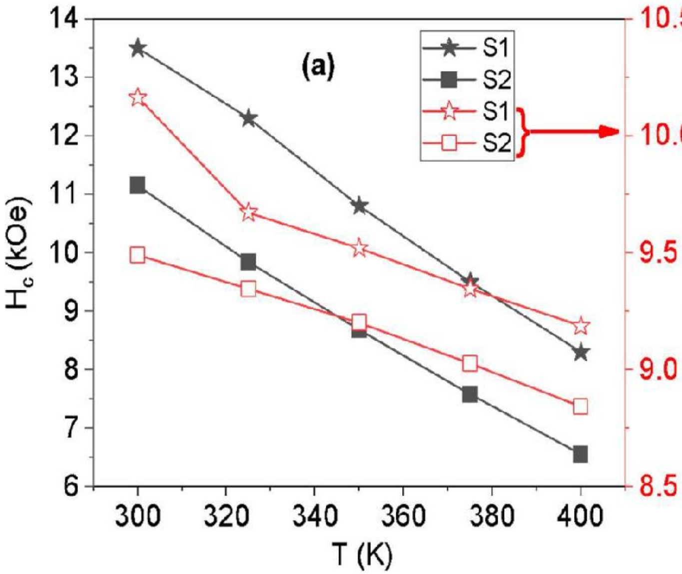


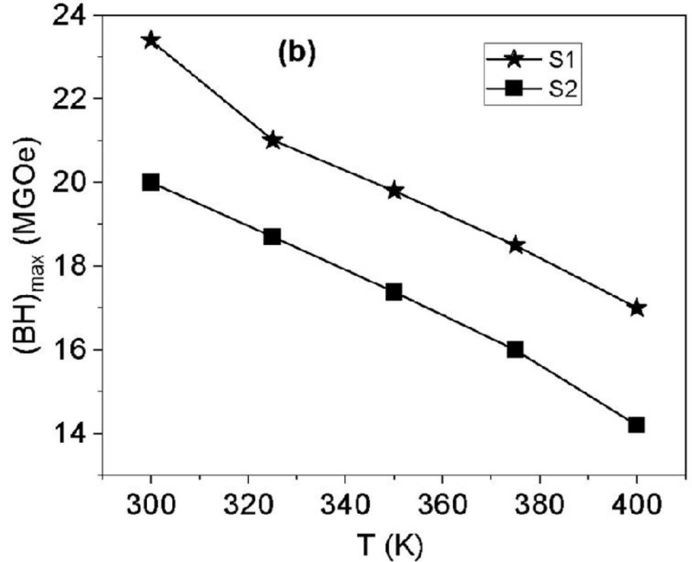




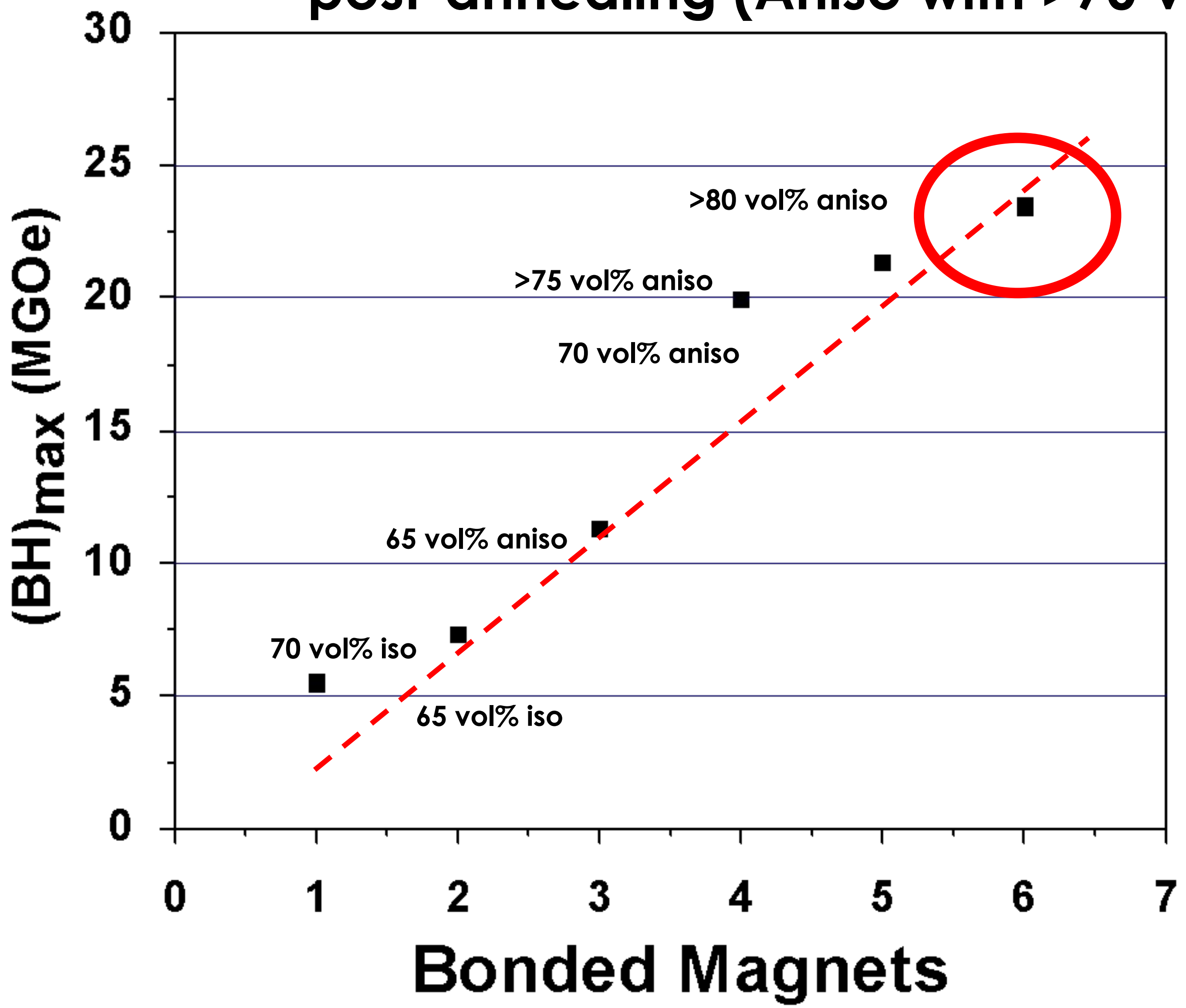
- *(BH)*max of 186.21 kJ.m^{-3} (23.4 MGOe); M_r: 10.1 kG is achieved in the 95 wt.% (74 vol%) bonded magnets

M. P. Paranthaman, H. Parmar, K. Mungale, J. W. Kemp, H. Wang, I. C. Nlebedim, and U. K. Vaidya, Materialia 39, 102359 (2025).





Magnets demonstrated gap magnets with high energy product with post-annealing (Aniso with >70 vol% magnet loadings)



- ✔ Additively printed magnets outperformed injection molded magnets and compression molded magnets
- ✔ High resistivity (3X sintered magnets)
- ✔ Eddy current loss (1000↓ sintered magnets)
- ✔ ~100% recyclability
- ✔ Improved thermal stability (up to 175 °C in air)
- ✔ Improved corrosion resistance (under high humidity and acid conditions)
- ✔ Mechanical properties
  - Medium energy product

Kinjal Gandha, Ikenna Nlebedim, Parans Paranthaman et al., Scripta Materialia (2020); Xubo Liu et al. (2023)

Summary

- MnBi and $Fe_{16}N_2$ are promising rare earth free magnets
- SmFeN is critical rare earth free magnets
- Energy product of ~24.0 MGOe has been achieved with >75 vol% anisotropic SmFeN in nylon with post-field annealing
- Results outperformed conventional injection and compression molding
- Demonstrated 3-D Printing of High-Performance Magnets Can