Rare Earth Magnets: Yesterday, Today And Tomorrow

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Quotes About Research

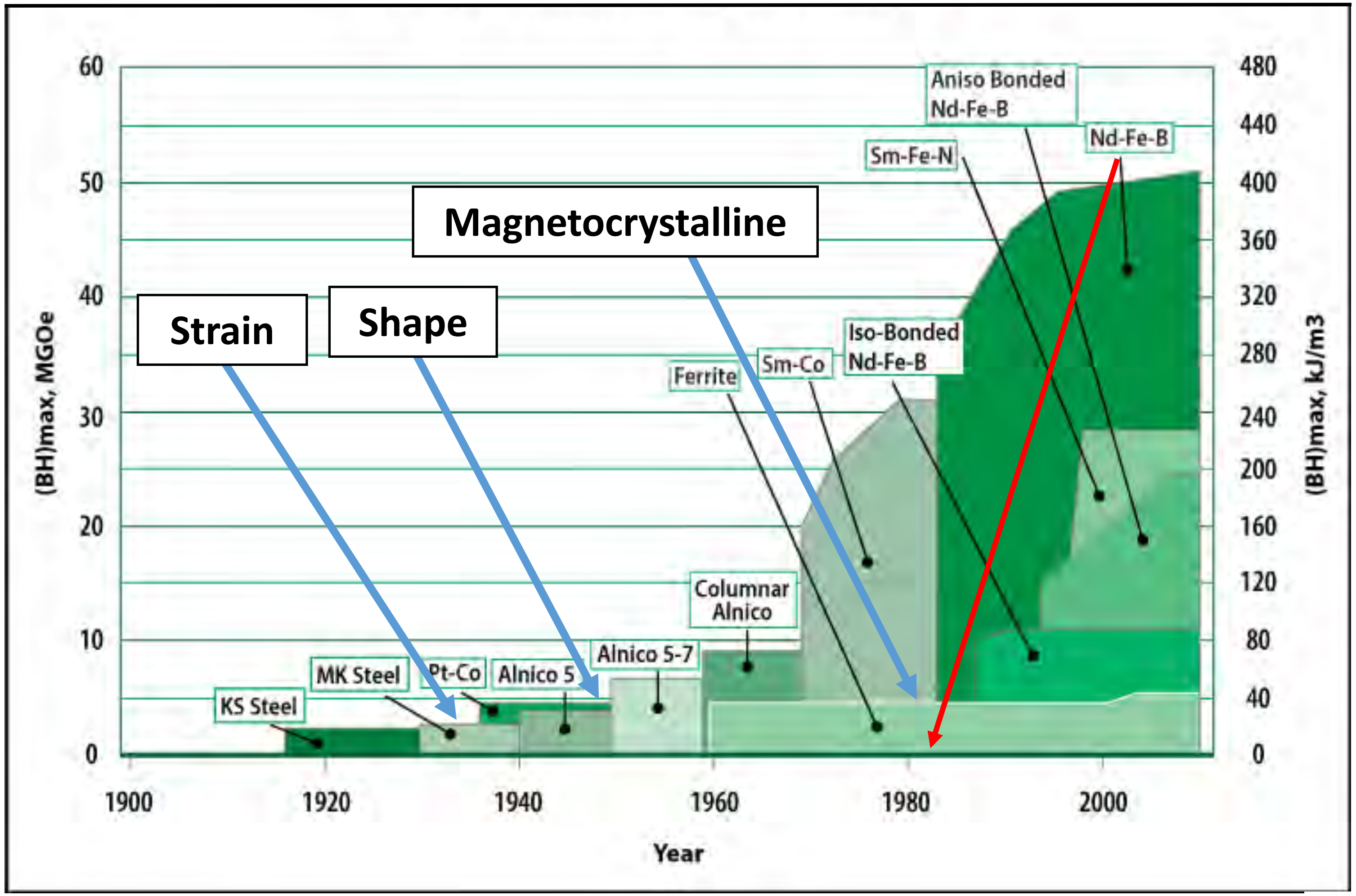
- **“If we knew what we were doing, it wouldn’t be called research.”**
  - Albert Einstein
- **“Basic research is what I am doing when I don't know what I am doing.”**
  - Wernher von Braun

Outline

- Markets And Applications
- REPM History
- Current Materials And Technologies.
  - Powder Metallurgy
  - Melt Spinning
  - Dy Diffusion
  - Hot Pressing
  - SmFeN
  - La-Co Ferrite
- Future trends
  - Toyota
  - 3D Printing
- Final thoughts

Markets and Applications

History of Permanent Magnet Development
Is It Time For A New Breakthrough?



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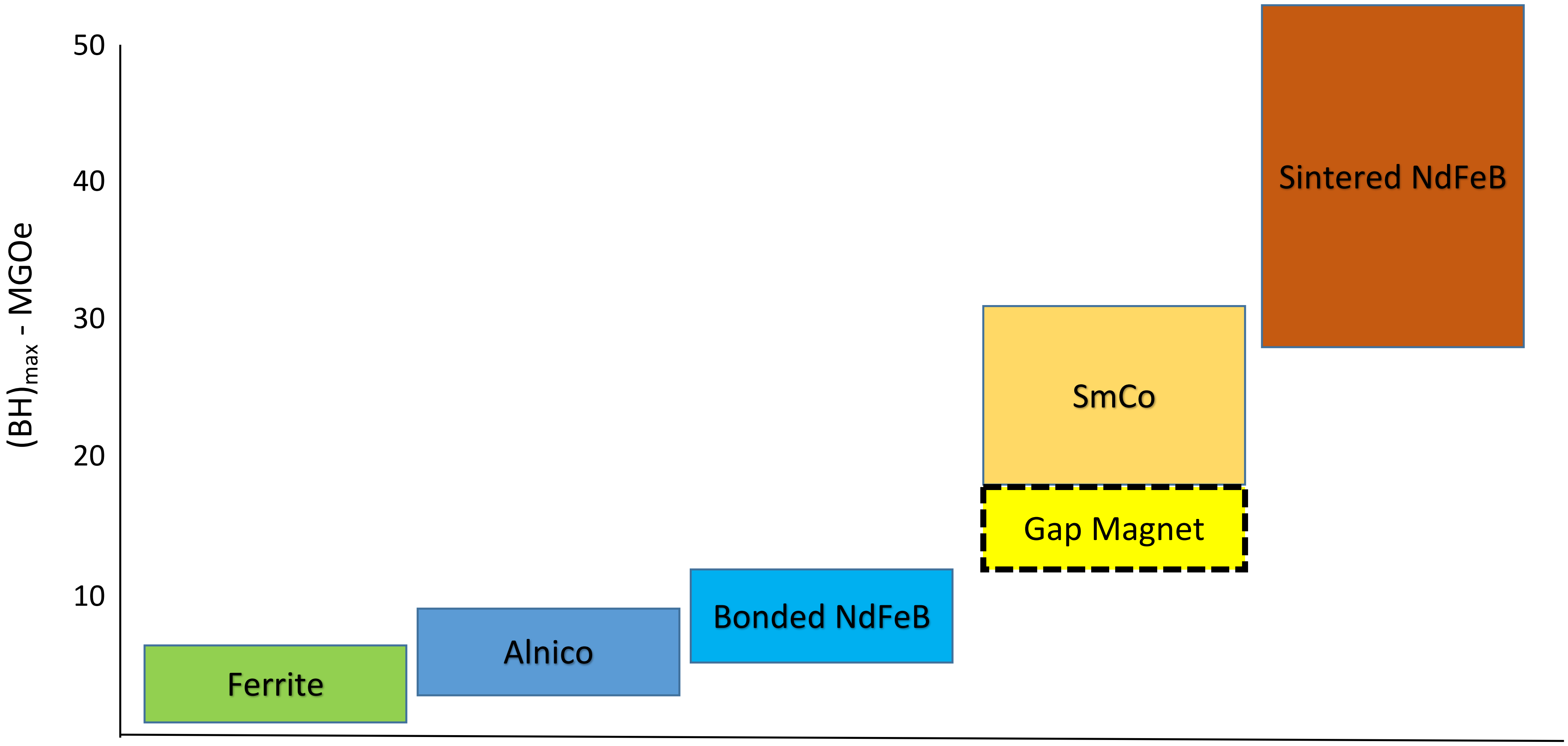
Commercially Important Permanent Magnets



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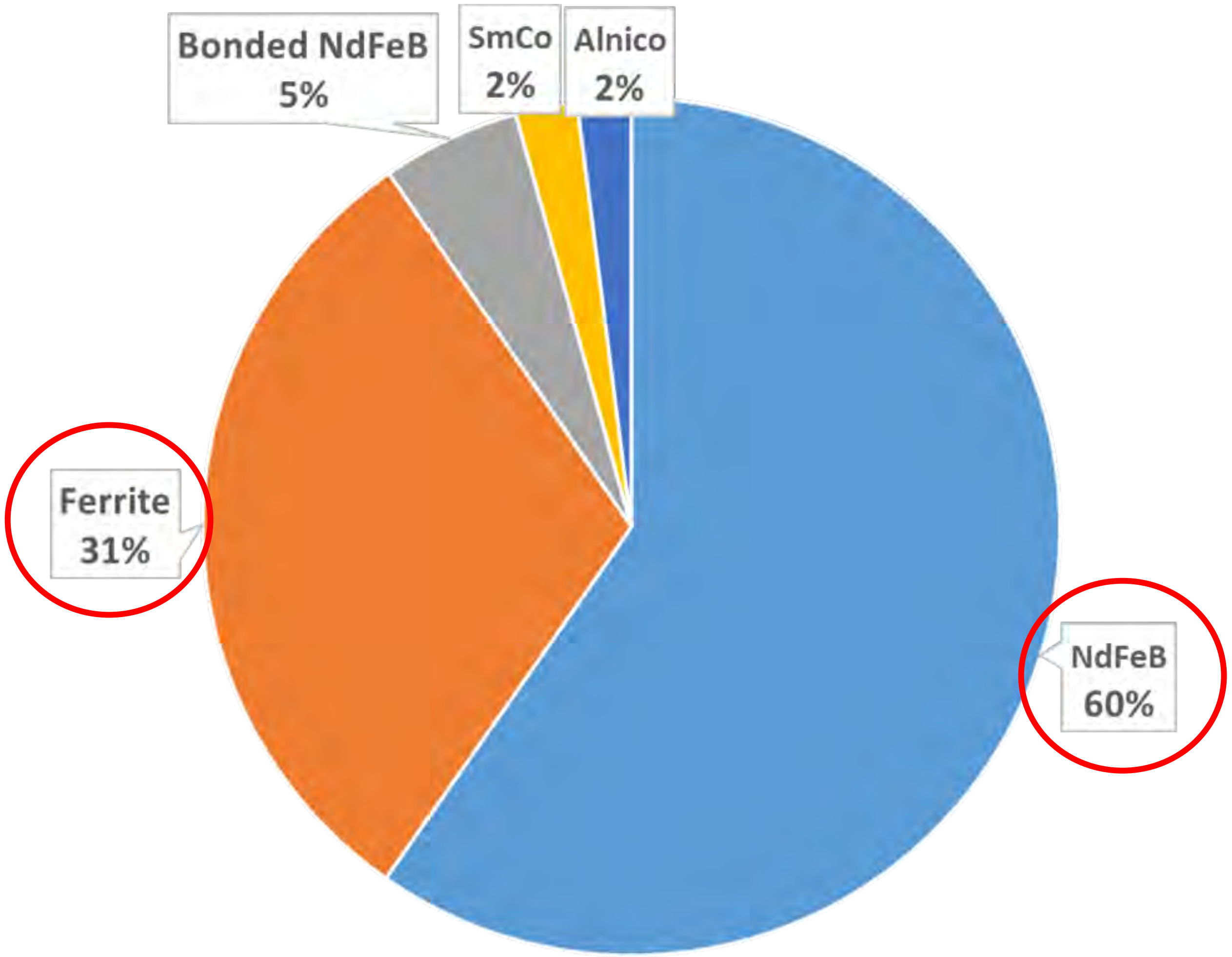
Estimated Permanent Magnet Market - 2016

Material	Weight (000’s kg)	Value ($ Millions)
NdFeB	137,500	10,300
Ferrite	750,000	5,300
Bonded NdFeB	10,000	900
SmCo	4,000	400
Alnico	6,000	350
	Total	Approximately $17 B

Market ($) Dominated By NdFeB And Ferrite



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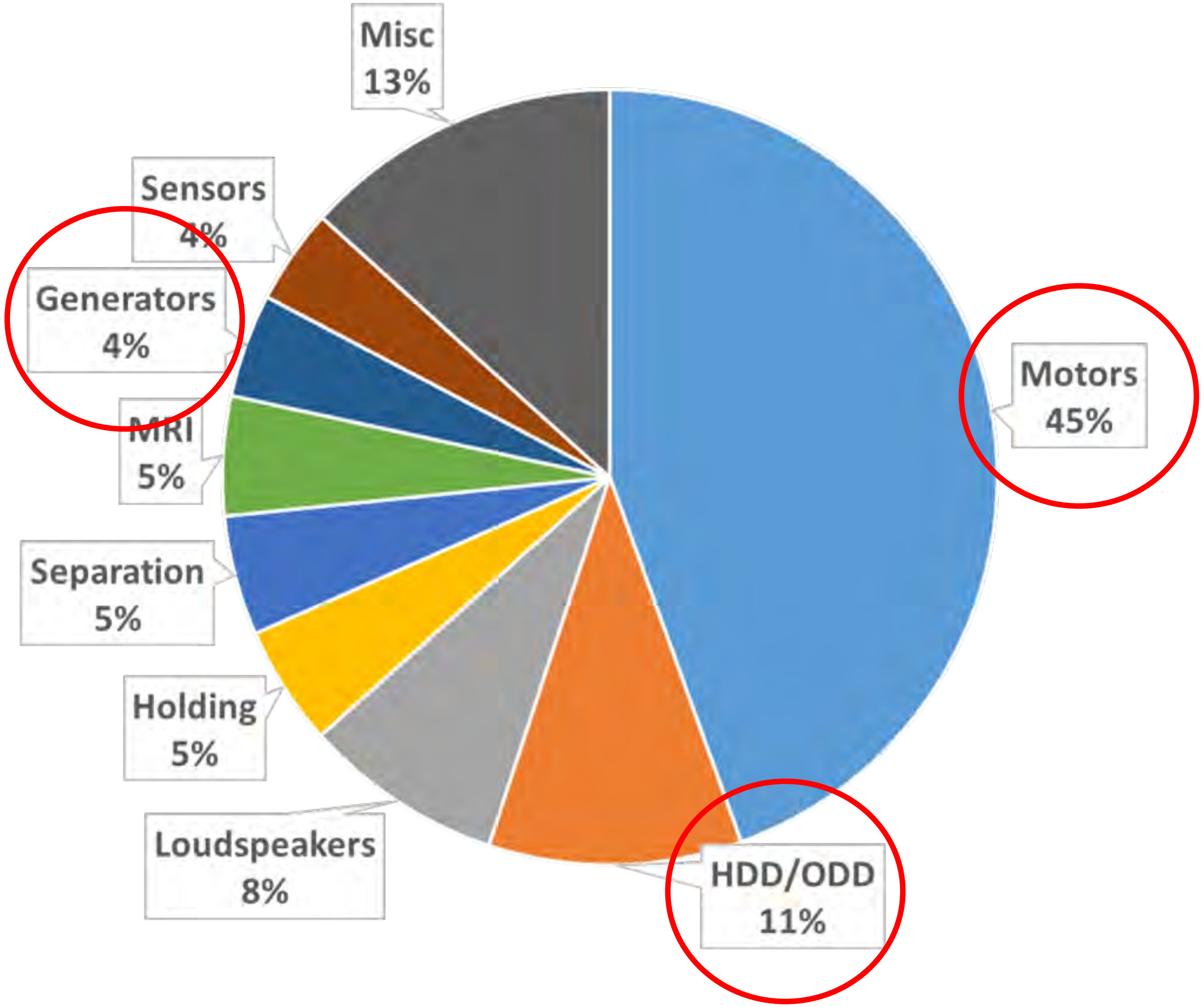
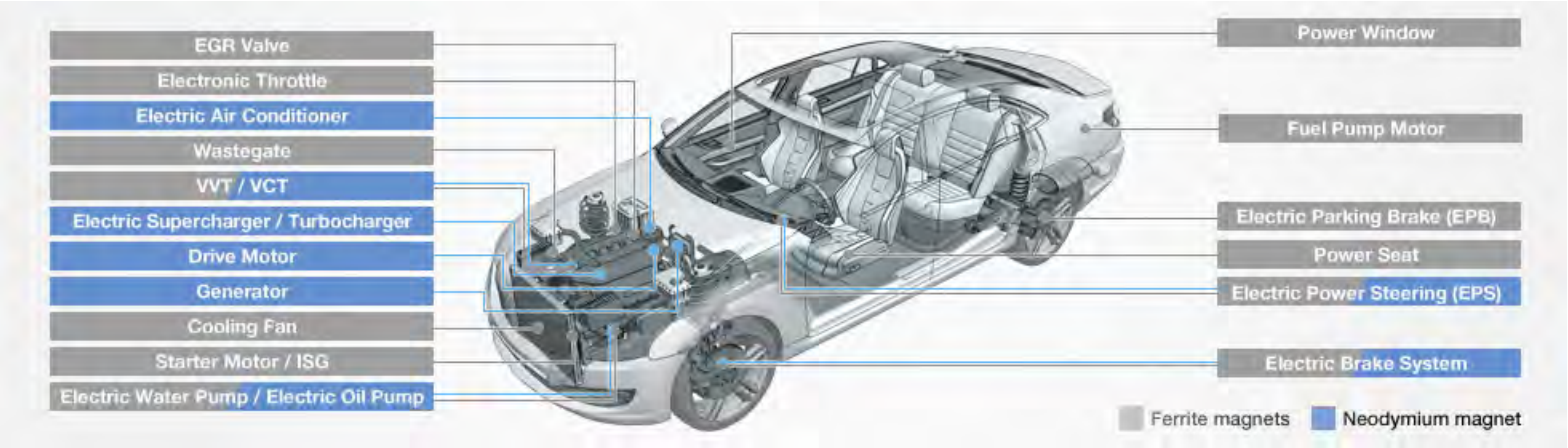
Major Functions Of A Magnet

Application Category	Physical Law	System Function is Proportional to	Application Examples
Electrical to Mechanical (with solid conductor)	Lorentz Force law	B	Loudspeakers, PM motors, HDD/ODD VCM
Mechanical to Electrical	Faraday's Law of Induced voltage	B	Generators, Alternator, Tachometer, Magneto, Microphone, Eddy current devices, sensors
Magnetostatic Field Energy to Mechanical Work	Coulomb Force Principles	B^2	Magnetic Chucks, Conveyors, Magnetic Separators, Reed Switches, Synchronous Torque Couplings
Electrical to Mechanical (with free charged particles)	Lorentz Force law	B	Travelling Wave Tubes, Magnetrons, Klystrons, MRI

Market By Major Application Type



Automotive Applications – NdFeB Is Gaining Ground!



Source: TDK: https://product.tdk.com/info/en/products/magnet/technote/ap_automotive.html

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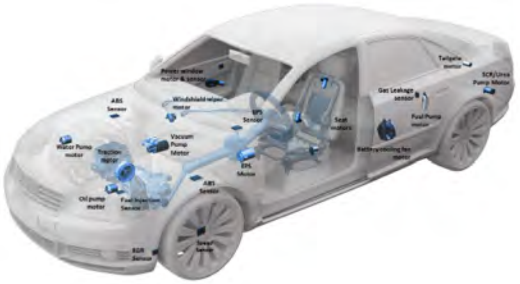
Current And Future Major Applications

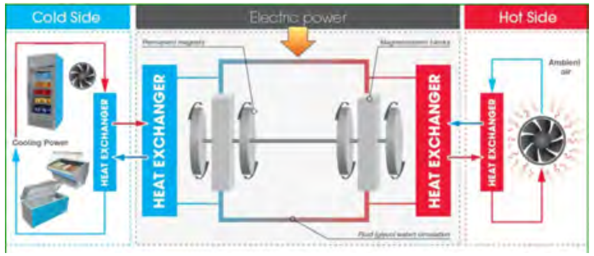
- Hybrid and electric cars & trucks are in a rapid growth phase:
  - 2018 forecast 25 million units.
  - 18,000 tons of REPM’s in 2020.
  - Forecast to be largest consumer of RE magnets by 2025.
- Electric bicycles is another large and growing application with an estimated 13,000 tons in 2020
- HDD (servers, cloud storage):
  - RE magnet esmated in 2018 is 8,000 tons.
  - Future demand flat to declining.

Source: Magnetics and Materials LLC, WTBenecki LLC, numerous industry sources

Current And Future Major Applications

- **Direct Drive wind turbines:**
  - **RE magnet weight forecast in 2020 is 25,000 tons.**
- **Automotive (ICE):**
  - **Over 100 PM devices in a typical car.**
  - **Estimated 12,000 tons usage in 2020.**
- **General industrial and commercial motors for robotics, appliances, HVAC etc.**
- **Acoustic transducers.**
- **Magneto calorific cooling for refrigeration and HVAC is a potential major application.**





Source: Magnetics and Materials LLC, WTBenecki LLC, numerous industry sources

REPM History

New Era Of Permanent Magnets

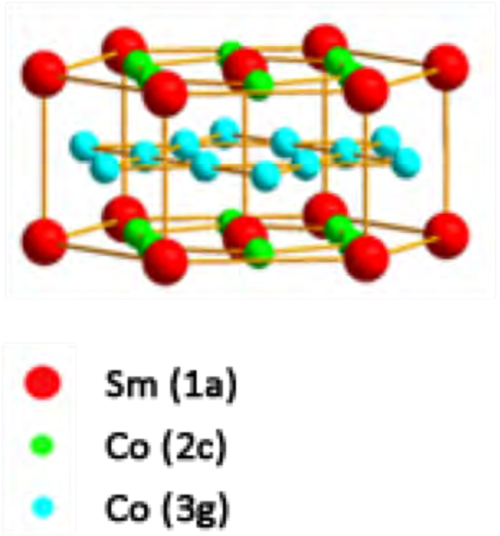
- Following the successful development of Alnico magnets, with energy products up to 13 MGOe, future major advances in permanent magnet materials would require shifting emphasis from shape anisotropy to crystal anisotropy.
- This led, in the 1960s, to studies to identify anisotropic crystalline phases, preferably hexagonal or tetragonal, which combined high saturation magnetization with high magnetocrystalline anisotropy.

New Era Of Permanent Magnets

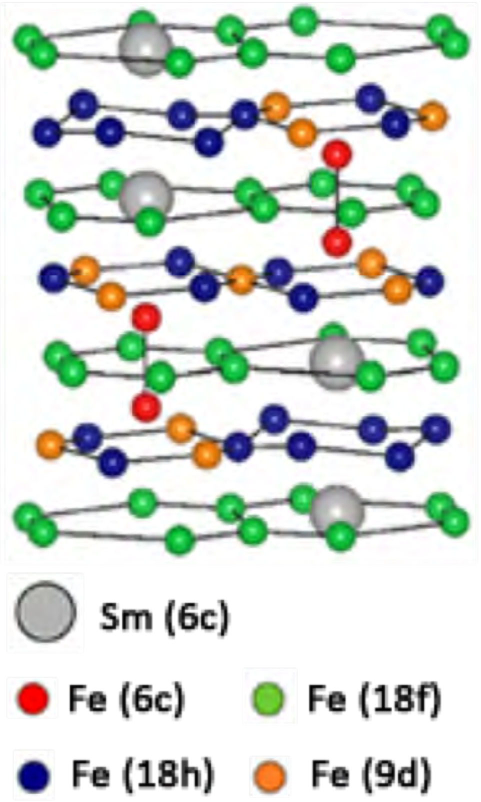
- Several factors focused attention on rare earth intermetallic compounds.
  - First, several of the rare earth elements display magnetic ordering and large magnetic moments at low temperatures.
  - Second, it was known that, because of the large difference in atomic radii between the rare earth and Mn, Fe, Co and Ni atoms, there is a tendency to form several intermetallic compounds in the binary systems.
  - Third, previous work had shown that many of these intermetallic compounds exhibited magnetic ordering by the coupling of the rare earth magnetic moment with the 3d transition element moment.

SmCo-Based Permanent Magnets

- **In order to be possible candidates for permanent magnet materials, the compounds must combine the basic attributes of:**
  - **High saturation magnetization**
  - **Elevated Curie temperature and**
  - **Large magnetocrystalline anisotropy with a magnetically unique crystallographic axis.**
- **All these considerations were found to narrow the group of binary compounds from to RCo_5 and R2Co17 with R =Y, Ce, Pr, Nd or Sm.**
- **This led to the development of commercial Sm-Co magnets based on the binary SmCo5 (nucleation controlled) or multicomponent Sm2Co17 (domain wall pinining) systems.**



$SmCo_5$ Crystal Structure



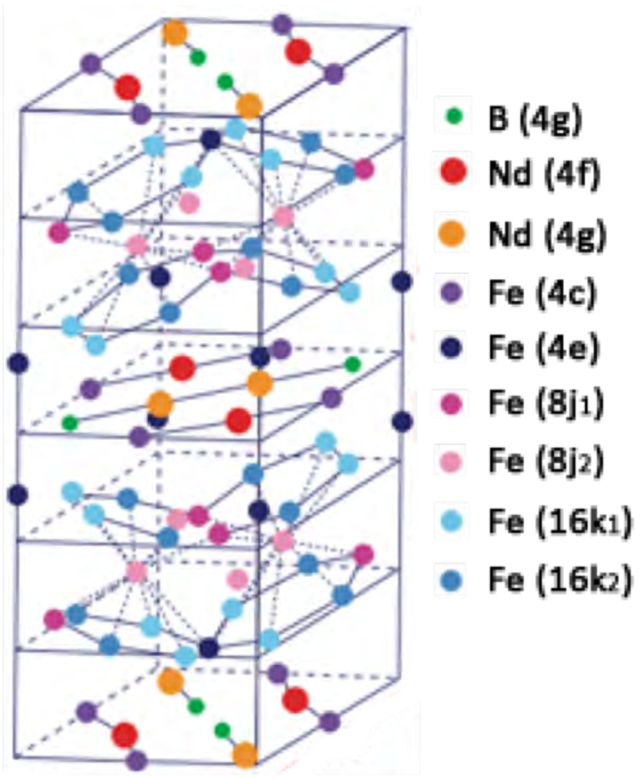
Sm_2Co_{17} Crystal Structure

The NdFeB Era

- Historically, the development of RFe-based permanent magnets, by powder metallurgical processing, has been hindered for several reasons:
  - First, Fe forms much fewer intermetallic compounds with the rare earths than Co.
  - Second, stable compounds of the RFe_5 composition are absent.
  - Third, compounds which are stable, e.g. R_2Fe_{17}, have low Curie temperatures and planar preference anisotropy.

The NdFeB Era

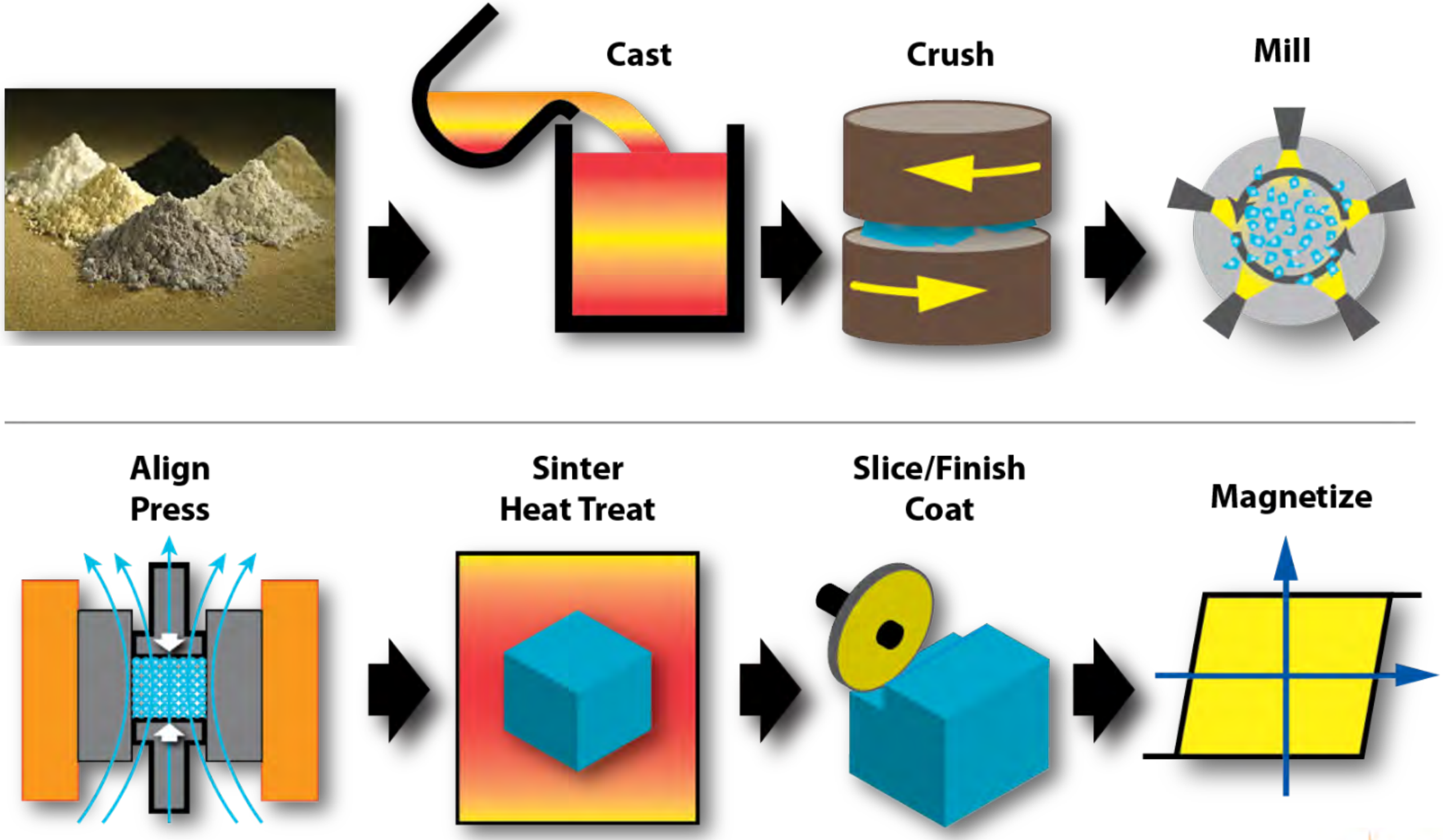
- By a strange coincidence permanent magnets based on the $Nd_2Fe_{14}B$ tetragonal compound were discovered, and the key inventive claims were filed, during 1982 by both General Motors Corporation (GMC) and Sumitomo Special Metals Corporation (SSMC). SSMC was later to form a JV with Hitachi and eventually merged as Hitachi Metals in 2007. GMC spun off the NdFeB magnet business as Magnequench; today part of Neo Materials.
- The Hitachi process is based on powder metallurgical processing whereas the Magnequench process is based on melt spinning or jet casting.



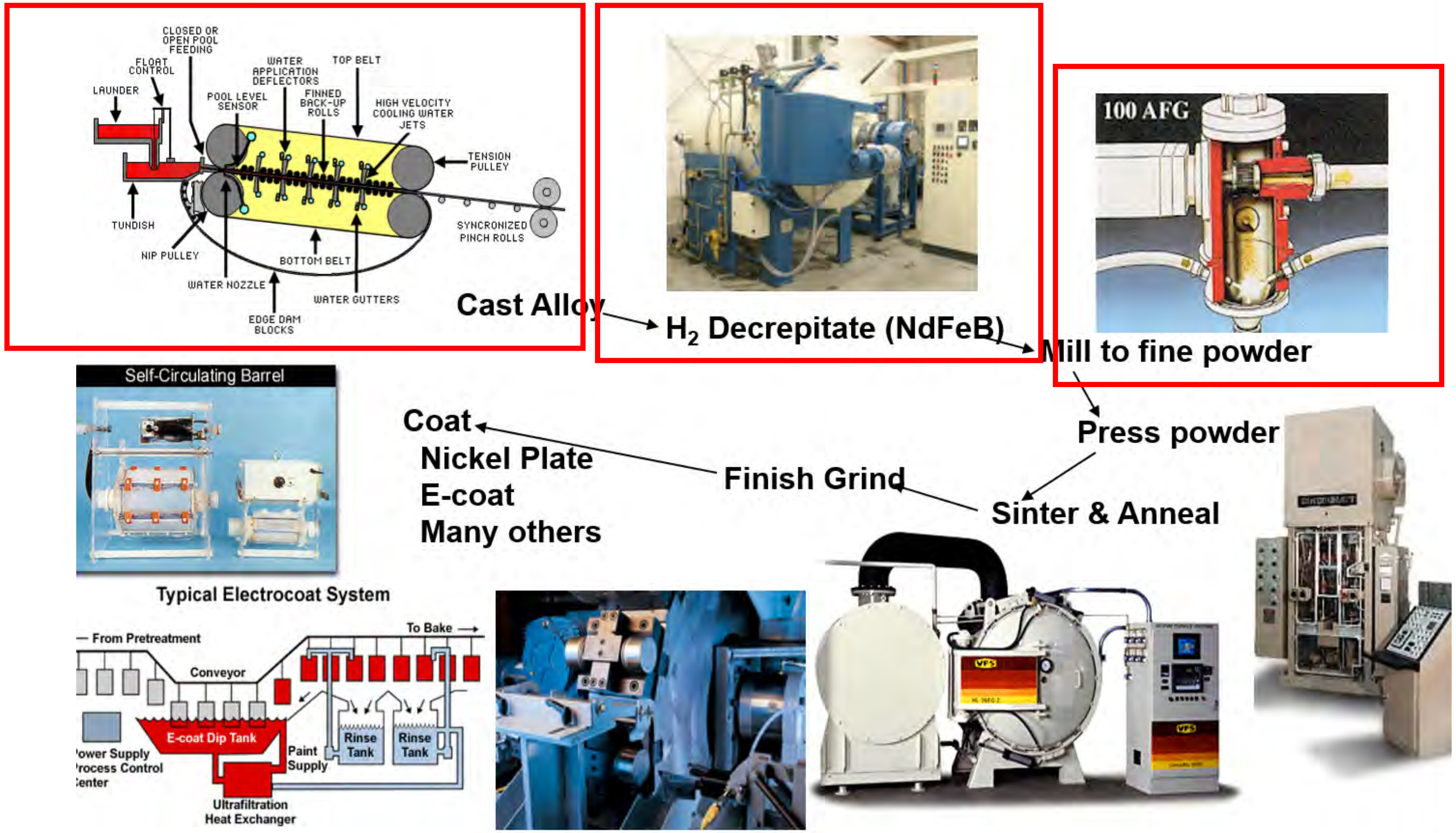
$Nd_2Fe_{14}B$ Crystal Structure

Current Materials And Processes

Generic Powder Metallurgical Processing of REPM's

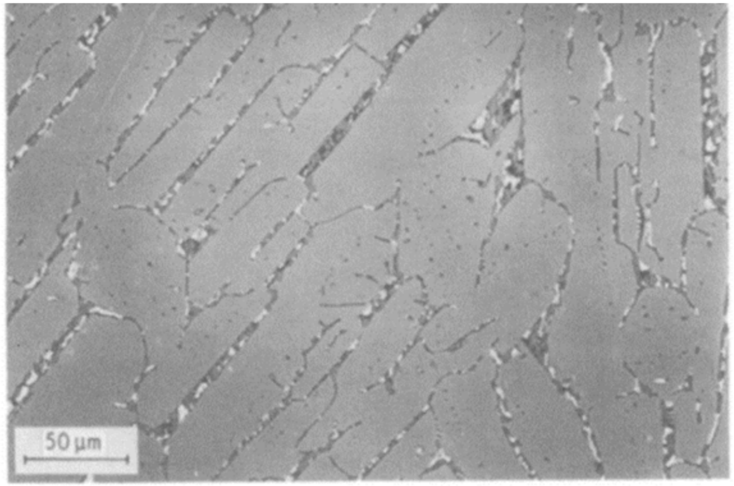


Typical Powder Metallurgical Processing of NdFeB

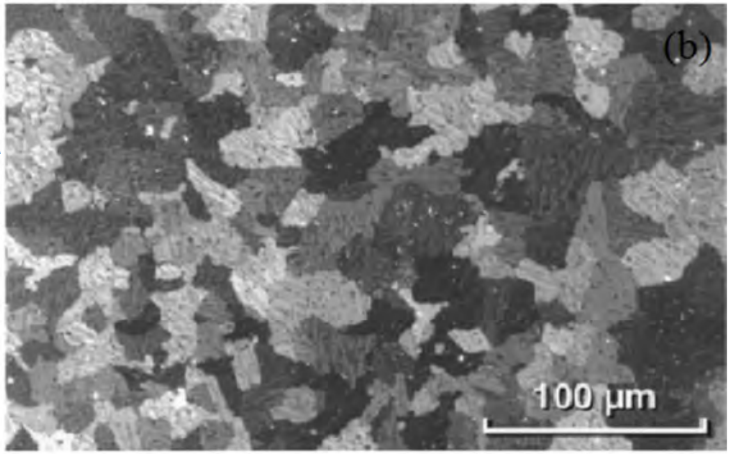


Source: Magnetics and Materials LLC, https://www.magmatllc.com/index.html

Strip Casting Of NdFeB Alloy

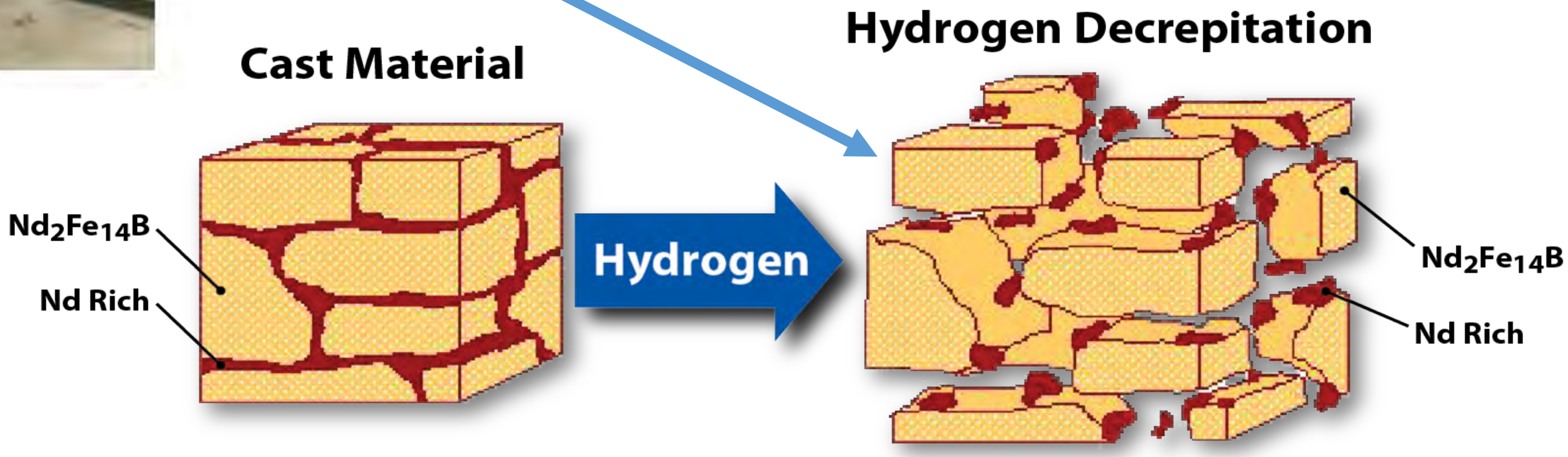


Ingot Cast

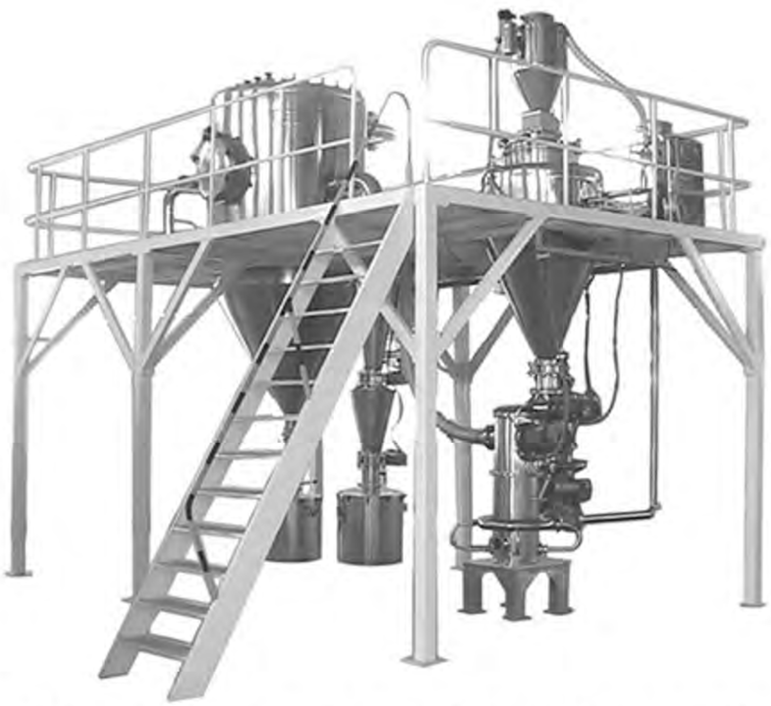


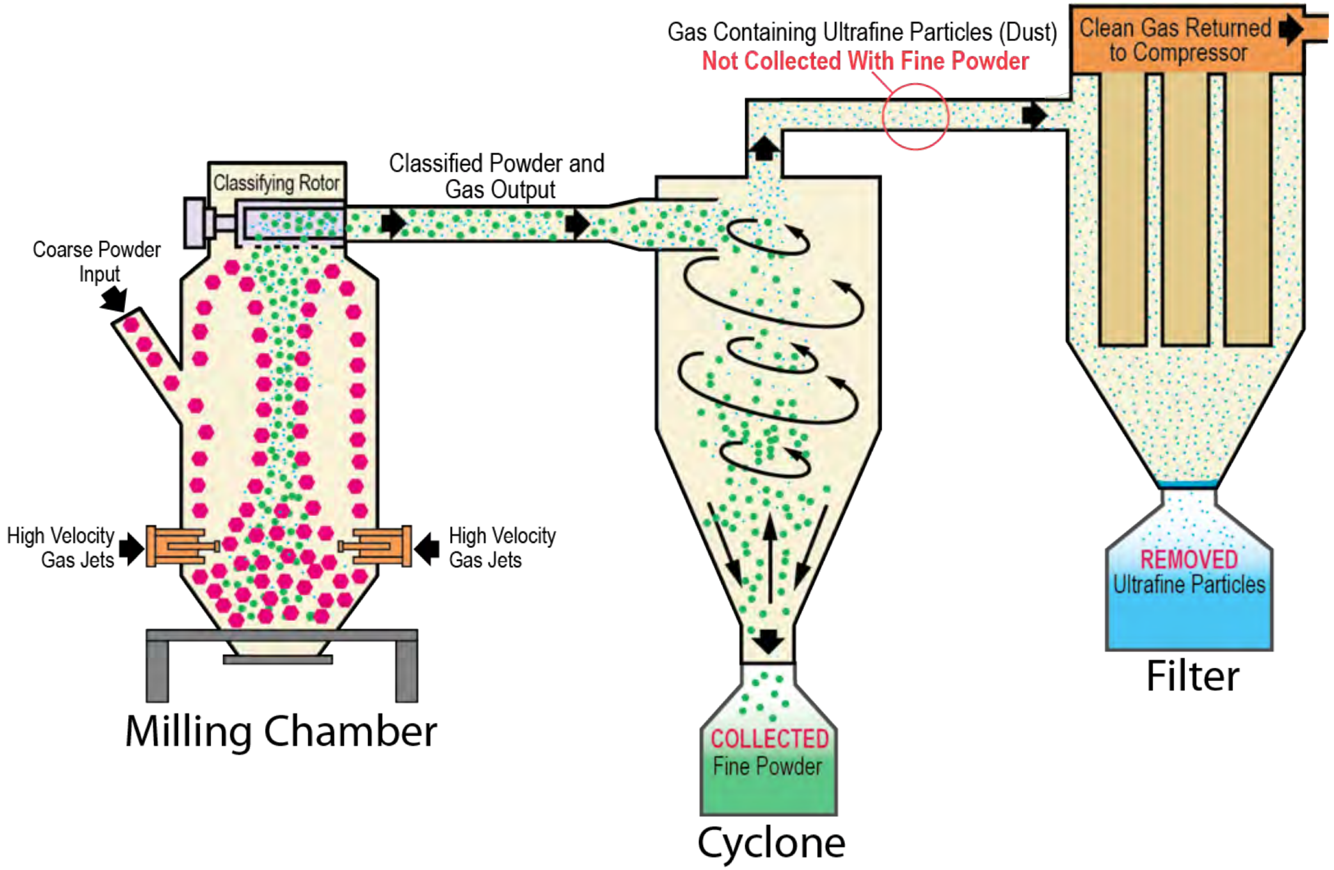
Strip Cast

Coarse Crushing By Hydrogen Decrepitation

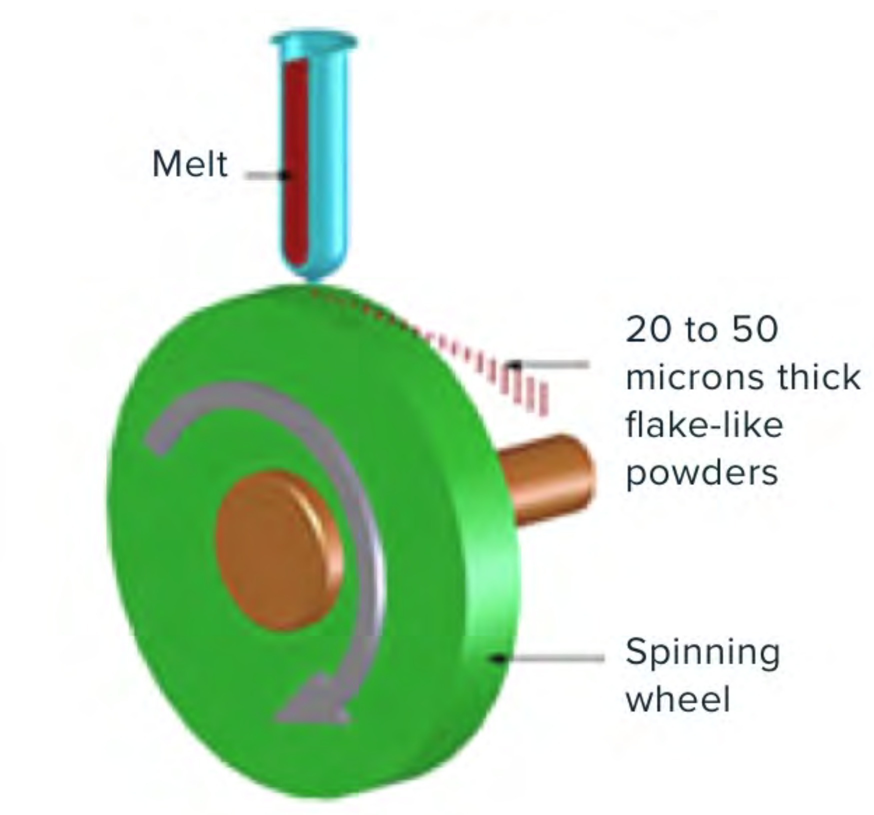


Jet Milling Of NdFeB Powder



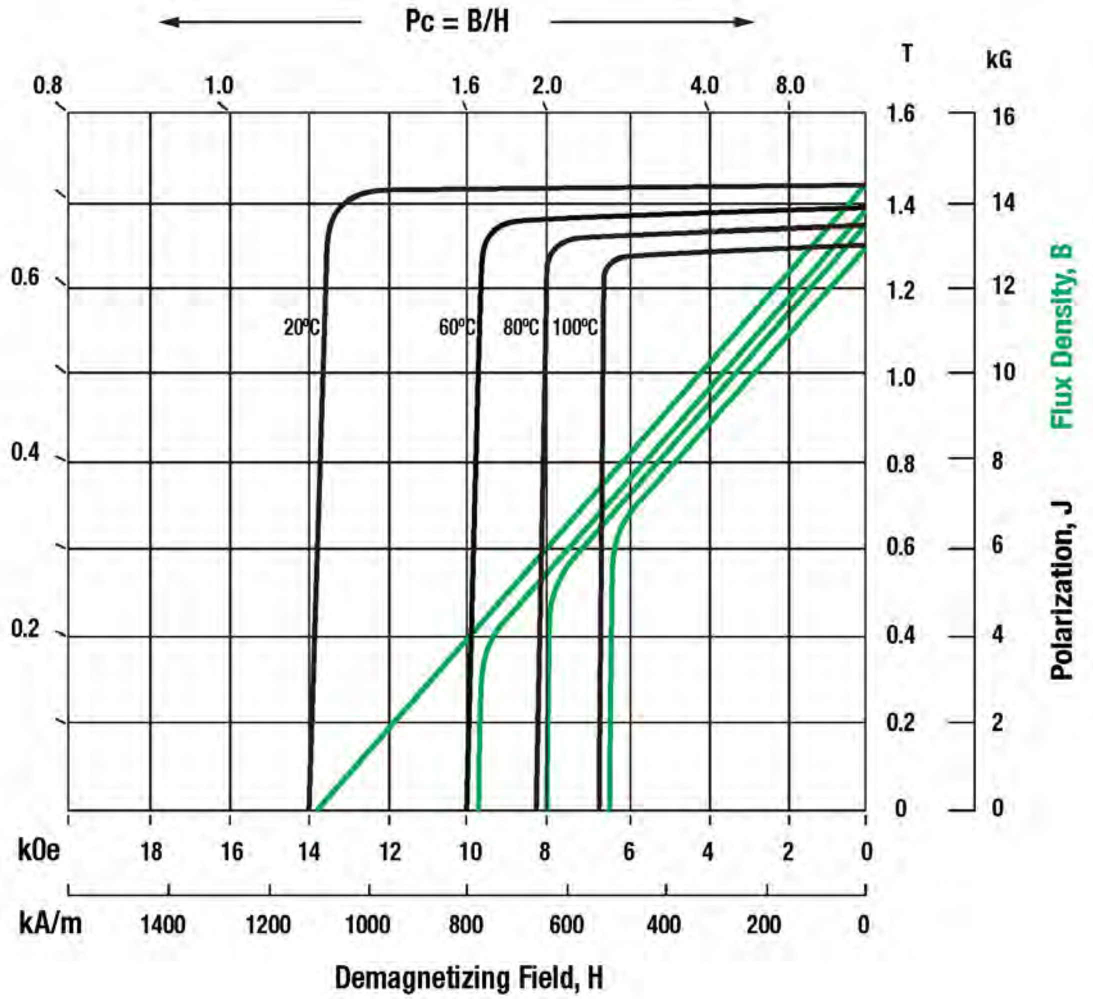


Melt Spinning (Jet Casting) Of NdFeB



- This method of melt-spinning consists of melting the alloy or elements in a tube either under vacuum or inert gas. The melt, under argon pressure, is sprayed through an orifice in the tube onto a rotating, water-cooled copper wheel or disc. Cooling rates in excess of 10^6 K/s are achieved.
- GM commercialized this technology for the production of magnets, known as Magnequench.
- The isotropic powders are mainly used in bonded magnet production.

Demagnetization Behavior At Temperature for NdFeB (N55M)



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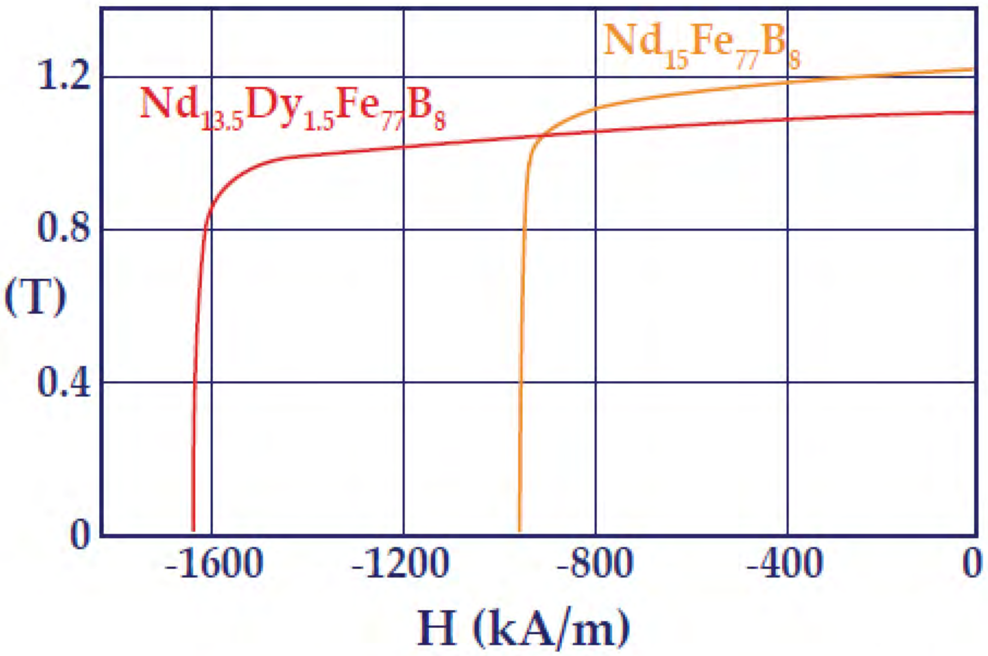
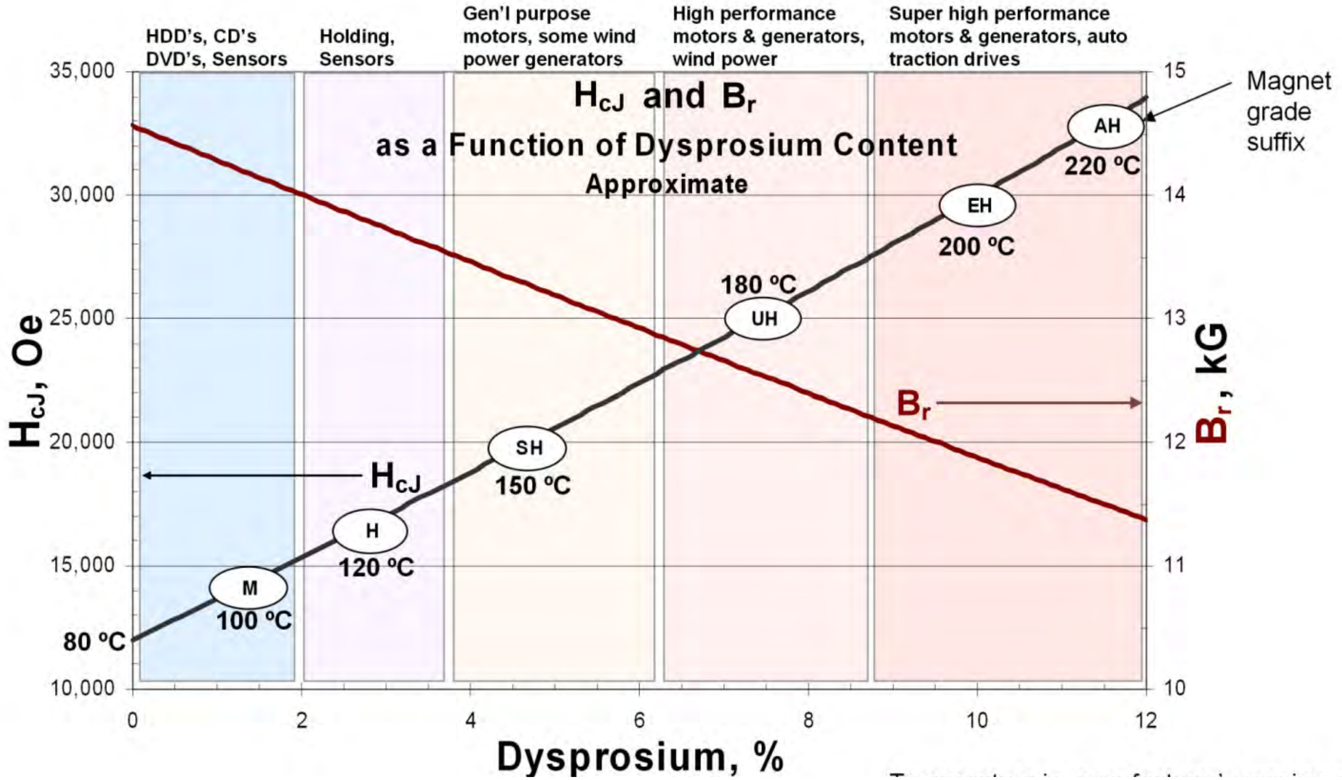
Effect Of Dy On Coercivity





Reference: IEEE Transactions on Magnetics, Volume 20, Issue 5, September 1984, pp. 1584-1589

Source: Magnetics and Materials LLC, https://www.magmatllc.com/index.html

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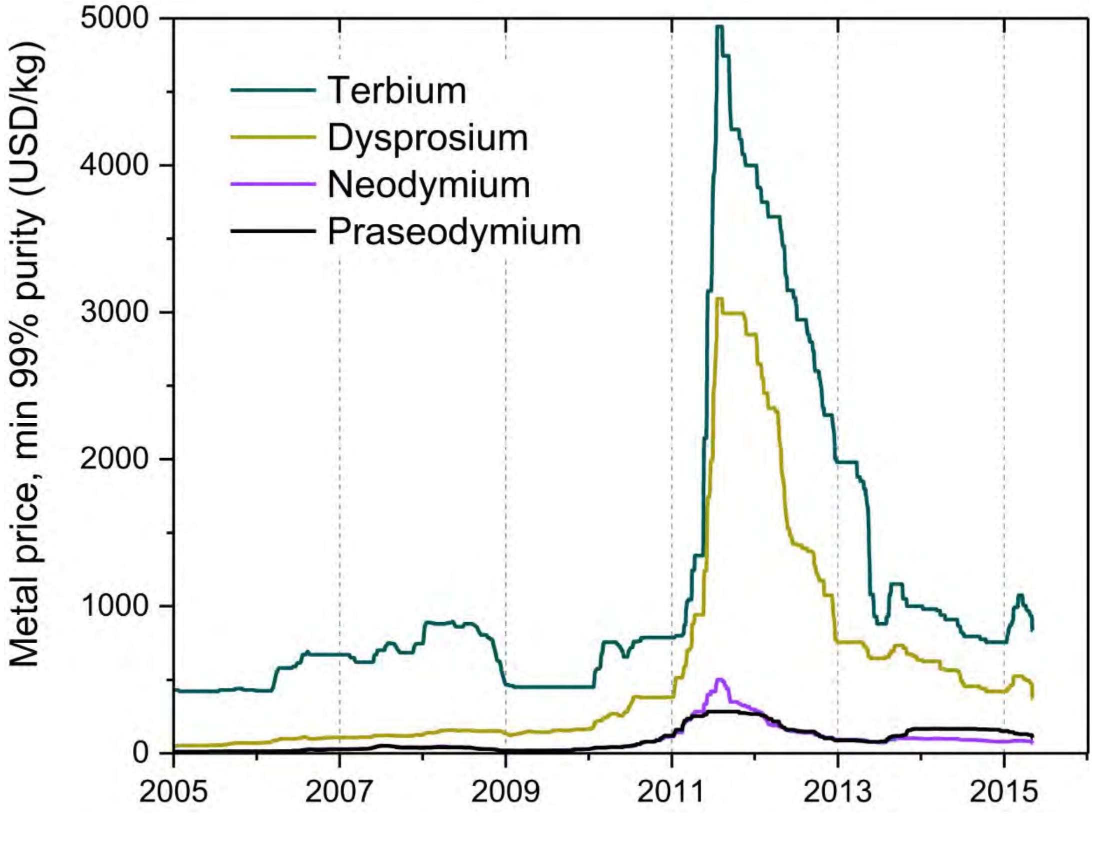
Rare Earth Price And Supply Disruption

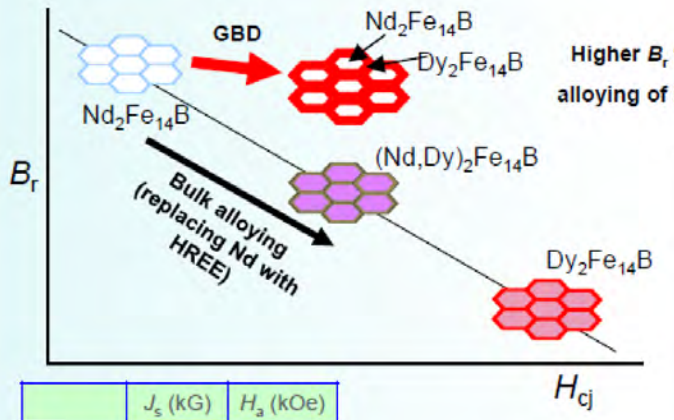


Reference: Resources Policy, Volume 52, June 2017, Pages 349-357

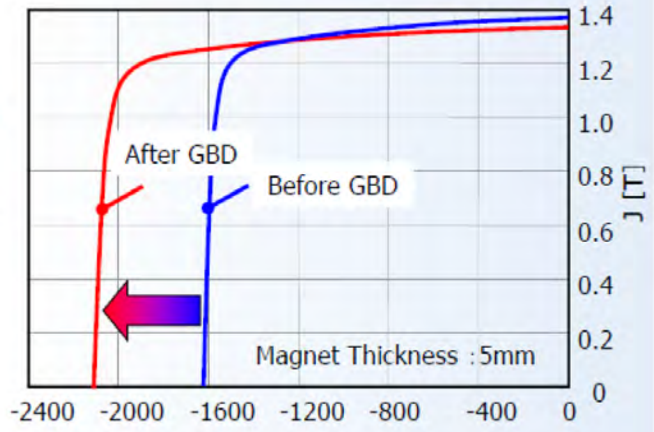
- **Rare Earth prices spiked in 2011/2012 e.g. Dy2O3 price increased 50 fold.**
- **Major investment in search for RE-free substitution and application redesign.**
- **Drove efforts to reduce Dy content for higher temperature/coercivity grades**

Dy Diffusion At Grain Boundaries

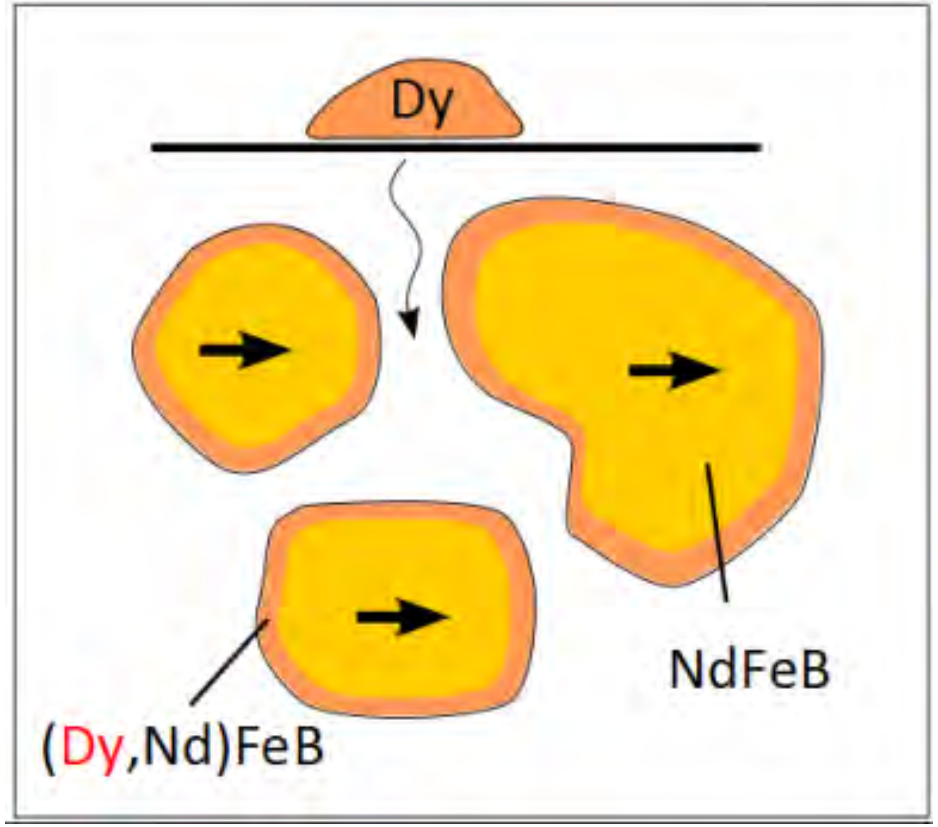
Enhancement of coercivity with small degradation of remanence by diffusing HREE into grain boundary phases and surfaces of grains



	J_s (kG)	H_a (kOe)
$Nd_2Fe_{14}B$	16.0	67
$Pr_2Fe_{14}B$	15.6	87
$Dy_2Fe_{14}B$	7.1	149
$Tb_2Fe_{14}B$	7.0	218



GBD can increase Hcj with minimum decrease in Br.



Reference: Yotaka Yoshida, Daido Steel, Magnetics 2016.

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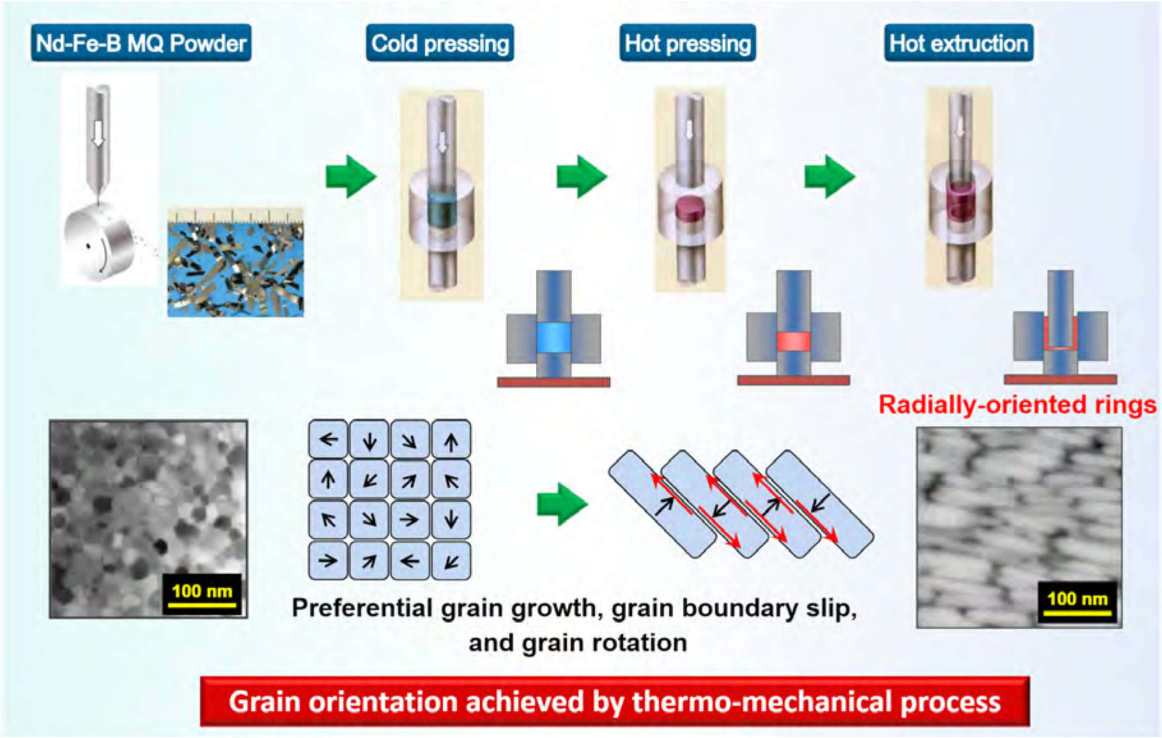
Hot Deformed Radially Oriented Rings



Daido Steel and Honda Adopt World's First Hybrid Vehicle Motor Magnet Free of Heavy Rare Earth Elements

– Honda Freed, on sale this fall, will be the first hybrid vehicle to adopt new magnet –

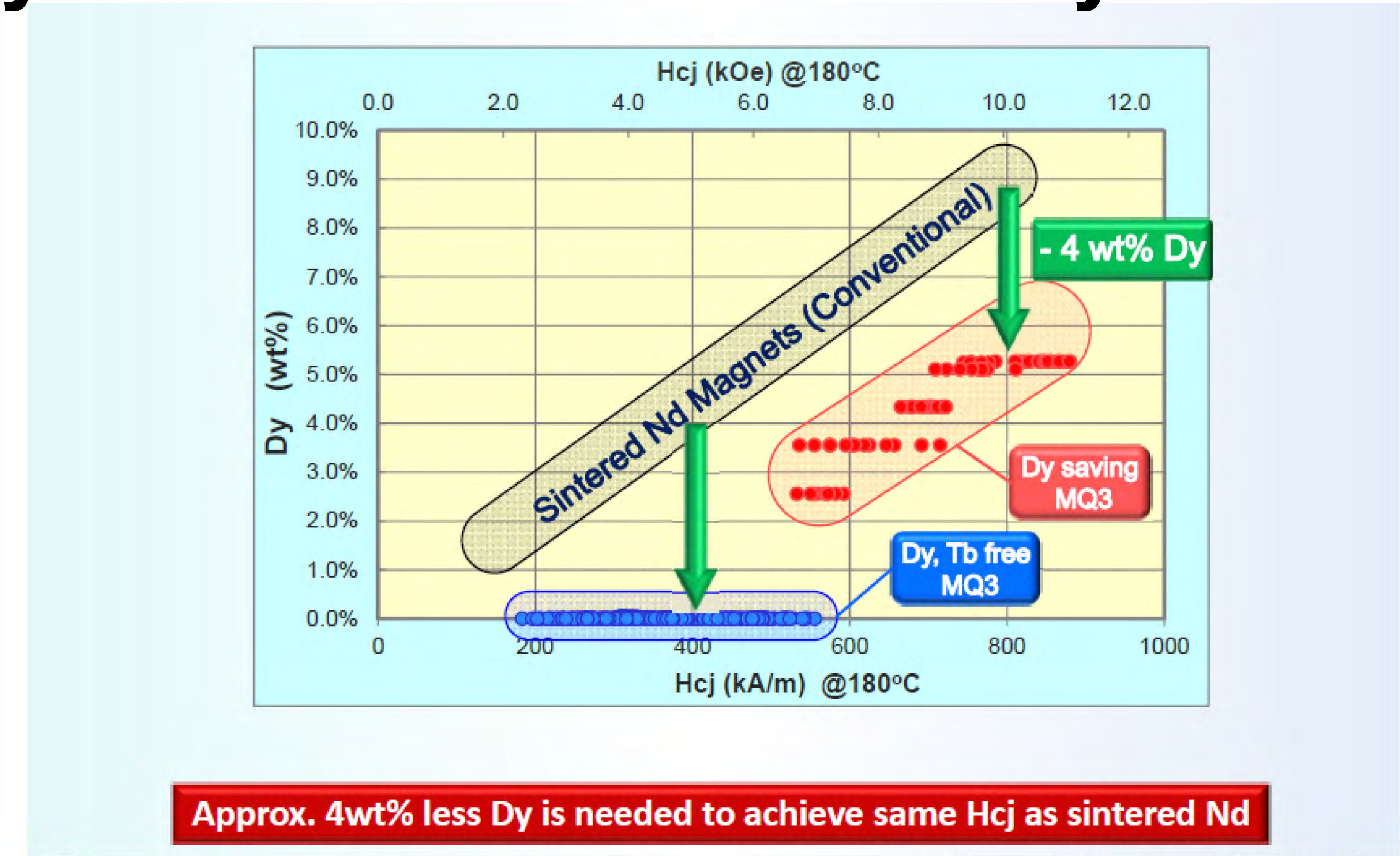
July 12, 2016, Japan   Automobile

DAIDO STEEL   HONDA
The Power of Dreams

TOKYO, Japan, July 12, 2016 - Daido Steel Co., Ltd. and Honda Motor Co., Ltd. became the world's first companies to achieve practical application of a hot deformed neodymium magnet containing no heavy rare earth[*1] and yet with high heat resistance properties and high magnetic performance required for the use in the driving motor of a hybrid vehicle. This heavy rare earth-free hot deformed neodymium magnet will be applied first to the all-new Honda FREED, scheduled to go on sale this fall.

Reference: Yotaka Yoshida, Daido Steel, Magnetics 2016.

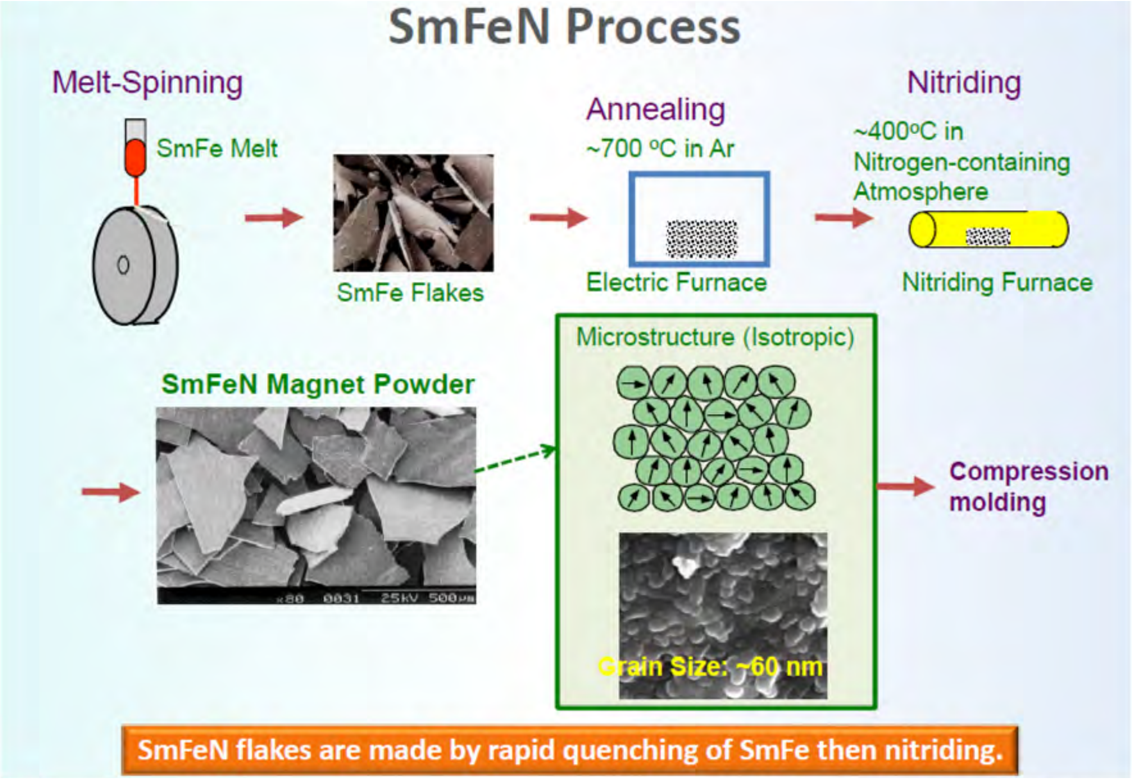
Dy Content versus Coercivity At 180 C



Reference: Yotaka Yoshida, Daido Steel, Magnetics 2016.

Sm-Fe-N Magnets

- Sm-Fe-N alloy is a promising candidate for high-performance permanent magnets.
- The $Sm_2Fe_{17}N_3$ intermetallic compound, which exhibits high saturation magnetization with a large anisotropy field and a high Curie temperature.
- $Sm_2Fe_{17}N_3$ intermetallic compound has been prepared by the production of Sm_2Fe_{17} alloy powder and subsequent nitrogenation of the powder by a gas-solid reaction. The resultant $Sm_2Fe_{17}N_3$ intermetallic compound has thus been produced in powder form for bonded magnets.

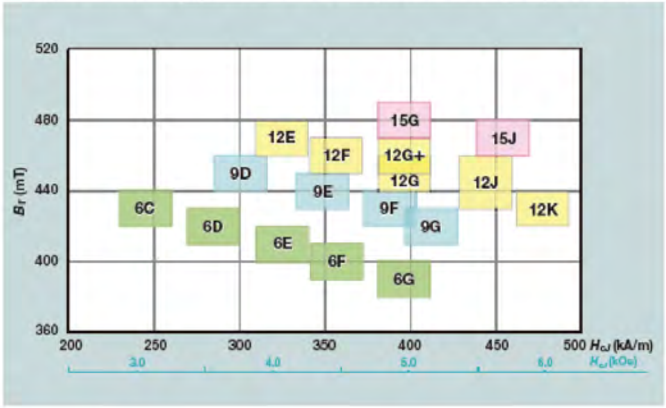


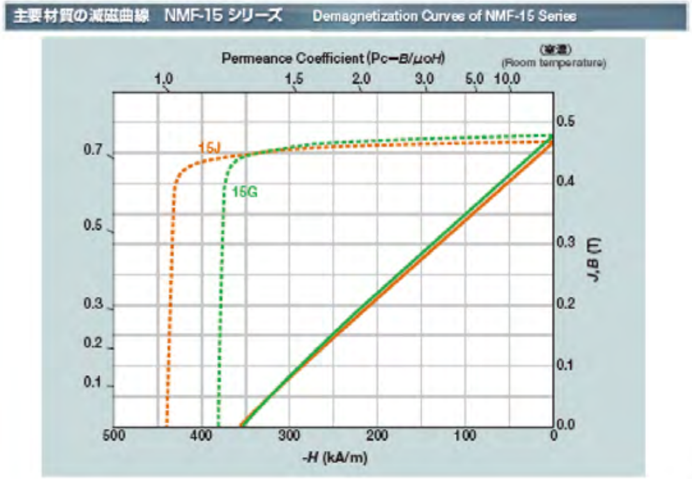
Reference: Yotaka Yoshida, Daido Steel, Magnetics 2016.

La-Co Doped Hard Ferrite Magnets

- **Ever since their discovery by Philips between 1952 and 1956, M-type ferrites have increasingly become widely used in many applications.**
- **Both saturation magnetization as well as magnetocrystalline anisotropy of M-type ferrite fine particles can be modified by the substitution of rare earths.**

The highest level magnetic properties available in a mass-produced ferrite magnets.(As of Mar. 2018)





Source: Hitachi Metals, http://www.hitachi-metals.co.jp/e/products/auto/el/pdf/hg-a27-i.pdf

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Future Trends

The Toyota Magnet Announcement

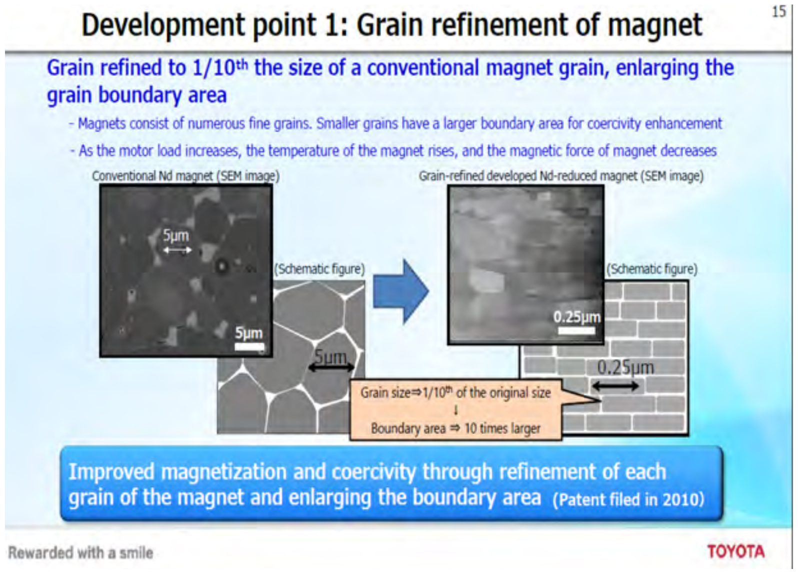
Toyota Motor Corporation

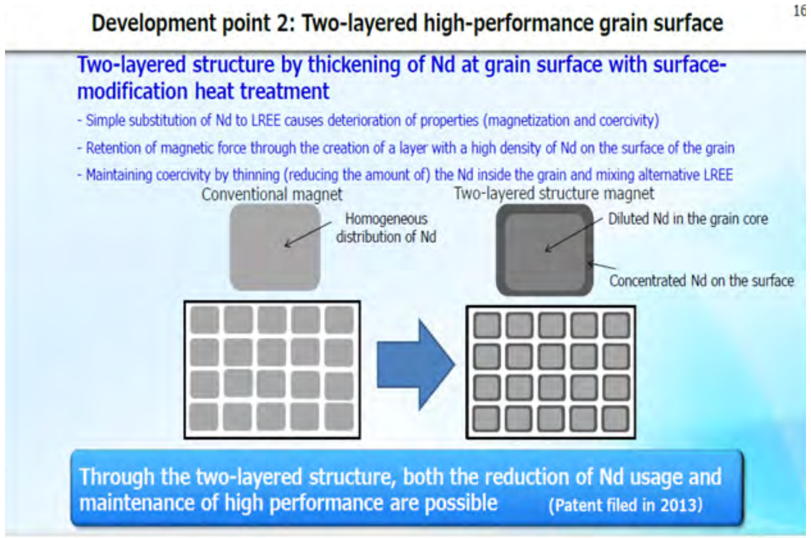
Toyota Develops New Magnet for Electric Motors Aiming to Reduce Use of Critical Rare-Earth Element by up to 50%

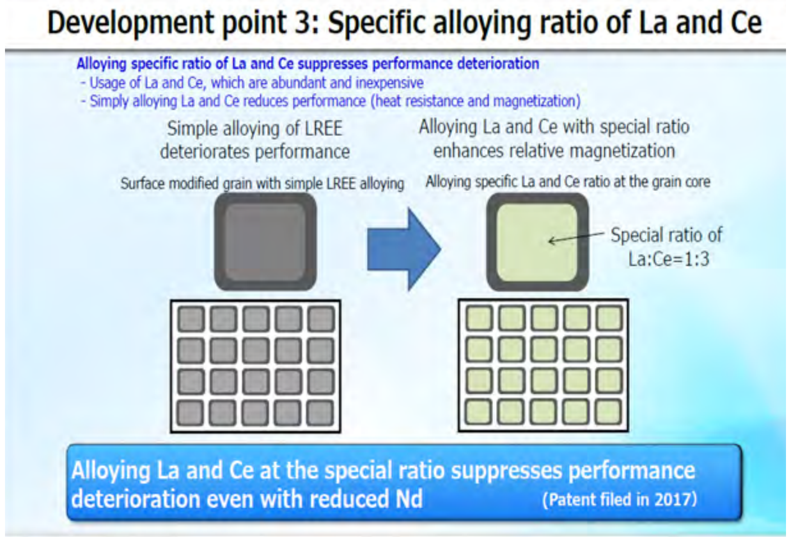
- **World's first neodymium-reduced, heat-resistant magnet developed by Toyota**
- **Key element of the foundation required to popularize electrified vehicles**

Toyota City, Japan, February 20, 2018—Toyota Motor Corporation (Toyota) announces that it has developed the world's first[*1] neodymium-reduced, heat-resistant magnet. Neodymium magnets are used in various types of motors such as the high-output motors found in electrified vehicles, use of which is expected to increase rapidly in the future. The new magnet uses significantly less neodymium, a rare-earth element[*2] ("rare earth"), and can be used in high-temperature conditions.

The Toyota Magnet Announcement





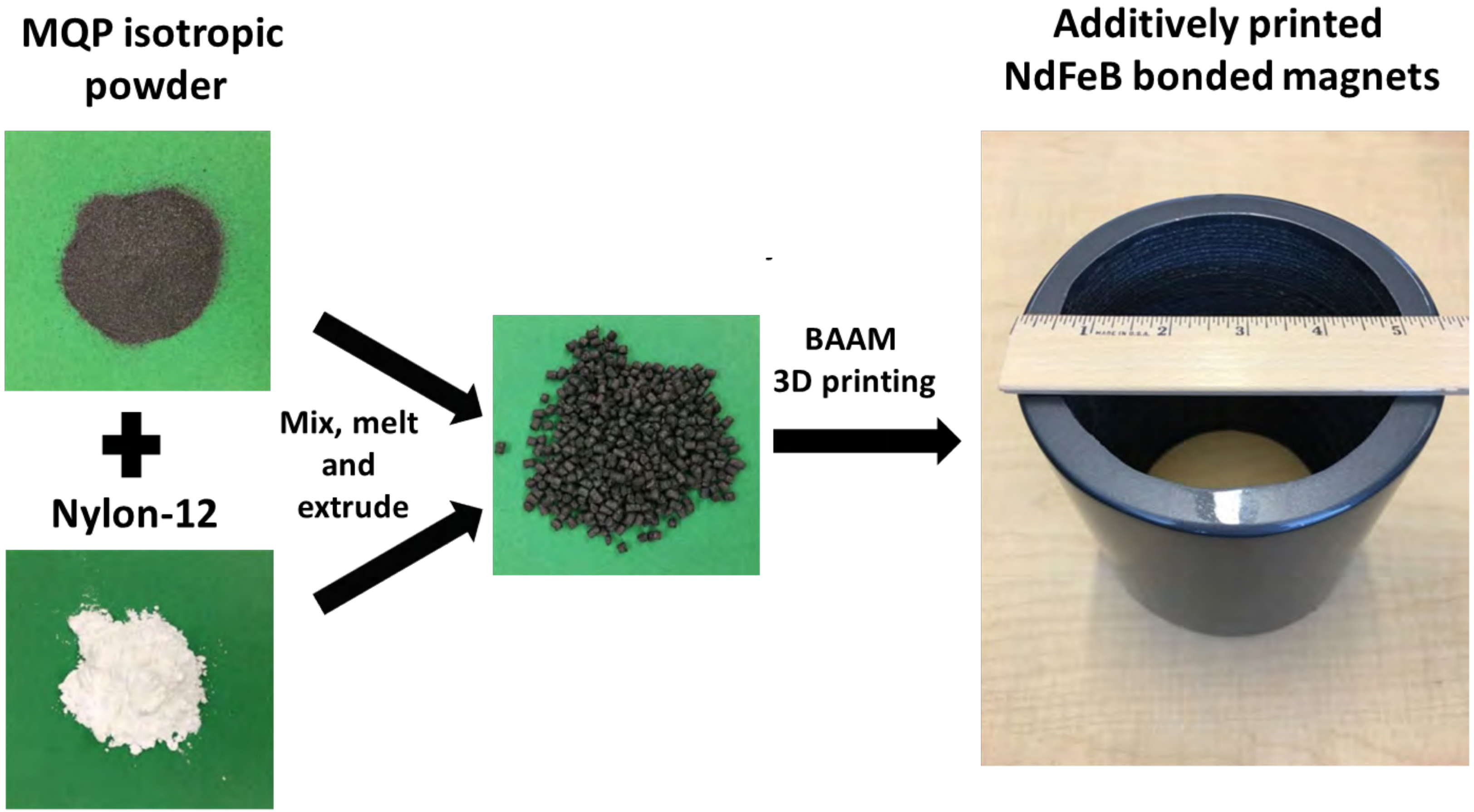


- **Appears to be La/Ce substituted alloy with a fine grained (melt spun) microstructure achieving enhanced coercivity.**
- **Similar to Dy-diffusion processing Nd is concentrated at the grain boundaries.**

Additive Manufacturing/3D Printing of Bonded Magnets

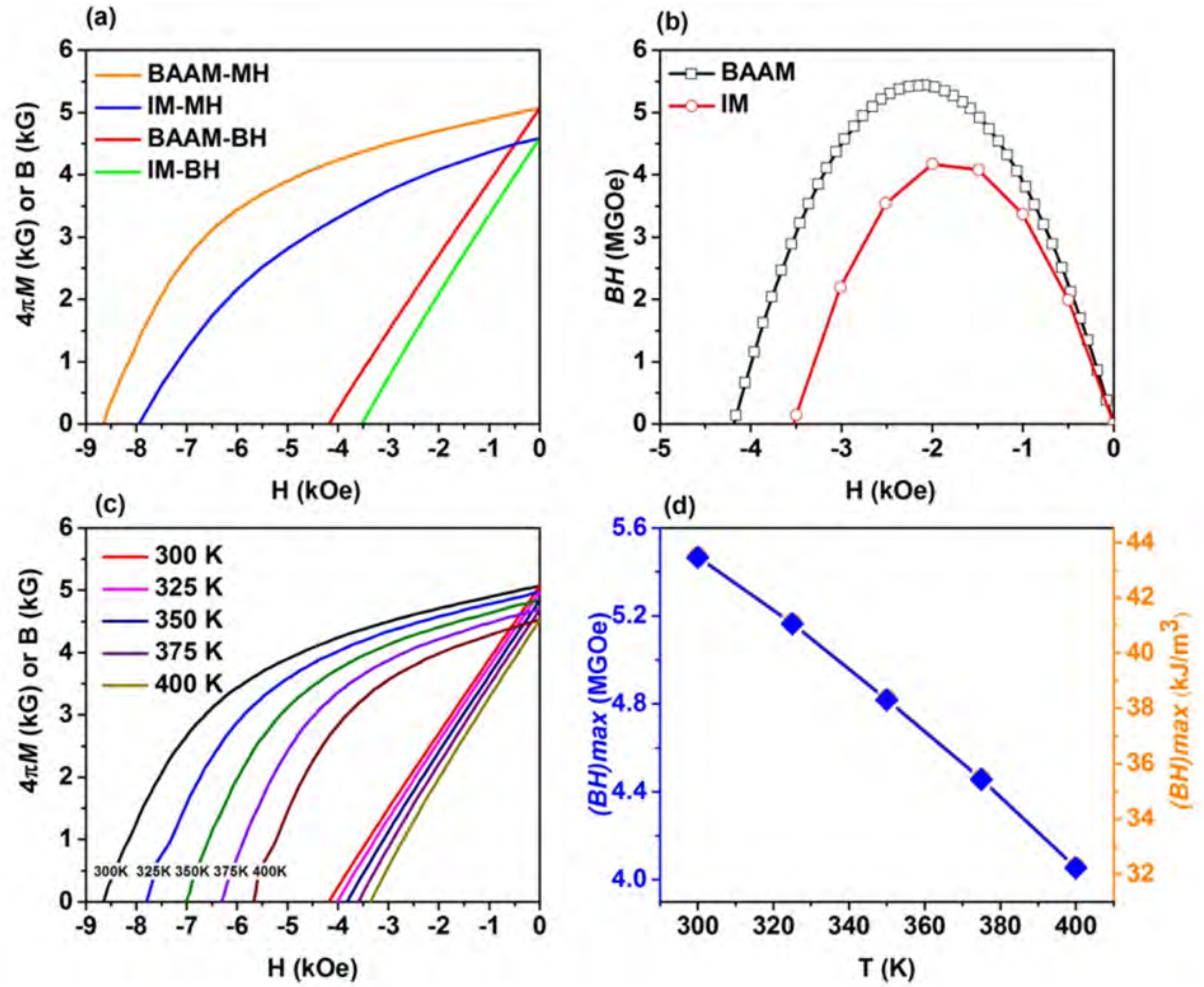
- Additive Manufacturing refers to a process by which digital 3D design data is used to build up a component in layers by depositing material. The term "3D printing" is increasingly used as a synonym for Additive Manufacturing.
- AM can form complex shapes requiring little or no tooling and post-processing thus reducing the amount of waste generated.
- Work performed at Oak Ridge National Laboratories, TN.

Big Area Additive Manufacturing of NdFeB Bonded Magnets



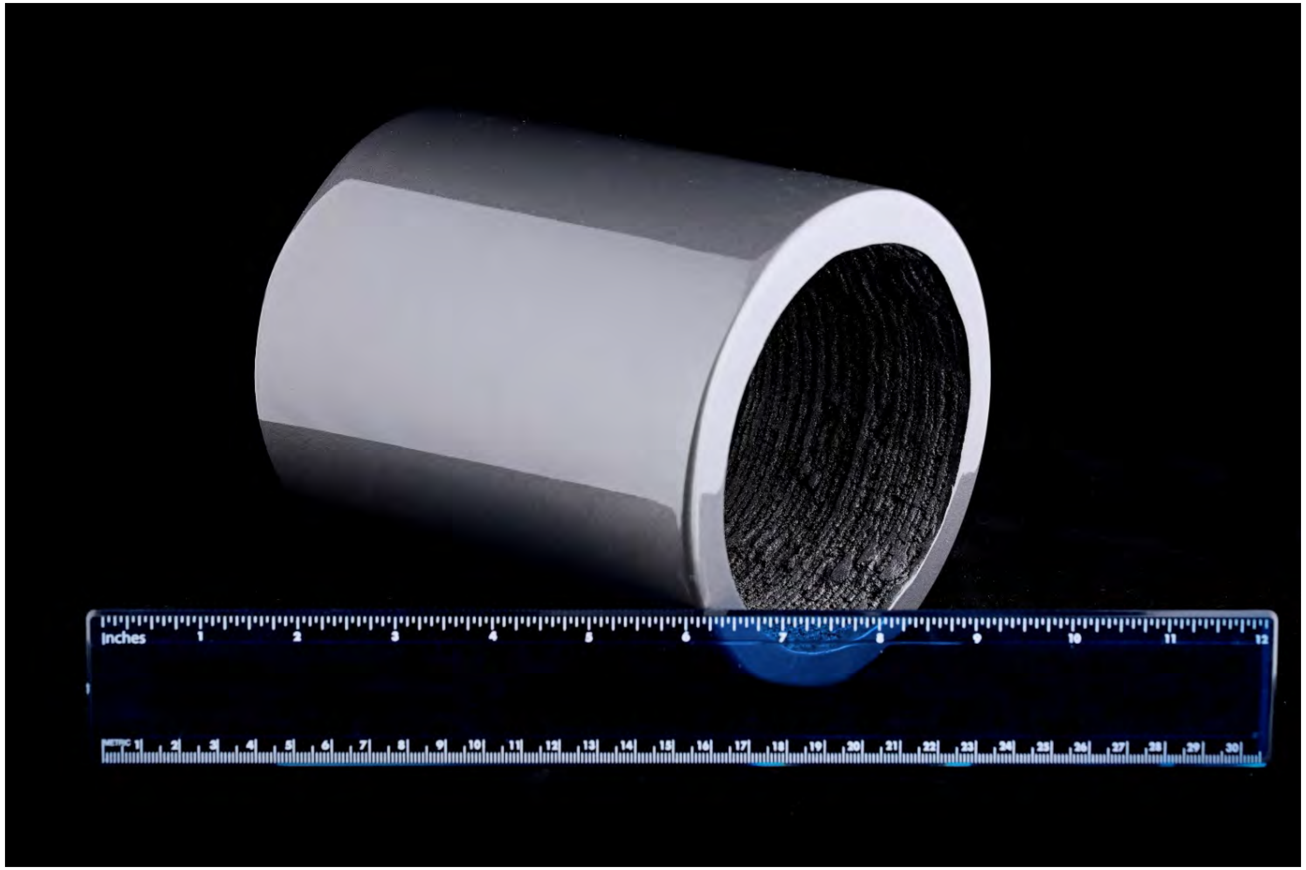
Reference: Li, L. et al. Big Area Additive Manufacturing of High Performance Bonded NdFeB Magnets. Sci. Rep. 6, 36212

BAAM versus IM Magnetic Properties



Reference: Li, L. et al. Big Area Additive Manufacturing of High Performance Bonded NdFeB Magnets. Sci. Rep. 6, 36212

Big Area Additive Manufacturing (BAAM) of NdFeB Bonded Magnets
Surprise – you can make big magnets!



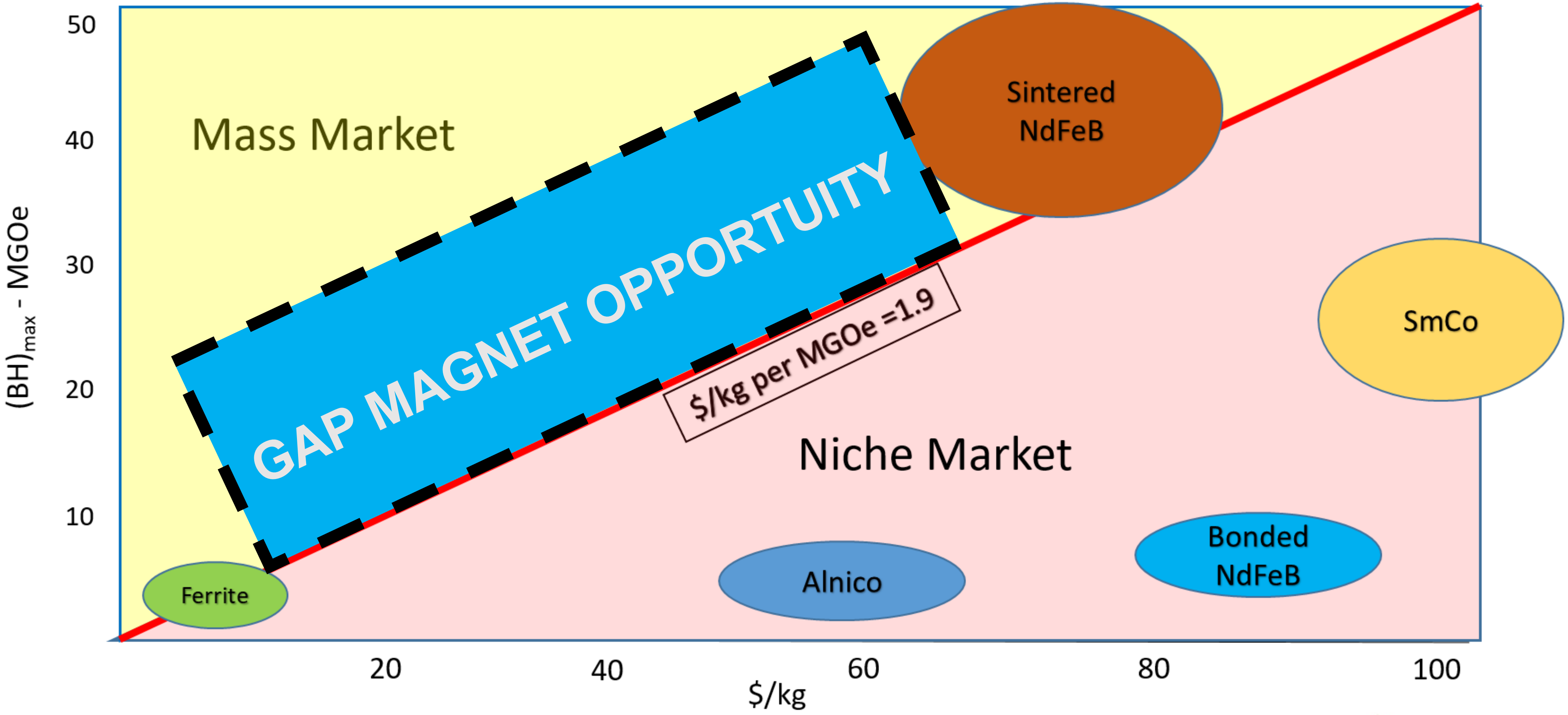
Reference: Li, L. et al. Big Area Additive Manufacturing of High Performance Bonded NdFeB Magnets. Sci. Rep. 6, 36212

Final Thoughts

Is There An Optimum Price-Performance Metric?

Material	Average $(BH)_{max}$ (MGOe)	Average price ($/kg)	Price/Performance ($/kg per MGOe)	Market %
NdFeB	40	75	1.9	60
Ferrite	3.8	7.1	1.9	31
Bonded NdFeB	8	90	11.3	5
SmCo	25	100	4.0	2
Alnico	7	58	8.3	2

Niche And Mass Market Materials



Thank you for your attention
Any Questions?

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