Current Technology Status and Future Needs For Rare Earth Permanent Magnets For Industrial Applications

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Magnet Applications, Inc.
Outline

• Markets And Applications
• PM Principles – Back to Basics
• 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
“The Nation That Controls Magnetism Will Control The Universe”

- Dick Tracy cartoon strip, created by Chester Gould.
- Circa early-1960’s i.e. before rare earth magnets and the Chinese dominance of RE supply chain and magnet industry!
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History of Permanent Magnet Development
Is It Time For A New Breakthrough?
Commercially Important Permanent Magnets

$\text{(BH)}_{\text{max}} - \text{MGOe}$

- Ferrite
- Alnico
- Bonded NdFeB
- SmCo
- Sintered NdFeB
- Gap Magnet
## Estimated Permanent Magnet Market - 2016

<table>
<thead>
<tr>
<th>Material</th>
<th>Weight (000’s kg)</th>
<th>Value ($ Millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NdFeB</td>
<td>137,500</td>
<td>10,300</td>
</tr>
<tr>
<td>Ferrite</td>
<td>750,000</td>
<td>5,300</td>
</tr>
<tr>
<td>Bonded NdFeB</td>
<td>10,000</td>
<td>900</td>
</tr>
<tr>
<td>SmCo</td>
<td>4,000</td>
<td>400</td>
</tr>
<tr>
<td>Alnico</td>
<td>6,000</td>
<td>350</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>Approximately $17 B</strong></td>
<td></td>
</tr>
</tbody>
</table>
Market ($) Dominated By NdFeB And Ferrite

- Ferrite: 31%
- NdFeB: 60%
- Bonded NdFeB: 5%
- SmCo: 2%
- Alnico: 2%
<table>
<thead>
<tr>
<th>Application Category</th>
<th>Physical Law</th>
<th>System Function is Proportional to</th>
<th>Application Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical to</td>
<td>Lorentz Force law</td>
<td>B</td>
<td>Loudspeakers, PM motors, HDD/ODD VCM</td>
</tr>
<tr>
<td>Mechanical (with</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>solid conductor)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mechanical to</td>
<td>Faraday’s Law of Induced voltage</td>
<td>B</td>
<td>Generators, Alternator, Tachometer, Magneto,</td>
</tr>
<tr>
<td>Electrical</td>
<td></td>
<td></td>
<td>Microphone, Eddy current devices, sensors</td>
</tr>
<tr>
<td>Magnetostatic Field</td>
<td>Coulomb Force Principles</td>
<td>B²</td>
<td>Magnetic Chucks, Conveyors, Magnetic Separators, Reed Switches, Synchronous Torque Couplings</td>
</tr>
<tr>
<td>Energy to Mechanical</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Work</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrical to</td>
<td>Lorentz Force law</td>
<td>B</td>
<td>Travelling Wave Tubes, Magnetrons, Klystrons, MRI</td>
</tr>
<tr>
<td>Mechanical (with free</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>charged particles)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Market By Major Application Type

- Motors: 45%
- HDD/ODD: 11%
- Sensors: 4%
- Generators: 4%
- MRI: 5%
- Separation: 5%
- Holding: 5%
- Loudspeakers: 8%
- Misc: 13%
Automotive Applications – NdFeB Is Gaining Ground!

Current And Future Major Applications

• Hybrid and electric cars & trucks are in a rapid growth phase:
  • 2018 forecast 25 million units.
  • 18,000 tonnes of REPM’s in 2020.
  • Forecast to be largest consumer of RE magnets by 2025.

• Electric bicycles is another large and growing application:
  • Estimated 13,000 tonnes in 2020

• HDD (servers, cloud storage):
  • Future demand flat to declining.
  • 9,000 tonnes in 2018

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 tonnes.

• Automotive (ICE):
  • Over 100 PM devices in a typical car.
  • Estimated 12,000 tonnes 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
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The Three Magnetic Vectors

• **H** - Magnetic field (from current).

• **B** - Magnetic flux density or Induction.

• **M** – Magnetization (a material property).
  
  • These vectors are not independent, but are related.
  
  • Induction is the combination of magnetization and magnetic field.

Source: Spontaneous Materials, http://www.spontaneousmaterials.com/
How Are B, H and M Related?

\[ B = H + 4\pi M \quad \text{cgs units} \]

\[ B = \mu_0 (H + M) \quad \text{SI units} \]

\[ \mu_0 = 4\pi \times 10^{-7} \text{ Tesla-m/A} \]
Hysteresis Loops – Normal and Intrinsic

2nd Quadrant Demagnetization

Normal curve (B-H)

Intrinsic curve (4πM-H)

Curves typical of a permanent magnet
Permanent Magnet Key Characteristics

2\textsuperscript{nd} Quadrant Demagnetization

**Graph:**
- \( B, 4\pi M \)
- \( B_r \)
- \( B_m \)
- \( H_c \)
- \( H_m \)
- Load line
- Intrinsic Curve
- Normal Curve

**Equations:**
- \( B(H) \)
- \( B_r \)
- \( B_m \)
- \( H_c \)
- \( H_m \)
What Is (BH)max?

\[ H_g^2 = (B_m H_m) V_m / V_g \]  
Hence, Vm is minimum when BH is maximum
What Is (BH)\(_{\text{max}}\)?

- \(H_g^2 = (B_mH_m)V_m/V_g\)
- \(E_g = H_g^2V_g/8\pi\)

- Hence in order to minimize magnet volume (\(V_m\)) the magnet is designed to operate at \((BH)_{\text{max}}\).
- It's possible for static applications but not for dynamic applications.
- \((BH)_{\text{max}} \rightarrow B_r^2/4\)
Many Other Important Characteristics (BH)_{max} Is Only One!

- $B_r$
- $BH_c$
- $IH_c$
- $H_k$
- Recoil permeability
- Rate of change of B and $BH_c$ with temperature
- Maximum operating temperature
- Ease of magnetizing

- Resistivity
- Mechanical properties
- Machinability
- Shape availability
- Raw material cost and availability
- Corrosion resistance
- Manufacturability and ease of device/sub assembly integration
- Economics of total raw materials and manufacturing process
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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 RCo₅ 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 pinning) systems.
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$_2$Fe$_{17}$, have low Curie temperatures and planar preference anisotropy.
The NdFeB Era

- By a strange coincidence permanent magnets based on the Nd$_2$Fe$_{14}$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 Performance Materials.

- The Hitachi process is based on powder metallurgical processing whereas the Magnequench process is based on melt spinning or jet casting.
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Generic Powder Metallurgical Processing of REPM’s
Typical Powder Metallurgical Processing of NdFeB

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)
Effect Of Dy On Coercivity


Rare Earth Price And Supply Disruption

- 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

Reference: Resources Policy, Volume 52, June 2017, Pages 349-357
Dy Diffusion At Grain Boundaries

Hot Deformed Radially Oriented Rings

Dy Content versus Coercivity At 180 C

Sm-Fe-N Magnets

- Sm-Fe-N alloy is a promising candidate for high-performance permanent magnets.
- The Sm$_2$Fe$_{17}$N$_3$ intermetallic compound, which exhibits high saturation magnetization with a large anisotropy field and a high Curie temperature.
- Sm$_2$Fe$_{17}$N$_3$ intermetallic compound has been prepared by the production of Sm$_2$Fe$_{17}$ alloy powder and subsequent nitrogenation of the powder by a gas-solid reaction. The resultant Sm$_2$Fe$_{17}$N$_3$ intermetallic compound has thus been produced in powder form for bonded magnets.

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.

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The Toyota Magnet Announcement

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 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 ("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

BAAM versus IM Magnetic Properties

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

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Is There An Optimum Price-Performance Metric?

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<thead>
<tr>
<th>Material</th>
<th>Average (BH)$_{max}$ (MGOe)</th>
<th>Average price ($/kg)</th>
<th>Price/Performance ($/kg per MGOe)</th>
<th>Market %</th>
</tr>
</thead>
<tbody>
<tr>
<td>NdFeB</td>
<td>40</td>
<td>75</td>
<td>1.9</td>
<td>60</td>
</tr>
<tr>
<td>Ferrite</td>
<td>3.8</td>
<td>7.1</td>
<td>1.9</td>
<td>31</td>
</tr>
<tr>
<td>Bonded NdFeB</td>
<td>8</td>
<td>90</td>
<td>11.3</td>
<td>5</td>
</tr>
<tr>
<td>SmCo</td>
<td>25</td>
<td>100</td>
<td>4.0</td>
<td>2</td>
</tr>
<tr>
<td>Alnico</td>
<td>7</td>
<td>58</td>
<td>8.3</td>
<td>2</td>
</tr>
</tbody>
</table>
Niche And Mass Market Materials

GAP MAGNET OPPORTUNITY

Mass Market

Niche Market

$\langle BH \rangle_{max}$ - MGOe

$/kg$ per MGOe = 1.9

Ferrite

Alnico

Bonded NdFeB

Sintered NdFeB

SmCo
Thank you for your attention
Any Questions?

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