Permanent Magnet Material Options: Why $/kg And (BH)_{max} Are Misleading Metrics!

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Senior Technology Advisor
Magnet Applications, Inc.
“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!
Presentation Outline

• Introduction to Magnet Applications, Inc.

• Price/Performance – Niche or mass market?

• $/kg – Who buys magnets by weight?

• \((BH)_{\text{max}}\) – Is it really the best performance metric?

• NdFeB patent litigation update.
Introduction: Magnet Applications, Inc.

• Visit the latest website at: http://magnetapplications.com.

• A Bunting Magnetics Company: https://buntingmagnetics.com/.

• Only North American manufacturer of compression bonded NdFeB and injection molded ferrite, NdFeB and hybrid magnets.

• Supply full range of engineered magnets and magnetic assemblies.

• Located in DuBois, PA – Originally established in UK over 50 years ago – sister company located in Berkhamsted, UK.

• Primary applications are BLDC motors and sensors in the automotive, medical, defense and industrial markets.
Introduction: Magnet Applications, Inc.

- Pre-production magnetic design services including 3D magnetic modeling.
- State of the art manufacturing capabilities including in-house coating and complete magnetic testing suite.
- Investing in R & D for next generation of magnetic materials e.g. high Br compression bonded, 3D printed magnets.
- The backing of strong family ownership – in business for over 55 years.
- ISO-9001 Certified Quality System with a strong continuous improvement culture.
- Very strong international supply chain for the complete range of permanent magnet materials.
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Historical Development Of Permanent Magnets
Commercially Important Permanent Magnets

- Ferrite
- Alnico
- Bonded NdFeB
- SmCo
- Sintered NdFeB
- Gap Magnet

(BH)\(_{\text{max}}\) - MGOe
Permanent Magnet Market Estimates – It’s A Challenge

• Fragmented Industry with 100’s of suppliers (over 800 in Asia Pacific region) – for NdFeB there are 20 Top tier, 50 mid-level and 100’s third tier suppliers.


• Installed capacity versus sales.

• In house production.

• Value added assemblies.

• Exchange rate fluctuations.

• RE raw material price volatility.
Permanent Magnet Market (2016) – Don’t Mistake Precision For Accuracy!

- Markets and Markets $14.76B
- Grandview Research $23.37B
- Global Market Insights $23.32B
- Transparency Market Research $21.86B
- Market Research Reports $14.53B
- Walt T. Benecki LLC (Global PM Industry 3rd Ed.) $21.54B
- Magnets and Magnetic Materials LLC $13.77B
Permanent Magnet Market – My Guess

<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></td>
<td><strong>Approximately $17 B</strong></td>
</tr>
</tbody>
</table>
Market ($) Dominated By NdFeB And Ferrite – Why?
Is There An Optimum Price-Performance Metric?

<table>
<thead>
<tr>
<th>Material</th>
<th>Average (BH)$_{\text{max}}$ (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**
  - $\langle B H \rangle_{\text{max}} - \text{MGOe}$
  - $$/kg per MGOe = 1.9$

- **Mass Market**
  - Sintered NdFeB
  - Bonded NdFeB
  - SmCo

- **Niche Market**
  - Ferrite
  - Alnico
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$/kg – What Are The Problems?

• From first principles the field produced in a airgap ($H_g$) is a function of the volume of magnetic material ($V_m$).

\[
H_g^2 = (B_m H_m) \frac{V_m}{V_g}
\]

(see Culity and Graham, 2nd Ed)
$/kg – What Are The Problems?

• By experience we specify magnets by dimensions and geometry not weight.
• We buy and use a volume of magnet material.
### Material Density (g/cm³)

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<td>NdFeB</td>
<td>7.5</td>
</tr>
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<td>Ferrite</td>
<td>5.0</td>
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<tr>
<td>Bonded NdFeB</td>
<td>5.1</td>
</tr>
<tr>
<td>SmCo</td>
<td>8.4</td>
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- Different magnet materials have different densities.
- On a volume basis Ferrite has a price performance ratio of approximately 50% better than NdFeB.
Normalized Price/Performance Based On Weight and Volume (Ferrite is 1.0)

<table>
<thead>
<tr>
<th>Material</th>
<th>Average ((BH)_{\text{max}}) (MGOe)</th>
<th>Average price ($/kg)</th>
<th>Price/Performance (Unit Weight)</th>
<th>Price/Performance (Unit Volume)</th>
</tr>
</thead>
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<tr>
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$/kg – What Are The Problems? Magnets Come In All Shapes And Sizes!

Source: Audemars Microtec
$/kg – What Are The Problems?

• Processing costs and material loss tend to be higher for smaller magnets.
• e.g. magnets that require machining the $/kg is a function of size:
  • Assume machining allowance of 0.1 mm.
  • Material loss for small block is 73% and 6% for large block.
$/kg – What Are The Problems?

- Average is well just average.
- Wide range of grades (therefore cost) within a material class:
  - Ferrite from dry pressed isotropic < 1 MGOe to LaCo doped at > 5 MGOe.
  - Prices range over an order of magnitude.
  - Over 100 NdFeB grades - Dy drives operating temperature and cost.

Source: Magnetics and Materials LLC
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What Is \((BH)_{\text{max}}\)?

- \(H_g^2 = (B_m H_m) V_m / V_g\) – Hence, \(V_m\) is minimum when \(BH\) is maximum
- \(E_g = H_g^2 V_g / 8\pi\) – Energy in airgap is proportional to \(BH\)
  
  (see Culity and Graham, 2\textsuperscript{nd} Ed)
What Is \((BH)_{\text{max}}\)?

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

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.
- \((BH)_{\text{max}} \rightarrow B_r^2 / 4\)
## Major Functions Of A Magnet

<table>
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<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 Mechanical (with solid conductor)</td>
<td>Lorentz Force law</td>
<td>$B$</td>
<td>Loudspeakers, PM motors, HDD/ODD VCM</td>
</tr>
<tr>
<td>Mechanical to Electrical</td>
<td>Faraday’s Law of Induced voltage</td>
<td>$B$</td>
<td>Generators, Alternator, Tachometer, Magneto, Microphone, Eddy current devices, sensors</td>
</tr>
<tr>
<td>Magnetostatic Field Energy to Mechanical Work</td>
<td>Coulomb Force Principles</td>
<td>$B^2$</td>
<td>Magnetic Chucks, Conveyors, Magnetic Separators, Reed Switches, Synchronous Torque Couplings</td>
</tr>
<tr>
<td>Electrical to Mechanical (with free charged particles)</td>
<td>Lorentz Force law</td>
<td>$B$</td>
<td>Travelling Wave Tubes, Magnetrons, Klystrons, MRI</td>
</tr>
</tbody>
</table>
Many Other Important Characteristics

- $B_r$
- $BH_c$
- $IH_c$
- $H_k$
- 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
- Process Control and Quality Assurance
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NdFeB Patent Litigation Update
“Oh what a tangled web we weave..........”

• Update from Magnetics 2017 presentation and LinkedIn article (https://www.linkedin.com/pulse/ndfeb-magnet-patents-oh-what-tangled-web-we-weave-john-ormerod/)

• HML’s Federal Court Appeal of PTAB invalidity ruling on IPR’s of 6,537,385 and 6,491,765.

• ‘765 and ‘385 – Removal of RE-rich particles less than 1 micron from RE alloy magnetic powder.

• April 2017 the court affirmed most of the conclusions that lower courts had previously ruled in the “Hitachi Metals, Ltd. v. Alliance of Rare-Earth Industry” case.

• The Federal Court ordered the PTAB to reconsider whether the 2 claims (‘765) requiring some amount of oxygen in the high speed gas in the jet mill are obvious.

• Currently awaiting PTAB ruling (and Supreme Court decision on IPR constitutionality).
NdFeB Patent Litigation Update
“Oh What A Tangled Web We Weave..........”

• On April 24, 2017, three Chinese companies (DMEGC, Zhejiang Innuovo and Zhejiang Dongyang East Magnetic Rare Earth) filed IPR petitions challenging HML’s US patents 6,461,565 and 6,527,874.

• ‘565 – Method of pressing a RE alloy magnetic powder in a controlled environment from 5°C to 30°C and RH from 40% to 65%.

• ‘874 – RE magnetic alloy containing 0.1 to 1.0 At % Nb.

• On November 5th, 2017 the USPTO initiated IPR proceedings for ‘565 but denied the petition for ‘874.

• Discovery phase for the ‘565 IPR began January 2018.
Final Thoughts

• When selecting the optimum material the application details and environmental conditions are critical.
• Need to compare cost and performance for specific magnet geometry and grades – averages can be misleading.
• $/kg is misleading when comparing material types.
• Consider all the magnet parameters not just \((BH)_{\text{max}}\).
• Mass market “Gap Magnet” opportunity is very large.
• 2018 – 35 years since the commercial introduction of NdFeB magnets.
  • Still litigating the IP rights!
  • Many thousands of hours by very smart researchers have been devoted and millions of $‘s invested in the search for the next big thing.

“If you really look closely, most overnight successes took a long time”
- Steve Jobs
Driverless vehicles and AI are the future
More magnetic applications!