Permanent Magnet Options: How To Select The Optimum Solution For Your Application.

Dr. John Ormerod
Senior Technology Advisor
Magnet Applications, Inc.
Presentation Outline

• Introductions.

• Major permanent magnet materials and types.

• Key permanent magnet characteristics.

• Be careful of $/kg.

• Thermal and environmental considerations.
Introduction: John Ormerod

• BSc, MSC and PhD in Metallurgy from the University of Manchester (1972 – 1978).
• Magnetics career began with Philips (UK and Holland) - 1979 – 1990.
  • Developed and commercialized SmCo5, 2:17 and NdFeB magnets
• Joined Arnold Engineering (US) responsible for soft and hard magnetic materials development and GM for permanent magnets (1990 – 2002).
• 2002 - 2014 President of Res Manufacturing in Milwaukee.
  • Metal stamping and value added assemblies to the automotive market (Toyota, GM, Nissan)
  • Major supplier to Tesla Motors for Model S and future Model X
• Founded business and technology consultancy for magnetics and metals related industries in 2015 – JOC LLC (www.jocllc.com).
• Recently provided expert testimony on issues of invalidity during the rare earth magnet ITC investigation and currently advising the Rare Earth Magnet Alliance on prior art relative to Hitachi Metals key patents.
• Advisory Board member for Bunting Magnetics, Senior Technology Advisor for MAI and Technology Advisor for Niron Magnetics.
Introduction: Magnet Applications, Inc.

- 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

![Diagram showing historical development of permanent magnets with labels for Magnetocrystalline, Strain, and Shape.]
Commercially Important Permanent Magnets

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

(BH)_{max} - MGOe
Manufacturing Methods

• Sintered Magnets
  • Most NdFeB Magnets and SmCo

• Casting
  • Alnico

• Ceramic Magnets
  • Ferrites

• Compression Bonded Magnets
  • Mainly Isotropic NdFeB

• Injection Molded Magnets
  • NdFeB or Ferrite

• Flexible Magnets
  • Mainly Ferrite but also some NdFeB

• 3D Printed Magnets?
## 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

- NdFeB: 60%
- Ferrite: 31%
- Bonded NdFeB: 5%
- SmCo: 2%
- Alnico: 2%
Market By Major Application Type

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

Source: TDK Tech Notes
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The Three Magnetic Vectors

• B - Magnetic flux density or Induction.

• H - Magnetic field (from current).

• M – Magnetization (a material property).

• These vectors are not independent, but are related.

• Induction is the combination of magnetization and magnetic field.
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

Intrinsic curve

Curves typical of a permanent magnet
Permanent Magnet Key Characteristics

2\textsuperscript{nd} Quadrant Demagnetization

- $H$
- $IHc$
- $BHc$
- $Hm$
- $Br$
- $Bm$
- $B, 4\pi M$

Load line

Intrinsic Curve

Normal Curve
Demagnetization Curves

Material: N52M

\[ P_c = \frac{B}{H} \]

- Flux Density, B
- Polarization, J
- Demagnetizing Field, H
- T, kg

Graph showing demagnetization curves for different temperatures (20°C, 50°C, 60°C, 100°C).
Key PM Magnetic Properties

• **Br**, Remanence or Remanent Induction – indicates available flux output from the magnet after magnetized to saturation.

• **Hci** (or Hcj), Intrinsic coercivity or **Hcb**, normal coercivity – indicates the magnet’s resistance to demagnetization.

• **(BH)max**, Maximum Energy Product – a figure of merit for how much potential magnetostatic energy is available in a circuit.

• **Hk**, Value in Oersteds (kA/m) that indicates the loop squareness.

• **Reversible Temperature Coefficients** (Br and Hci) – these indicate how the magnetic characteristics change with temperature.
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
- \(E_g = H_g^2 V / 8\pi\) – Energy in airgap is proportional to \(BH\)

(see Culity and Graham, 2nd 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.
- \((BH)_{\text{max}} \rightarrow B_r^2 / 4\)
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
# Major Functions Of A Magnet

<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><strong>Electrical to</strong></td>
<td><strong>Lorentz Force law</strong></td>
<td><strong>B</strong></td>
<td><strong>Loudspeakers, PM motors, HDD/ODD VCM</strong></td>
</tr>
<tr>
<td><strong>Mechanical (with</strong></td>
<td><strong>Faraday’s Law of Induced voltage</strong></td>
<td><strong>B</strong></td>
<td><strong>Generators, Alternator, Tachometer, Magneto, Microphone, Eddy current devices, sensors</strong></td>
</tr>
<tr>
<td><strong>solid conductor)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Mechanical to</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Electrical</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Magnetostatic Field</strong></td>
<td><strong>Coulomb Force Principles</strong></td>
<td><strong>B²</strong></td>
<td><strong>Magnetic Chucks, Conveyors, Magnetic Separators, Reed Switches, Synchronous Torque Couplings</strong></td>
</tr>
<tr>
<td><strong>Energy to Mechanical</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Work</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Electrical to</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Mechanical (with</strong></td>
<td><strong>Lorentz Force law</strong></td>
<td><strong>B</strong></td>
<td><strong>Travelling Wave Tubes, Magnetrons, Klystrons, MRI</strong></td>
</tr>
<tr>
<td><strong>free charged particles)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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$/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.
What Are The Problems?

• Different magnet materials have different densities.
• On a volume basis Ferrite has a price performance ratio of approximately 50% better than NdFeB.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (g/cm3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NdFeB</td>
<td>7.5</td>
</tr>
<tr>
<td>Ferrite</td>
<td>5.0</td>
</tr>
<tr>
<td>Bonded NdFeB</td>
<td>5.1</td>
</tr>
<tr>
<td>SmCo</td>
<td>8.4</td>
</tr>
<tr>
<td>Alnico</td>
<td>7.3</td>
</tr>
</tbody>
</table>
## 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>
<tbody>
<tr>
<td>Ferrite</td>
<td>3.8</td>
<td>7.1</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>NdFeB</td>
<td>40</td>
<td>75</td>
<td>1.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Bonded NdFeB</td>
<td>8</td>
<td>90</td>
<td>5.9</td>
<td>6.1</td>
</tr>
<tr>
<td>SmCo</td>
<td>25</td>
<td>100</td>
<td>2.1</td>
<td>3.5</td>
</tr>
<tr>
<td>Alnico</td>
<td>7</td>
<td>58</td>
<td>4.4</td>
<td>6.4</td>
</tr>
</tbody>
</table>
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# Types of Thermal Effects

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Reversible</td>
<td>Change in output as a function of temperature – reversible temperature coefficient of $B$ - $\alpha$ (function of Curie temperature of the material).</td>
</tr>
<tr>
<td>2. Irreversible-Recoverable</td>
<td>Critical conditions exceeded, magnet partially demagnetized – reversible temperature coefficient of coercivity - $\beta$</td>
</tr>
<tr>
<td>3. Structural (Irreversible-Unrecoverable)</td>
<td>Permanent loss due to corrosion or excessive temperature (or radiation) causing structural change</td>
</tr>
</tbody>
</table>
N42 Thermal Properties
With Different Load Lines (Pc)
## Thermal Properties: Comparisons

<table>
<thead>
<tr>
<th>Material</th>
<th>Grade</th>
<th>Temp. Range</th>
<th>Max Use</th>
<th>Alpha</th>
<th>Beta</th>
<th>Tc</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Min °C</td>
<td>Max °C</td>
<td>°C</td>
<td>°C</td>
<td>°C</td>
</tr>
<tr>
<td>Alnico, cast</td>
<td>5</td>
<td>20</td>
<td>100+</td>
<td>520</td>
<td>-0.02</td>
<td>-0.01</td>
</tr>
<tr>
<td>Alnico, cast</td>
<td>8</td>
<td>20</td>
<td>100+</td>
<td>520</td>
<td>-0.02</td>
<td>-0.01</td>
</tr>
<tr>
<td>Sm$<em>2$Co$</em>{17}$</td>
<td>27 MGOe</td>
<td>20</td>
<td>120</td>
<td>350</td>
<td>-0.035</td>
<td>-0.20</td>
</tr>
<tr>
<td>SmCo$_5$</td>
<td>20 MGOe</td>
<td>20</td>
<td>120</td>
<td>250</td>
<td>-0.04</td>
<td>-0.40</td>
</tr>
<tr>
<td>NdFeB, Bonded</td>
<td>MQP-A, O</td>
<td>20</td>
<td>100</td>
<td>110, 140</td>
<td>-0.13</td>
<td>-0.40</td>
</tr>
<tr>
<td>NdFeB, Bonded</td>
<td>MQP-B</td>
<td>20</td>
<td>100</td>
<td>110</td>
<td>-0.11</td>
<td>-0.40</td>
</tr>
<tr>
<td>NdFeB, Bonded</td>
<td>MQP-C, D</td>
<td>20</td>
<td>100</td>
<td>125, 110</td>
<td>-0.07</td>
<td>-0.40</td>
</tr>
<tr>
<td>NdFeB, Sintered</td>
<td>L-38UHT</td>
<td>20</td>
<td>180</td>
<td>180</td>
<td>-0.10</td>
<td>-0.50</td>
</tr>
<tr>
<td>NdFeB, Sintered</td>
<td>N38UH</td>
<td>20</td>
<td>180</td>
<td>180</td>
<td>-0.12</td>
<td>-0.65</td>
</tr>
<tr>
<td>NdFeB, Sintered</td>
<td>N48M</td>
<td>20</td>
<td>100</td>
<td>100</td>
<td>-0.12</td>
<td>-0.65</td>
</tr>
<tr>
<td>Ferrite</td>
<td>C-5, 8</td>
<td>20</td>
<td>120</td>
<td>400</td>
<td>-0.20</td>
<td>0.27</td>
</tr>
</tbody>
</table>
Corrosion of NdFeB

1990’s NdFeB magnets with excess Nd content

Current NdFeB magnets with optimized compositions
# Coating Effectiveness on NdFeB

<table>
<thead>
<tr>
<th>COATING MATERIAL</th>
<th>NICKEL</th>
<th>EPOXY RESIN</th>
<th>Ni + EPOXY RESIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coating Method</td>
<td>Electroplating</td>
<td>Powder Spray Coating</td>
<td>Electroplating + E-Coat</td>
</tr>
<tr>
<td>Thickness</td>
<td>Range (inches)</td>
<td>0.0005 to 0.0010</td>
<td>0.0008 to 0.0016</td>
</tr>
<tr>
<td></td>
<td>Homogeneity</td>
<td>Excellent</td>
<td>Good</td>
</tr>
<tr>
<td>Size Capability</td>
<td>Small (&lt;20 grams)</td>
<td>Excellent</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td>Large (&gt;20 grams)</td>
<td>Fair</td>
<td>Good</td>
</tr>
<tr>
<td>Reliability (Hours)</td>
<td>Temp. &amp; Humidity (60°C, 95%RH)</td>
<td>&gt;2500</td>
<td>&gt;500</td>
</tr>
<tr>
<td></td>
<td>Temp. &amp; Humidity (85°C, 85%RH)</td>
<td>&gt;500</td>
<td>&gt;100</td>
</tr>
<tr>
<td></td>
<td>Salt Spray (35°C, 5% NaCl)</td>
<td>&lt;24</td>
<td>&lt;24</td>
</tr>
<tr>
<td>Comments</td>
<td>Large magnets may need to be rack plated versus barrel plated</td>
<td>Epoxy resins are not hermetic</td>
<td>Thickness buildup can be a problem</td>
</tr>
</tbody>
</table>
Thank you for your attention
Any Questions?

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DuBois, Pennsylvania, USA
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John_ormerod@magnetus.com