Low Loss Soft Magnetic Materials for Industrial Motor

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Impact of cost effective low-loss magnetics

A successful development of cost effective soft magnet materials and manufacturing processes may
• Save energy and
• Increase U.S. share of global markets (soft magnets, motor, power electronics).

Soft magnetic materials global market is $14B in 2010 [1]

Loss comparison of motors made of FeSi and amorphous motor (5.5 kW, 380 V, 50 Hz) [3]

<table>
<thead>
<tr>
<th>Loss (W)</th>
<th>Amorphous Motor</th>
<th>Classical Motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core</td>
<td>5</td>
<td>28</td>
</tr>
<tr>
<td>Stator Winding</td>
<td>1119</td>
<td>1505</td>
</tr>
<tr>
<td>Rotor Winding</td>
<td>1140</td>
<td>1537</td>
</tr>
<tr>
<td>Total Losses</td>
<td>2265</td>
<td>3071</td>
</tr>
</tbody>
</table>

• A 1% increase in efficiency through advanced soft magnetic materials would realize 159 TWh energy savings

Priority of motor industry

- 91% reported that all motor purchase decisions were made at the plant level.
- 8% included efficiency in their specifications for the motor to be purchased.
- Customers most often use the size of the failed motor being replaced as a key factor in selecting the size of the new motor.
- Reducing capital costs is the most important consideration driving customers’ decision.
- The energy saving due to higher efficiency may command a small premium if there is any.

- **Cost is more important than efficiency**
- **A motor is competitive if it has higher efficiency while maintaining competitive price**

Cost Breakdown of PMM Motors

- Magnetic materials (PM+SM) account more than 52% of raw materials cost
- Labor accounts a significant fraction, but not much room to reduce

- Magnetic materials (laminate) account 37% of raw materials cost
- IM is more labor intensive than PMM, less efficient, bigger in size, and require more expensive/complex drives electronics, but IM is cheaper and free of REE
Higher frequency, higher power density, smaller size, lower cost

- Increasing $f$ increases RPM, HP
- Increasing # of poles increases power density (due to shorted end winding & back iron) but it also increases $f$.
- Increasing $f$ lead to higher loss
- To improve machine power density without compromising efficiency, it requires SM with
  - Higher Resistivity
  - Lower Hysteresis
  - Higher flux density
  - Maintaining mechanical properties

$P_{\text{Hys}} = k_{\text{Hys}} B^2 f$
$P_{\text{Eddy}} = k_{\text{Eddy}} B^2 f^2$
$P_{\text{Excess}} = k_{\text{Excess}} B^{1.5} f$

$RPM = \frac{120 f}{\# P}$
$HP = \frac{\text{Torque} \times RPM}{5252}$

Higher $f$ is beneficial only if new soft magnetic materials can keep the loss low.
### SOA Soft Magnetic Materials

<table>
<thead>
<tr>
<th>Type</th>
<th>Materials</th>
<th>Bs (T)</th>
<th>Hc (A/m)</th>
<th>$10^3$μr 1 kHz</th>
<th>R (μΩ-cm)</th>
<th>λ (ppm)</th>
<th>W1.5/50 (W/kg)</th>
<th>W10/400 (W/kg)</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystalline</td>
<td>Electrical Steel, 0.2 mm, NGO, 3.2% Si</td>
<td>2</td>
<td>26</td>
<td>15</td>
<td>57</td>
<td>8</td>
<td>0.7-1.2</td>
<td>11</td>
<td>[1,5]</td>
</tr>
<tr>
<td></td>
<td>Electrical Steel, 0.2 mm, NGO, 6.5% Si</td>
<td>1.4</td>
<td>45</td>
<td>19</td>
<td>82</td>
<td>0.01</td>
<td>0.6</td>
<td>8.1</td>
<td>[1,2]</td>
</tr>
<tr>
<td></td>
<td>Molypermalloy, 0.5 mm, Ni78Fe17Mo5</td>
<td>0.65-0.82</td>
<td>0.25-0.64</td>
<td>100-800</td>
<td>60</td>
<td>2-3</td>
<td>0.07</td>
<td>0.3</td>
<td>[3,4]</td>
</tr>
<tr>
<td></td>
<td>Hiperc 50, Fe49Co49V2</td>
<td>2.4</td>
<td>16-400</td>
<td>5-50</td>
<td>27</td>
<td>60</td>
<td>4</td>
<td>10</td>
<td>[4]</td>
</tr>
<tr>
<td>Nano-crystalline</td>
<td>FINEMET, Fe$<em>{73.5}$Si$</em>{13.5}$Nb$_3$B$_6$Cu$_1$</td>
<td>1.2</td>
<td>0.5-1.4</td>
<td>80</td>
<td>110</td>
<td>0-2</td>
<td>--</td>
<td>1.1</td>
<td>[4-6]</td>
</tr>
<tr>
<td></td>
<td>NANOPERM, Fe$_{18}$B$_4$Zr$_7$Cu$_1$</td>
<td>1.5-1.6</td>
<td>2.4-4.5</td>
<td>48</td>
<td>56</td>
<td>~0</td>
<td>--</td>
<td>3</td>
<td>[4-6]</td>
</tr>
<tr>
<td></td>
<td>HITPERM, (FeCo)$_{4.4}$Zr$_7$B$_4$Cu$_1$</td>
<td>1.6-2.0</td>
<td>80-200</td>
<td>1-10</td>
<td>120</td>
<td>36</td>
<td>--</td>
<td>20</td>
<td>[4-6]</td>
</tr>
<tr>
<td>Amorphous</td>
<td>Metglas, Fe78Si9B13</td>
<td>1.54</td>
<td>3</td>
<td>2.1</td>
<td>135</td>
<td>27</td>
<td>0.7</td>
<td>2.5</td>
<td>[7]</td>
</tr>
<tr>
<td></td>
<td>Metglas 2650C0, Fe$<em>{67}$Co$</em>{18}$B$_{14}$Si$_1$</td>
<td>1.8</td>
<td>3.5</td>
<td>50</td>
<td>123</td>
<td>35</td>
<td>0.3</td>
<td>3</td>
<td>[4,8]</td>
</tr>
<tr>
<td>Ferrite</td>
<td>Ferrite, MnZnFeO</td>
<td>0.36-0.5</td>
<td>10-100</td>
<td>0.5-10</td>
<td>$10^7$-$10^8$</td>
<td>5</td>
<td>--</td>
<td>--</td>
<td>[4]</td>
</tr>
<tr>
<td></td>
<td>Ferrite, NiZnFeO</td>
<td>0.25-0.42</td>
<td>14-1600</td>
<td>0.01-1</td>
<td>$10^{11}$</td>
<td>-20</td>
<td>--</td>
<td>--</td>
<td>[4]</td>
</tr>
</tbody>
</table>

Fe-3.2%Si steel offers the most attractive cost/performance ratio (raw materials $1.3/kg, stamped laminate $2.1/kg)

**REF**

High Si content electrical steel promises more efficient motor

<table>
<thead>
<tr>
<th>FeSi steels</th>
<th>Saturation Magnetization (T)</th>
<th>DC Max relative permeability</th>
<th>Electric resistance (μΩ-cm)</th>
<th>Magnetostriction (ppm)</th>
<th>Core loss W10/400 (W/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2% Si</td>
<td>1.96</td>
<td>18,000</td>
<td>52</td>
<td>7.8</td>
<td>14.4</td>
</tr>
<tr>
<td>6.5% Si</td>
<td>1.8</td>
<td>23,000</td>
<td>82</td>
<td>0.1</td>
<td>5.7</td>
</tr>
</tbody>
</table>

- Increasing Si wt.% improves magnetic/electric properties (6.5% Si is the optimum, lower Eddy current, smaller hysteresis loss, near zero noise
- Less heat, less demand on cooling system, higher carrier frequency, higher power density, smaller size

Fe-Si alloys with >4% Si is brittle

<table>
<thead>
<tr>
<th>Phase</th>
<th>Structure</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>α-FeSi</td>
<td>A2</td>
<td>All sites are randomly occupied by Fe or Si</td>
</tr>
<tr>
<td>α₂-FeSi</td>
<td>B2</td>
<td>C, B sites are randomly occupied by Fe or Si</td>
</tr>
<tr>
<td>α₁-FeSi</td>
<td>D0₃</td>
<td>C sites are randomly occupied by Fe or Si</td>
</tr>
</tbody>
</table>

The heterogeneous formation of α-FeSi and Fe₃Si(α₁) ordered phases is responsible for severe materials embrittlement.
Commercial methods of manufacturing 6.5% Si steel

- CVD, PVD, or a hot dipping process followed by diffusion annealing
  - Pro: great mechanical and magnetic properties
  - Con: expensive, adverse impact to environment, thin thickness

Current methods of manufacturing 6.5% Si steel are expensive, and the product has limited applications
State-of-the-art researches on high Si steel

- Melt spinning
- Rapid solidification
- Hot/cold spray
- Direct powder rolling
- Thermal-mechanical process
  - Hot roll
  - Warm roll
  - Cold roll

Major progress was made in China through tailored cold-rolling process
- 0.05 to 0.5 mm 6.5%Si (with 500ppm B) sheet was successfully cold rolled and stamped
- Achieved the expected magnetic properties

Remaining challenges:
- Large ingot casting without micro-crack.
- Continuous cold rolling under tension without side cracks