GREAT DESIGNS IN STEEL

NON-ORIENTED ELECTRICAL STEELS FOR EV APPLICATIONS

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AGENDA

• Introduction
• Material Production
• Material Properties
• Typical Properties
• Future Products
INTRODUCTION
CLIFFS’ ELECTRICAL STEEL INNOVATIONS

- **1903**: First electrical steel for magnetic applications
- **1905**: First silicon electrical steel for magnetic purposes
- **1913**: Commercialization of grain-oriented silicon steel
- **1941**: CARLITE® Coating for electrical steels
- **1942**: First decarburization of steel in strip form
- **1945**: Superior magnetic quality in continuous slab casting
- **1946**: CARLITE, improved high permeability electrical steel
- **1971**: TRAN-COR® H, H-O CARLITE, improved high permeability electrical steel
- **1975**: CARLITE 3, superior insulative coating
- **1985**: TRAN-COR® H DR®, laser scribed with 10% fewer core losses
- **1985**: TRAN-COR® H, H-0 CARLITE, improved high permeability electrical steel
- **1986**: CARLITE 3, superior insulative coating
- **2005**: HF-Series, new gen of electrical steel for use in electric vehicles
- **2018**: TRAN-COR X, new gen of high permeability, grain oriented electrical steel
- **2022**: HF NOES for improved magnetic and mechanical performance in EV
ELECTRICAL STEEL BASICS

- Soft magnetic material
- Iron-silicon alloy with a silicon content of 0.5 to 3.5%
- Excellent magnetic properties
- Low core loss and exciting power
- Final properties controlled by alloy content, process routing and thickness
GOES VS NOES

Grain oriented electrical steel (GOES)

• Strong crystallographic texture
• Highly anisotropic

Non-grain oriented electrical steel (NOES)

• Weak crystallographic texture
• Almost isotropic
GOES PRODUCTS

• Grain Oriented Electrical Steel (GOES)
  • Used in stationary applications, such as power distribution transformers
  • Large grains (poor strength but good magnetics)
  • Excellent magnetic properties in rolling direction

• Conventional grain oriented (< 5° of ideal (110)[001]):
  • LITE CARLITE®: M-grades
  • CARLITE®: Mill Anneal

• Highly grain oriented (< 2° of ideal (110)[001]):
  • TRAN-COR®: H grades
NOES PRODUCTS

• Non-grain-oriented Electrical Steel (NOES)
  • Used in rotating applications, such as motors and generators
  • Magnetic properties are virtually the same in all directions
  • Smaller grains (better strength than GOES)

• NOES products:
  • DI-MAX® M-grades
  • MOTOR-MAX™ HF-grades
ELECTRIC MOTOR BASICS

- Rotor
  - Rotating part of the motor
  - Magnets are placed or cast into the rotor core (PM motor)

- Stator
  - Stationary part of the motor
  - A copper winding is wound through the slots
  - When current is applied to the winding this induces a magnetic field resulting in the rotor rotating
• The rotor and the stator cores are made up of electrical steel laminations

• A lamination is a single sheet of electrical steel stamped into the rotor or stator geometry

• Typically, there are 300 (0.25 mm) or more laminations per motor core depending on the design

• These laminations are stacked and mechanically fastened or welded to form the motor core

• There is also an insulative coating applied to both sides of the steel sheet in coil form
MATERIAL PRODUCTION
ROUTING COMPARISON

Typical Cold Rolled Carbon Steel Routing

Two stage NOES Routing
CHEMISTRY CONTROL IS IMPORTANT

- Both integrated and EAF routing can be used
- Excellent control of alloy additions and tramp elements is needed to produce desired magnetic properties
MATERIAL PROPERTIES
MAGNETIC PROPERTIES

Core Loss \([W/kg, W/lb]\)
- A measurement of the power lost when magnetizing the material
- Lower is better
- Typically measured at 400 Hz, 1 T induction

Induction \([T]\)
- How easy it is to induce magnetic flux in the material
- Higher is better
- Induction typically measured at 5000 A/m applied field strength, known as B50

Magnetic properties measured commonly measured using an Epstein frame
COMPONENTS OF CORE LOSS

Total core loss = Hysteresis loss + Eddy current loss
HYSTERESIS LOSS

• Energy spent to reverse the magnetic domains as alternating magnetic fields are applied to the motor core

• Loss = area bound by the hysteresis loop

$H = \text{Applied field}$

$B = \text{Induced flux density}$

Magnetization curve (dotted) and hysteresis loop (solid)
EDDY CURRENT LOSS

• Contributes to core loss
  • Magnetically induced electrical currents within the steel

• Reduction methods
  • Decreasing sheet thickness
  • Increasing material resistivity
  • Increasing material density

\[ P = \eta \frac{\pi^2 B^2 t^2 f^2}{6\rho D} \]

\( \eta \) = anomalous loss factor
\( B \) = magnetic field
\( t \) = thickness
\( f \) = frequency
\( \rho \) = resistivity
\( D \) = density
## VOLUME RESISTIVITY REFERENCE [µΩ • CM]

<table>
<thead>
<tr>
<th>Material</th>
<th>Resistivity (µΩ-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure Ag</td>
<td>1.6</td>
</tr>
<tr>
<td>Pure Cu</td>
<td>1.7</td>
</tr>
<tr>
<td>Pure Al</td>
<td>2.7</td>
</tr>
<tr>
<td>Pure Iron</td>
<td>10</td>
</tr>
<tr>
<td>Silicon steels</td>
<td>20-80</td>
</tr>
</tbody>
</table>
CONVENTIONAL vs HIGH FREQUENCY NOES

• Conventional (Starter, Alternator)
  • “M-” grades
  • 50/60 Hz
  • 2.1 – 5.3 W/kg (1.5 T, 60 Hz)
  • Gauge: 0.35 - 0.65 mm thick

• High Frequency (Traction Motor)
  • “HF-” grades
  • 200 - 1000 Hz
  • 11.7 - 16 W/kg (1.0 T, 400 Hz)
  • Gauge: 0.25, 0.27, 0.30 mm thick
BASIC PROPERTIES - COATING

• Coating resistivity often measured using a Franklin test

• Franklin current (A) measured -> resistivity calculated

• Coating resistivity [Ω•cm²]
  • Coatings prevent current from traveling between motor laminations
  • Higher is better
HIGH STRENGTH NEEDED FOR EV APPLICATIONS

TYPICAL PROPERTIES
## Non-Oriented Electrical Steels – Typical Properties

<table>
<thead>
<tr>
<th>Product</th>
<th>Nominal Thickness, mm (in)</th>
<th>Core Loss at 400 Hz, 1 T induction, W/kg (W/lb)</th>
<th>B50 Magnetic Induction at 5000 A/m, T</th>
<th>Electrical Resistivity, Ω•cm</th>
<th>Yield Strength, MPa (ksi)</th>
<th>Tensile Strength, MPa (ksi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOTOR-MAX™ 25HF1550</td>
<td>0.25 (0.010)</td>
<td>14.5 (6.60)</td>
<td>1.68</td>
<td>54 - 56</td>
<td>350 (50.8)</td>
<td>450 (65.3)</td>
</tr>
<tr>
<td>MOTOR-MAX™ 25HF1300</td>
<td>0.25 (0.010)</td>
<td>11.9 (5.40)</td>
<td>1.65</td>
<td>63</td>
<td>440 (63.8)</td>
<td>570 (82.7)</td>
</tr>
<tr>
<td>MOTOR-MAX™ 27HF1500</td>
<td>0.27 (0.011)</td>
<td>12.5 (5.67)</td>
<td>1.65</td>
<td>63</td>
<td>440 (63.8)</td>
<td>570 (82.7)</td>
</tr>
<tr>
<td>MOTOR-MAX™ 30HF1600</td>
<td>0.30 (0.012)</td>
<td>13.8 (6.30)</td>
<td>1.65</td>
<td>63</td>
<td>440 (63.8)</td>
<td>570 (82.7)</td>
</tr>
</tbody>
</table>
# Non-Oriented Electrical Steels - Coating Offerings

<table>
<thead>
<tr>
<th>Type</th>
<th>C-5-R Chromium Free ASTM A976 C-5</th>
<th>C-5 Phosphate Chromium Free ASTM A976 C-5</th>
<th>CARLITE® 3 ANTI-STICK™ ASTM A976 C-5-A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Components</td>
<td>Inorganic with some organic material</td>
<td>Inorganic with some organic material</td>
<td>Inorganic</td>
</tr>
<tr>
<td>Thickness (μm)</td>
<td>0.5 – 1.3 μm</td>
<td>2.3 – 2.8 μm</td>
<td>0.25 – 0.76 μm</td>
</tr>
<tr>
<td>Space Factor</td>
<td>97.2% @ 1.0 MPa</td>
<td>96.6% @ 1.0 MPa 96.4% @ 0.345 MPa</td>
<td>97.0% @ 1.0 MPa 97.4% @ 0.345 MPa</td>
</tr>
<tr>
<td>Typical Franklin Current</td>
<td>0.3</td>
<td>0.02</td>
<td>0.6</td>
</tr>
<tr>
<td>Typical Surface Resistivity (Ω-cm² /sheet)</td>
<td>15</td>
<td>300</td>
<td>5</td>
</tr>
<tr>
<td>Weldability</td>
<td>Excellent (no porosity)</td>
<td>Good (minimal porosity)</td>
<td>Excellent (no porosity)</td>
</tr>
</tbody>
</table>
FUTURE PRODUCTS
SI-CR-AL-MN ALLOY FOR HIGH SPECIFIC RESISTIVITY

• $1.8 Million Award from DOE Advanced Manufacturing Office (AMO)
• Development of High Resistivity Non-Oriented Electrical Steel (80 µΩ·cm alloy)
• Status: Preparing Application Evaluation
• Substantial increase in alloy resistivity for core loss reduction
• Research project to prove manufacturing feasibility
• 2023 completion
THANK YOU
FOR MORE INFORMATION

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