

GREAT DESIGNS IN **STEEL**

NON-ORIENTED ELECTRICAL STEELS FOR EV APPLICATIONS

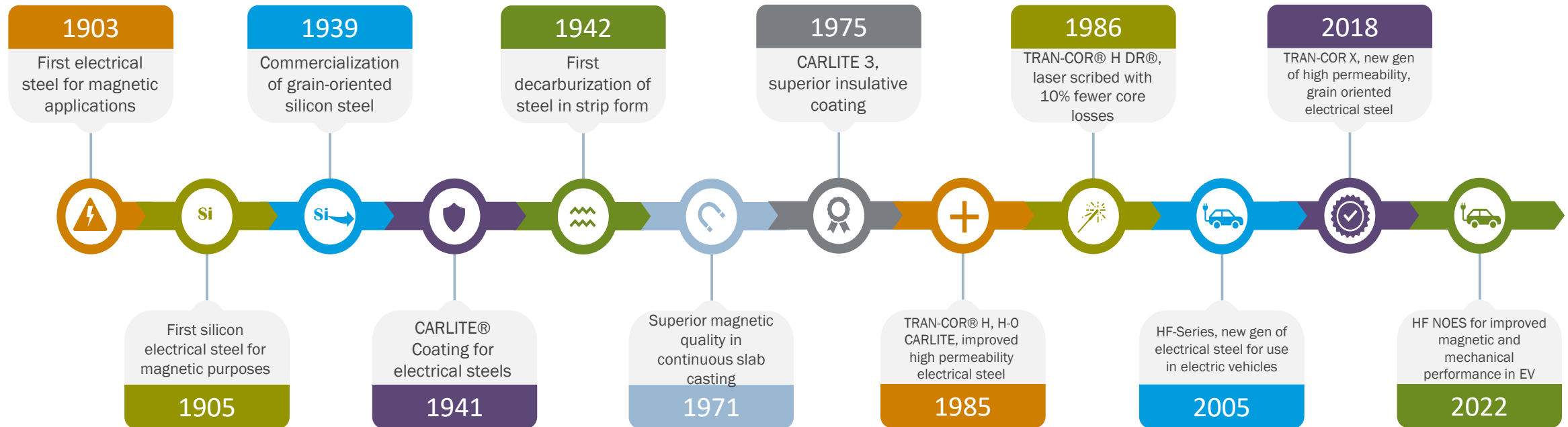
Chris Jones, PhD
Senior Product Research Engineer
Cleveland-Cliffs Inc.

AGENDA

- Introduction
- Material Production
- Material Properties
- Typical Properties
- Future Products

INTRODUCTION

CLIFFS' ELECTRICAL STEEL INNOVATIONS



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 ($< 5^\circ$ of ideal (110)[001]):
 - LITE CARLITE®: M-grades
 - CARLITE®: Mill Anneal
- Highly grain oriented ($< 2^\circ$ of ideal (110)[001]):
 - TRAN-COR®: H grades

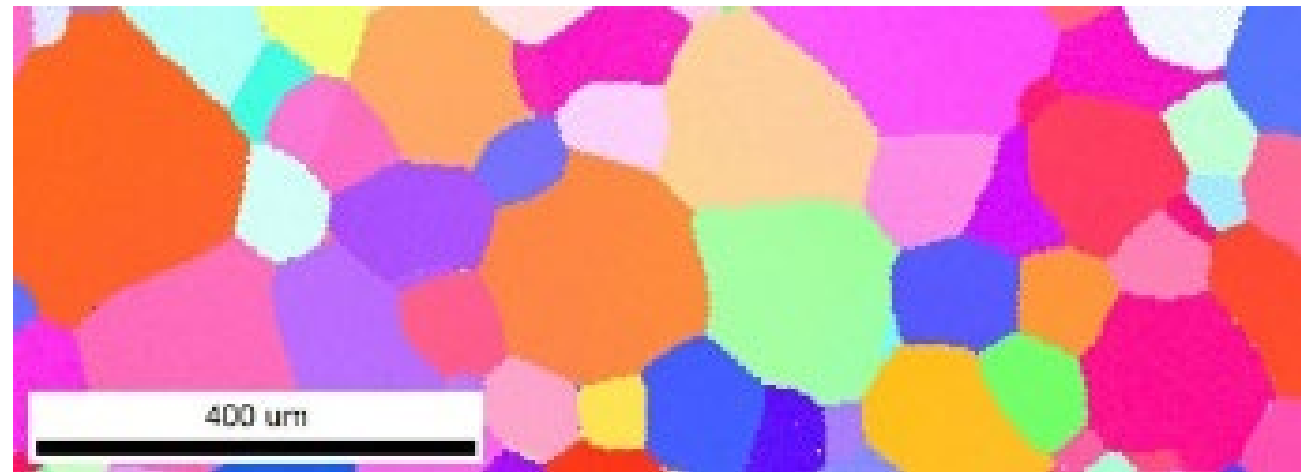


NOES PRODUCTS

- 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)

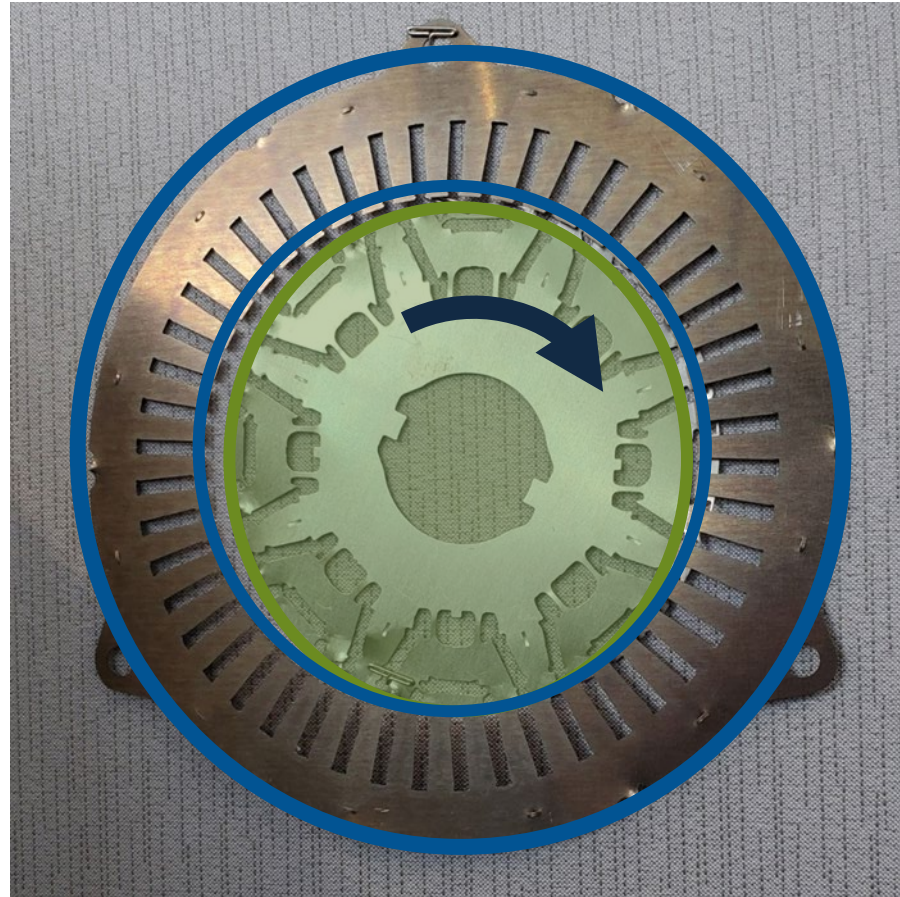


- NOES products:
 - DI-MAX® M-grades
 - MOTOR-MAX™ HF-grades



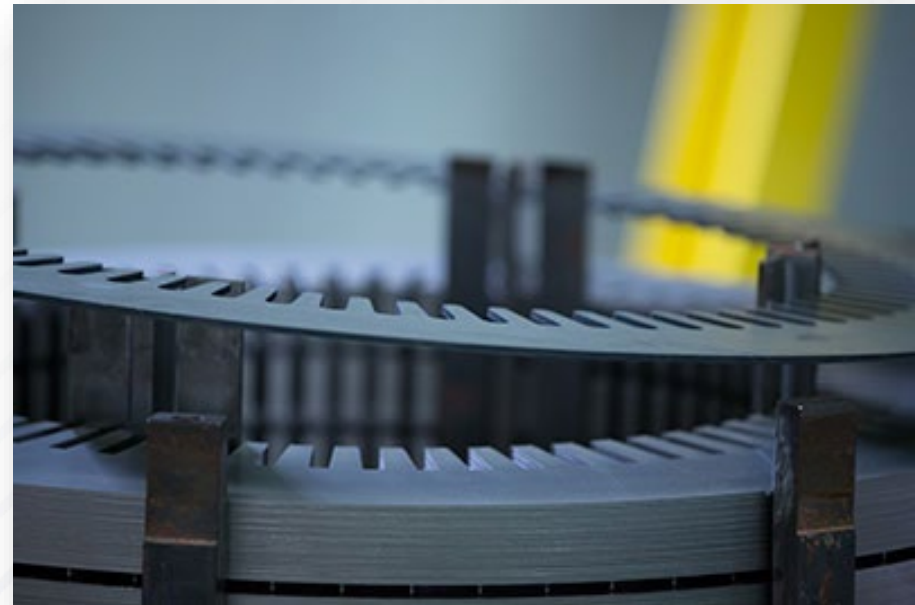
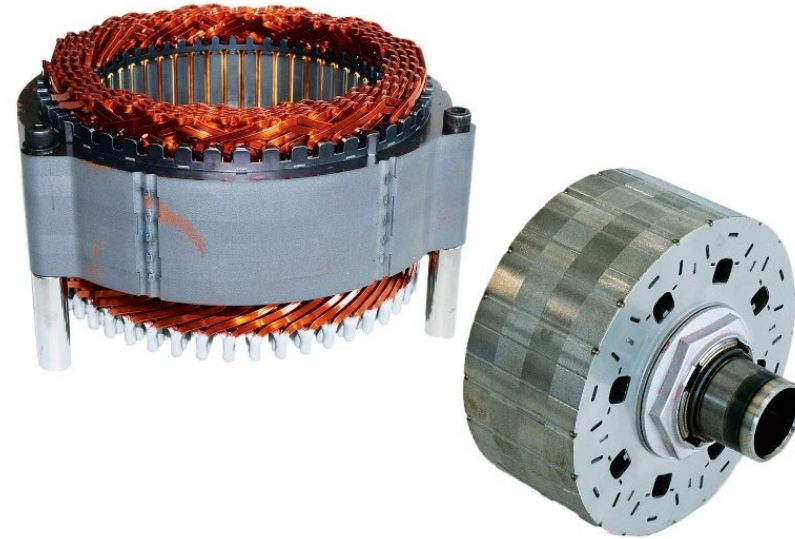
ELECTRIC MOTOR BASICS

- 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



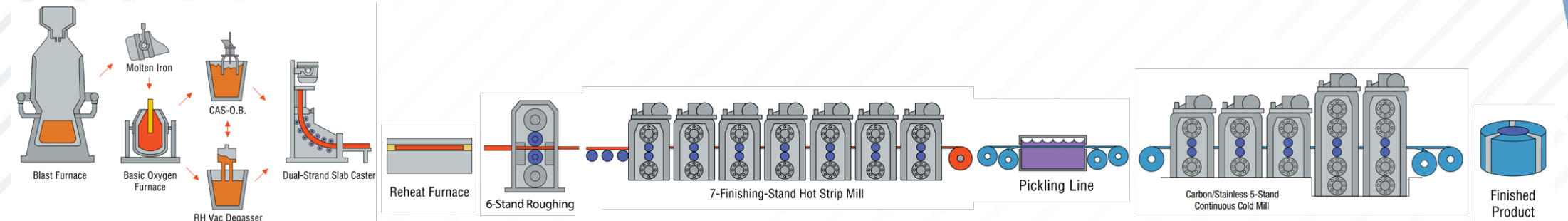
ELECTRIC MOTOR BASICS

- 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

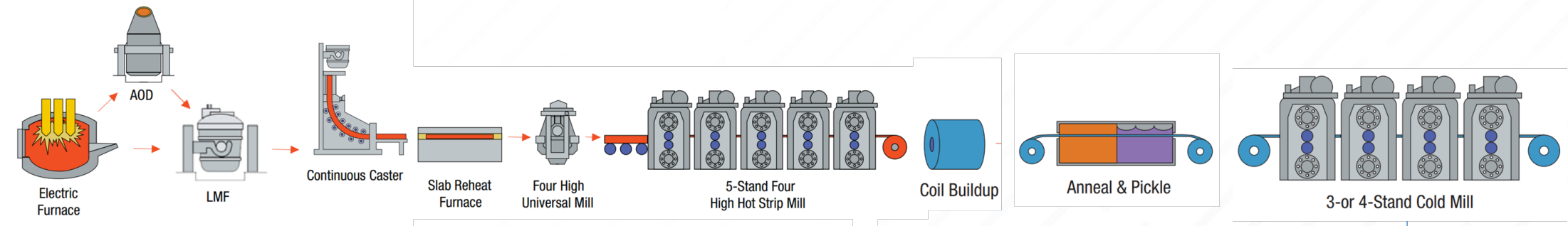


MATERIAL PRODUCTION

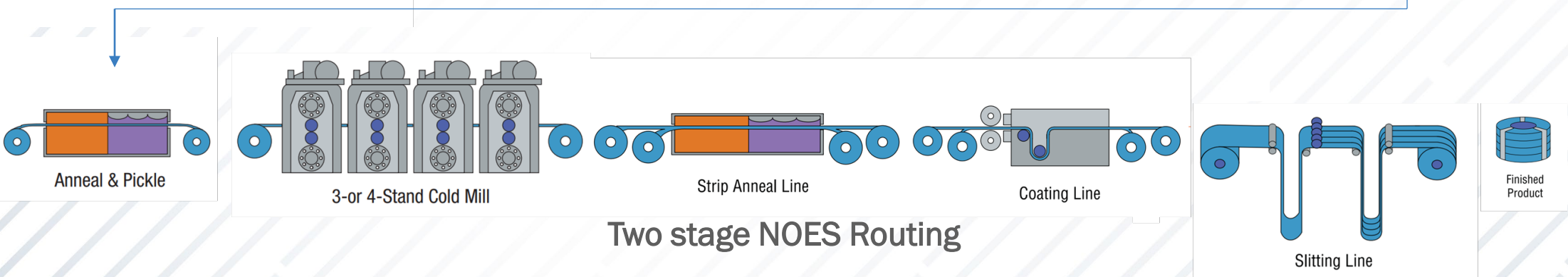
ROUTING COMPARISON



Typical Cold Rolled Carbon Steel Routing

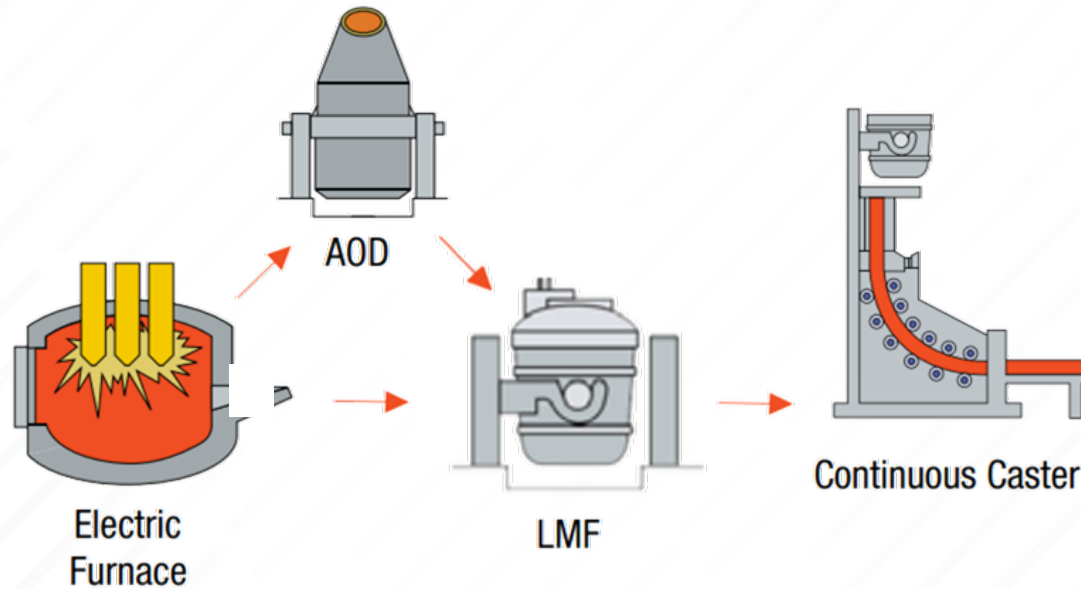


Two stage NOES Routing



CHEMISTRY CONTROL IS IMPORTANT

Electric Arc Furnace (EAF) Melt Shop



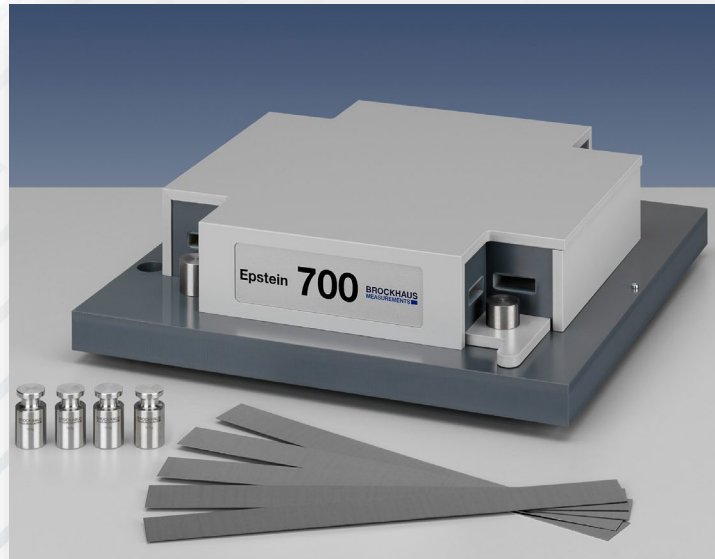
- Both integrated and EAF routing can be used
- Excellent control of alloy additions and tramp elements is needed to produce desired magnetic properties

MATERIAL PROPERTIES

MAGNETIC PROPERTIES

Core Loss [W/kg, W/lb]

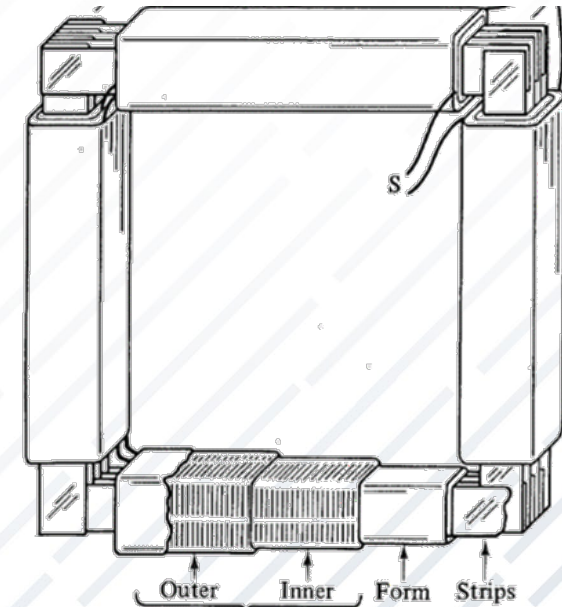
- A measurement of the **power lost** when magnetizing the material
- **Lower** is better
- Typically measured at **400 Hz, 1 T** induction



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

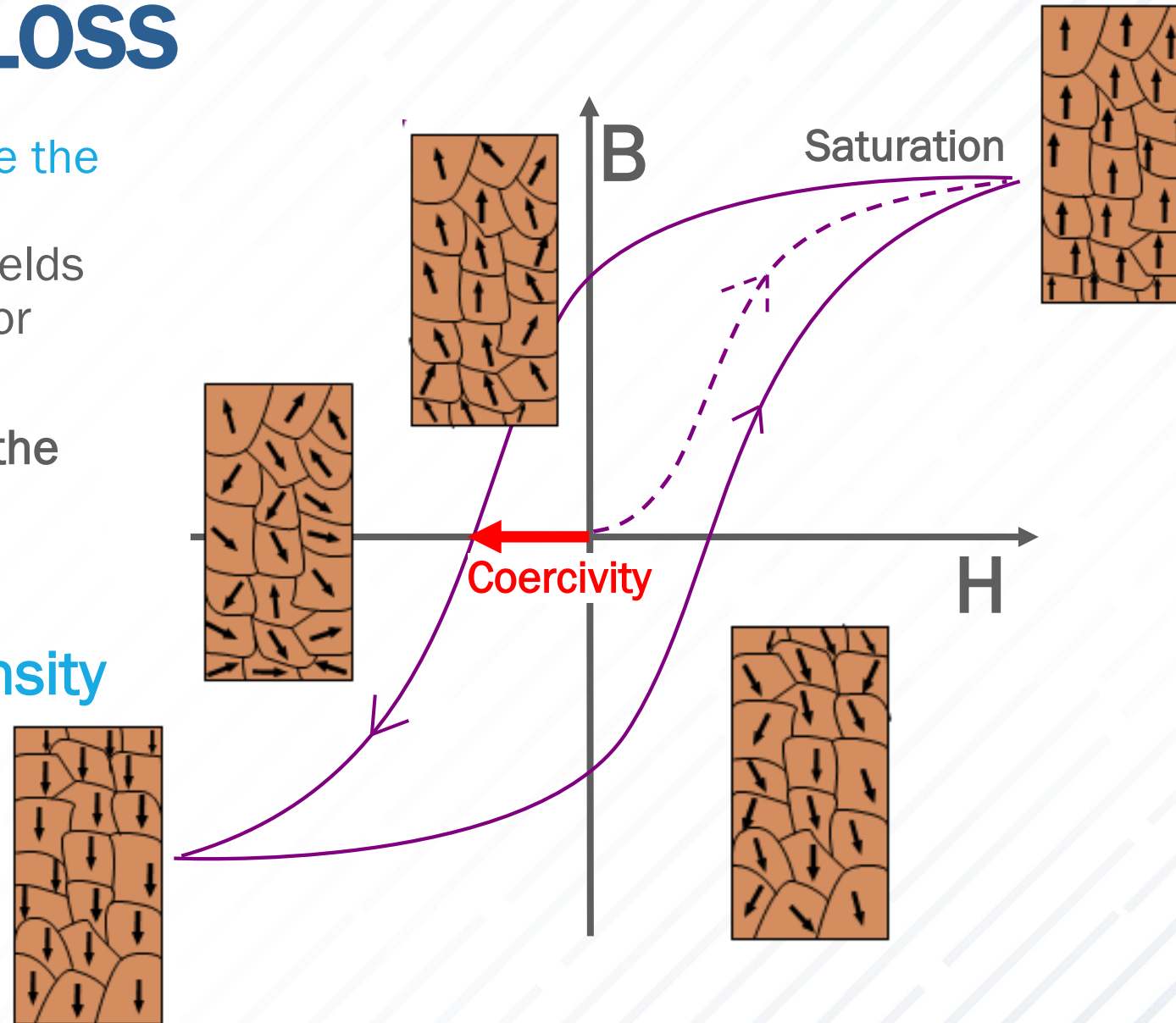
Total core loss = Hysteresis loss + Eddy current loss

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 = Applied field

B = Induced flux density



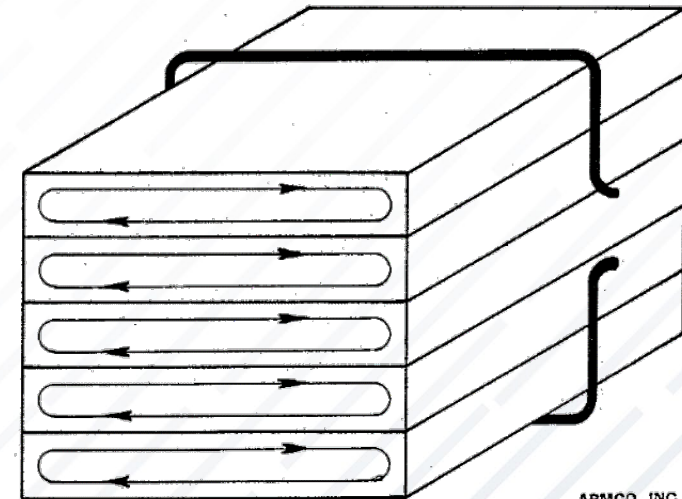
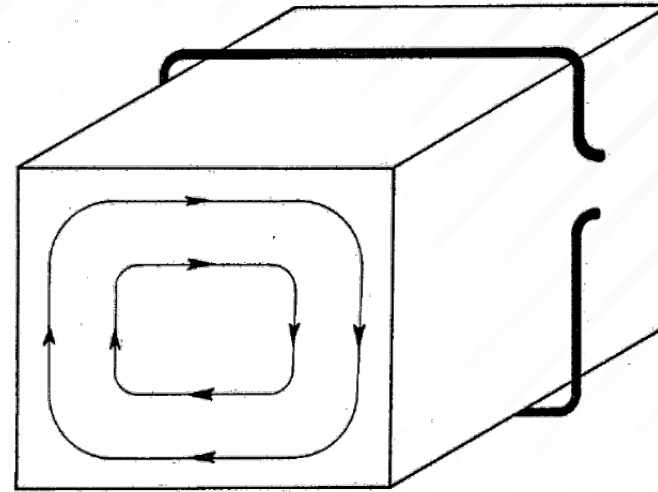
Magnetization curve (dotted) and hysteresis loop (solid)

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

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

- η = anomalous loss factor
- B = magnetic field
- t = thickness
- f = frequency
- ρ = resistivity
- D = density



ARMCO, INC.

VOLUME RESISTIVITY REFERENCE [$\mu\Omega \cdot \text{cm}$]

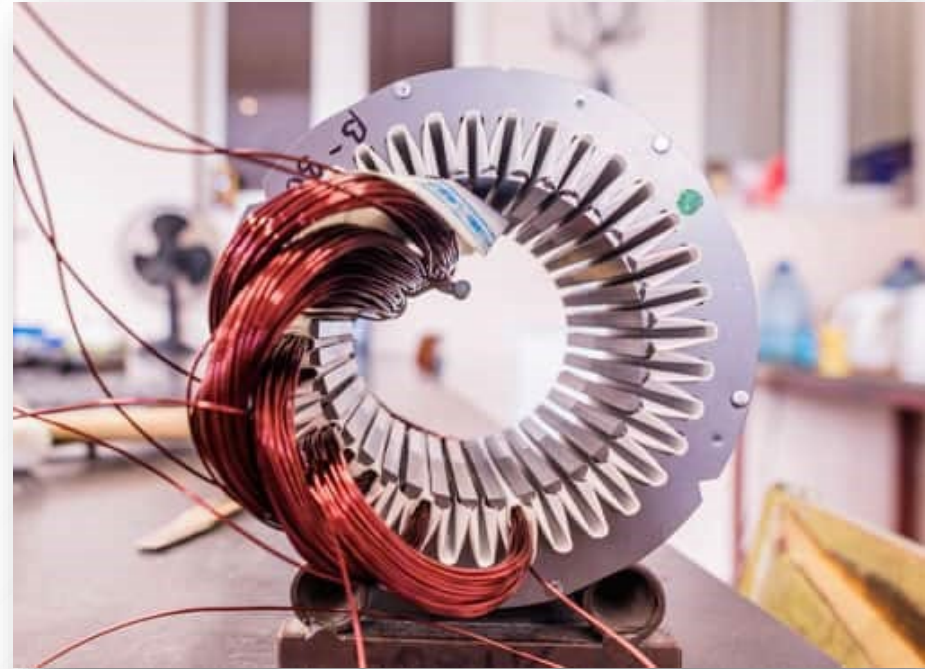
Pure Ag 1.6 $\mu\Omega\text{-cm}$

Pure Cu 1.7 $\mu\Omega\text{-cm}$

Pure Al 2.7 $\mu\Omega\text{-cm}$

Pure Iron 10 $\mu\Omega\text{-cm}$

Silicon steels 20-80 $\mu\Omega\text{-cm}$



CONVENTIONAL vs HIGH FREQUENCY NOES

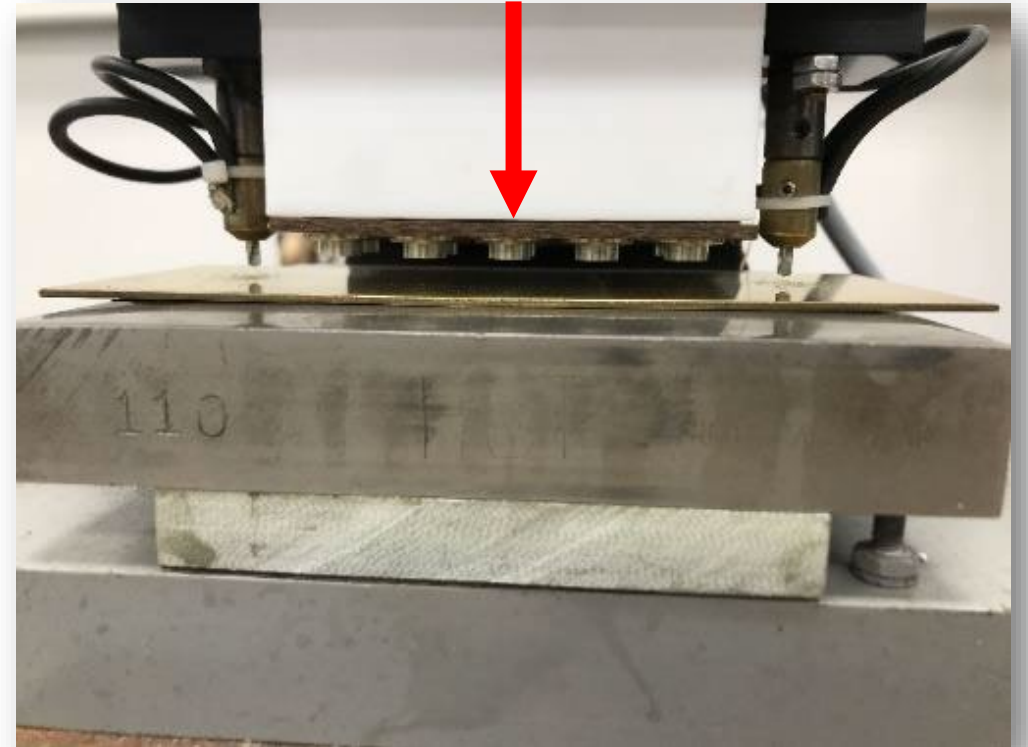
- Conventional ([Starter, Alternator](#))
 - “M-” grades
 - 50/60 Hz
 - 2.1 – 5.3 W/kg (1.5 T, 60 Hz)
 - Gauge: 0.35 - 0.65 mm thick
- High Frequency ([Traction Motor](#))
 - “HF-” grades
 - 200 - 1000 Hz
 - 11.7 - 16 W/kg (1.0 T, 400 Hz)
 - Gauge: 0.25, 0.27, 0.30 mm thick



Increasing Value

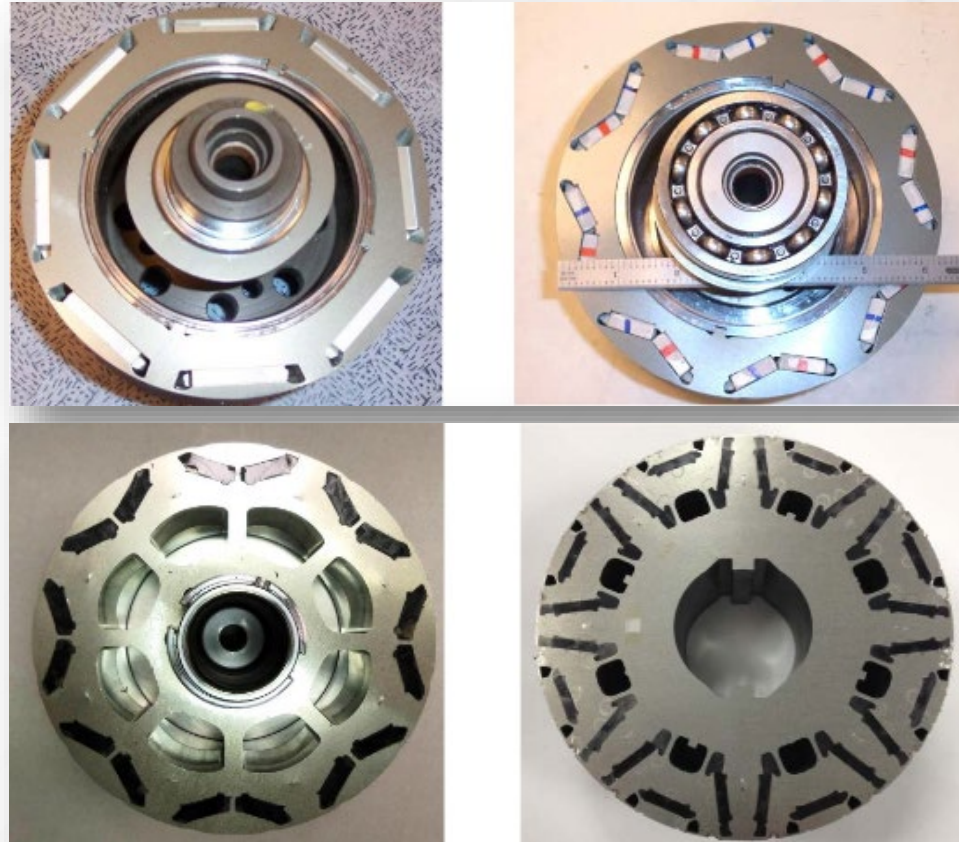
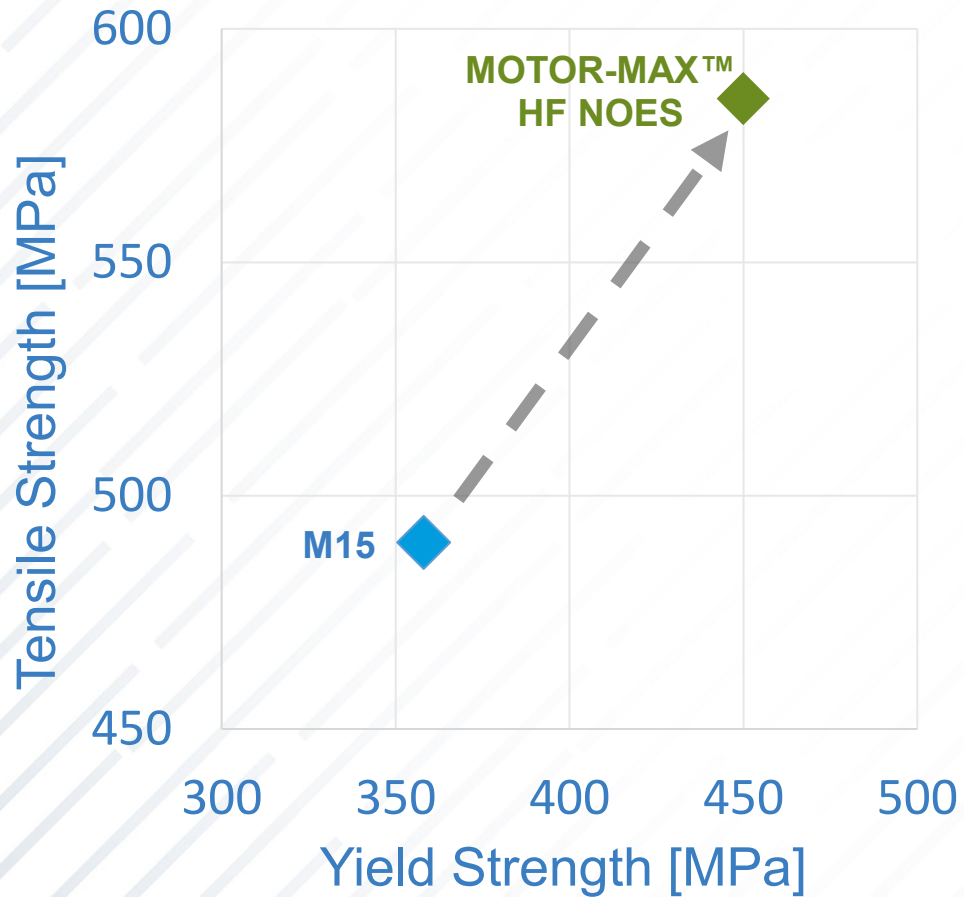
BASIC PROPERTIES - COATING

- Coating resistivity often measured using a Franklin test
- Franklin current (A) measured -> resistivity calculated
- Coating resistivity [$\Omega \cdot \text{cm}^2$]
 - Coatings **prevent current** from traveling between motor laminations
 - **Higher** is better



Franklin Resistivity Tester

HIGH STRENGTH NEEDED FOR EV APPLICATIONS



From "Electrical Performance, Reliability Analysis, and Characterization" by the 2017 U.S. Department of Energy Vehicle Technologies Office Annual Merit Review

TYPICAL PROPERTIES

NON-ORIENTED ELECTRICAL STEELS – TYPICAL PROPERTIES

Product	Nominal Thickness, mm (in)	Core Loss at 400 Hz, 1 T induction, W/kg (W/lb)	B50 Magnetic Induction at 5000 A/m, T	Electrical Resistivity, $\mu\Omega \cdot \text{cm}$	Yield Strength, MPa (ksi)	Tensile Strength, MPa (ksi)
MOTOR-MAX™ 25HF1550	0.25 (0.010)	14.5 (6.60)	1.68	54 - 56	350 (50.8)	450 (65.3)
MOTOR-MAX™ 25HF1300	0.25 (0.010)	11.9 (5.40)	1.65	63	440 (63.8)	570 (82.7)
MOTOR-MAX™ 27HF1500	0.27 (0.011)	12.5 (5.67)	1.65	63	440 (63.8)	570 (82.7)
MOTOR-MAX™ 30HF1600	0.30 (0.012)	13.8 (6.30)	1.65	63	440 (63.8)	570 (82.7)

NON-ORIENTED ELECTRICAL STEELS - COATING OFFERINGS

Type	C-5-R Chromium Free ASTM A976 C-5	C-5 Phosphate Chromium Free ASTM A976 C-5	CARLITE® 3 ANTI- STICK™ ASTM A976 C-5-A
Components	Inorganic with some organic material	Inorganic with some organic material	Inorganic
Thickness (µm)	0.5 – 1.3 µm	2.3 – 2.8 µm	0.25 – 0.76 µm
Space Factor	97.2% @ 1.0 MPa	96.6% @ 1.0 MPa 96.4% @ 0.345 MPa	97.0% @ 1.0 MPa 97.4% @ 0.345 MPa
Typical Franklin Current	0.3	0.02	0.6
Typical Surface Resistivity (Ω-cm ² /sheet)	15	300	5
Weldability	Excellent (no porosity)	Good (minimal porosity)	Excellent (no porosity)

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 $\mu\Omega\cdot\text{cm}$ 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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Or

Contact your Cleveland-Cliffs Inc. representative