Si-Cr-Al-Mn Alloy for High Specific Resistivity

Contract Number DE-EE0007866
AK Steel Corp. / Oak Ridge National Laboratories / Regal Beloit Corp.
BP2 (July 2018- June 2019)

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Overview

Project Title: **Si-Cr-Al-Mn Alloy for High Specific Resistivity**

Timeline:

Project Start: 5/01/2017

Budget Period End: 7/31/2019

Project End : 7/31/2020

Barriers and Challenges:

- Processability
- Cost – raw materials and processing
- Grain size and texture control

AMO MYPP Connection:

- Next Generation Electric Machines
- Target 3.4: Increase the efficiency of targeted electric machines by 2–3%

Project Budget and Costs:

Budget	DOE Share	Cost Share	Total	Cost Share %
Overall	$1,800,000	$520,269	$2,020,269	22.4%
Approved (BP-1,2)	$1,392,834	$400,687	$1,793,521	22.3%
Costs as of 4/1/19	$597,751	$246,544	$1,104,295	22.3%

Project Team and Roles:

AK Steel Corporation

- **Jerry Schoen**, Product Research
- Tom Thomas, Applications and Advanced Engineering
- Garrett Angus, Product Research
- Chris Jones, Product Research
- Erik Pavlina, Product Research
- **Ed Case**, Director of Research and Innovation

Regal Beloit

- **Paul Knauer**, Technology Manager

Oak Ridge National Laboratory

- **Timothy Burress**, Electric Machines Team Lead

Project Objectives

- Objective: >30% improvement in 400 Hz core loss versus existing non-oriented electrical steels (NOES)

- Problem: Achieve a combined chemistry and processing solution to make a NOES product having specific resistivity of 75–80 $\mu\Omega$-cm (comparable to Fe-6.5Si) at a manufacturing cost incrementally above a 3% Si steel

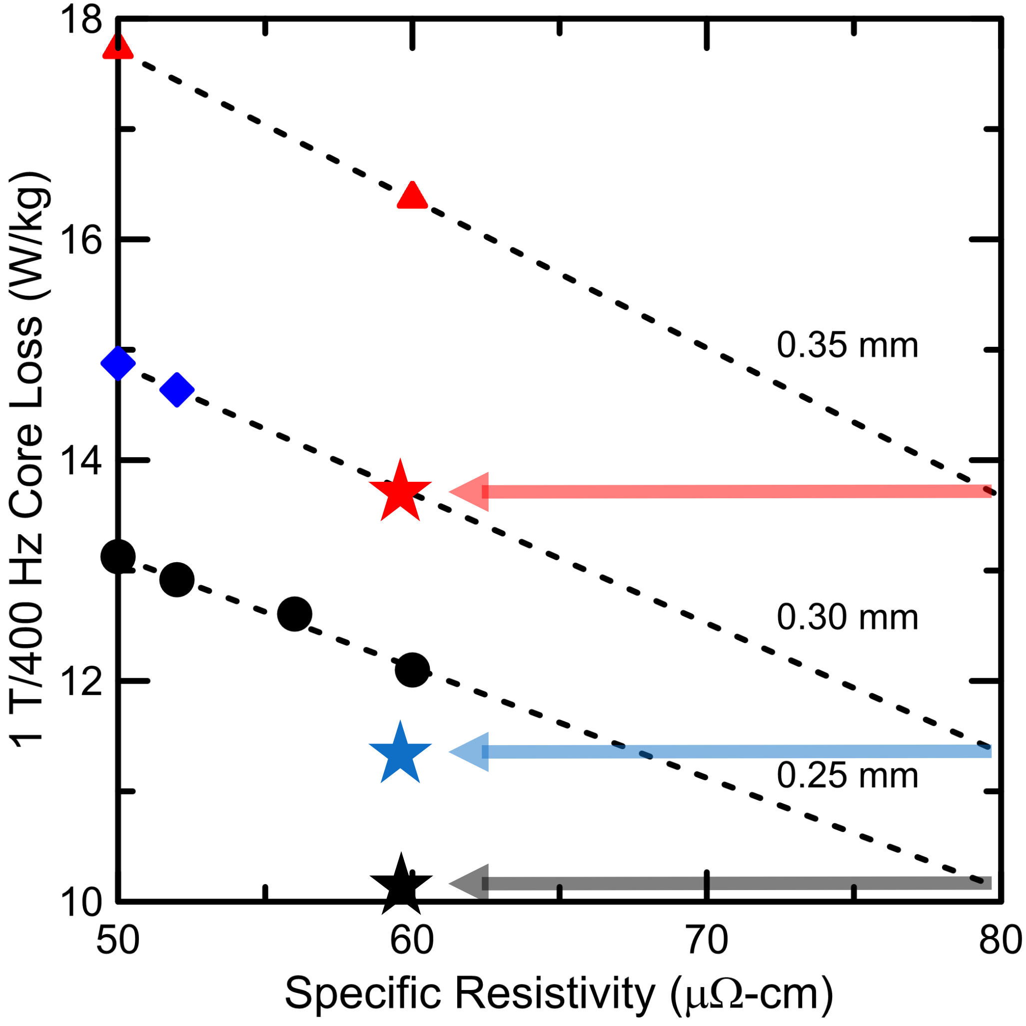
- Approach (BP1): Laboratory melt and test a series of Si-Cr-Al-Mn steels to target resistivity levels
  A. Maintain maximum compatibility with conventional cold-rolled NOES manufacturing method(s)
  B. Determine magnetic/metallurgical characteristics
- Approach (BP2 and BP3): Industrially melt and process a 80 $\mu\Omega$-cm Si-Cr-Al-Mn steel
  A. Determine magnetic/metallurgical characteristics
  B. Design / build / test series of 5HP induction motors using Si-Cr-Al-Mn steel and conventional NOES

Technical Innovation

- Core loss reduced in conventional NOES by
  - Using thinner laminations
  - Increasing specific resistivity via alloying → 6+ weight percent silicon
- Limitations of conventional methods
  - Slow and expensive steel processing
  - Extremely brittle
  - Difficulty blanking

Element	Resistivity Multiplier (μΩ-cm/at%)	Effect on Strength	Effect on Ductility	$/μΩ-cm	Other Barriers to Use
Si	5.8	Strong	Strong	Low	Embrittlement >3.5 wt%
Al	5.7	Moderate	Strong	Low	Pyrothermic during solidification, AlN precipitation
Mn	4.7	Strong	Weak	Low	Grain growth sensitive to S; challenging melt control
Cu	4.8	Strong	Moderate	High	Cost; precipitation >1 wt%
Cr	**5.9**	**Weak**	**Weak**	**Moderate**	**Cost**
Mo	7.2	Strong	Weak	High	Cost
Ni	0.9	Moderate	Weak	High	Cost

Technical Innovation



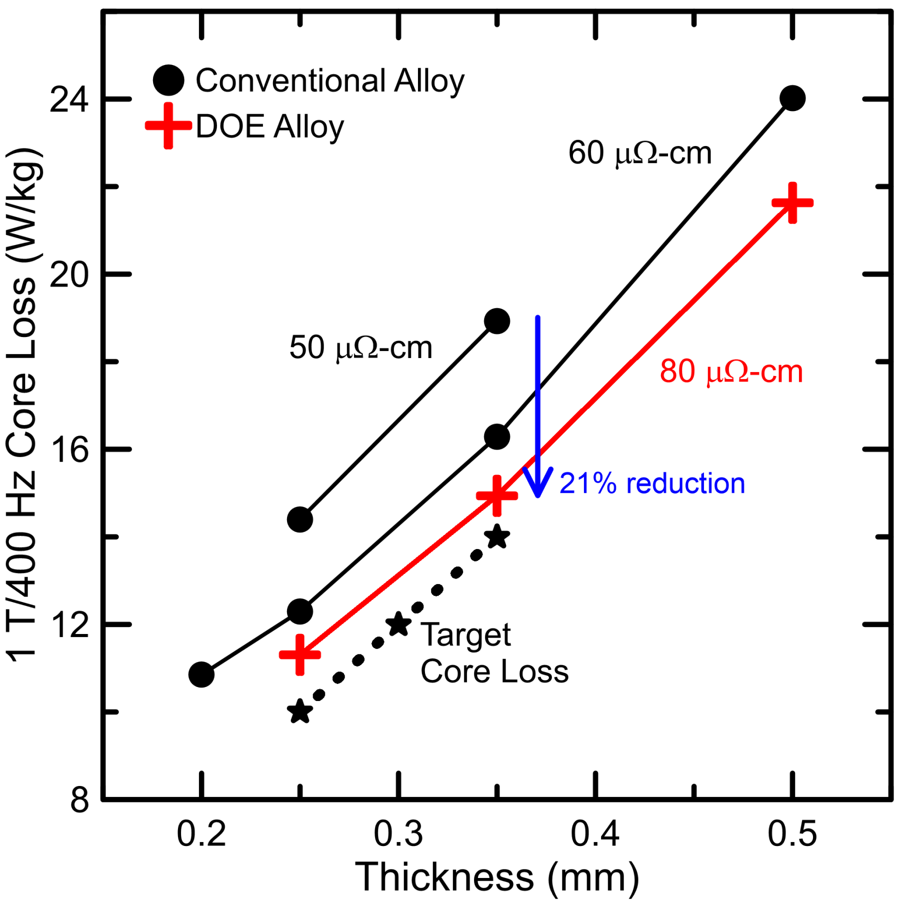
- Equivalent core loss at heavier gauges compared to conventional NOES

Technical Approach

- Si-Cr-Al-Mn alloying strategy
  - Maintain silicon levels <3.25 weight percent
  - Substantial chromium additions (>4 weight percent) for specific resistivity → limited degradation of mechanical properties
- Laboratory assessment electrical, magnetic, and mechanical properties (BP1, AK, ORNL)
  - Extend data for Fe-Si-Cr/Al/Mn/Mo alloys
  - Identification of processing windows for plant trials
  - Assessment of manufacturability
- Scale-up from laboratory to plant trials (BP2 – in progress, AK)
- Motor design, manufacture, and performance evaluation (BP3, AK, RB, ORNL)

				Mechanical Properties			Core Loss				Magnetic Permeability	
Steel	Thickness (mm)	Saturation Magnetization (T)	Resistivity (μΩ-cm)	YS (MPa)	UTS (MPa)	TEL (%)	1.0 T, 60 Hz	1.5 T, 60 Hz	1.0T, 400 Hz	1.0 T, 1000 Hz	B25 (T)	B50 (T)
M-15	0.47	2.01	50	360	490	23	1.42	3.28	24.4	113	1.56	1.65
M-15	0.35	2.01	50	360	490	23	1.35	3.19	18.9	80	1.56	1.65
Target	0.35 0.30 0.25	1.88–1.90	80	400–500	500–600	≥10	TBD	TBD	<14 <12 <10	<60 <50 <40	1.47	1.57

Results and Accomplishments – BP2



Property	Target	Actual
Specific Resistivity	≥80 μΩ-cm	80 μΩ-cm
Yield Strength	≥400 MPa	--
Ultimate Tensile Strength	≥500 MPa	--
Total Elongation	≥10%	--
Magnetic Flux Density (B50; 5000 A/m)	≥1.55 T	1.57 T
Core Loss (1 T; 400 Hz; 0.35 mm)	≤14 W/kg	14.9 W/kg

- Initial coils finished (May 2019) – planned optimization still required
- Goal of 35% reduction in core loss compared to 0.35 mm 50 μΩ-cm steel

Transition Plan

- Working with award partners to evaluate magnetic properties
- Perform manufacture and usage analysis for the transportation sector
    A. Market Assessment
    B. Manufacturing Cost
    C. Capital Investment
- Continued formal plant trials to refine processing windows and properties/performance
- Utilize existing relationships with OEMs to evaluate steels for EV application