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

Contract Number DE-EE0007866

AK Steel Corp. / Oak Ridge National Laboratories / Regal Beloit Corp.

BP1 (1 May 2017- 30 Apr 2018)

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Project Team

AK Steel Corporation, Research & Innovation Center

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- Erik Pavlina, Metallurgical Research
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Oak Ridge National Laboratory, Power Electronics and Electric Machinery Research Center

- Timothy Burress, Electric Machines Team Lead

Regal Beloit America, Inc., Enabling Technology Team

- Jason Kreidler, Manager & Chief Mechanical Engineer

Project Objective

- Objective: 30+% improvement in 400Hz 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 comparable to 6.5% Si steel with a manufacturing cost that would be incrementally above 3.2% Si steel
- Approach: Melt and test Si-Cr-Fe-X alloy designs to resistivity target levels of 75-80 μΩ-cm
  A. Maintain maximum compatibility with conventional CR-NOES manufacturing method(s)
  B. Determine magnetic/metallurgical characteristics
  C. Design / build / test series of 5HP induction motors using X-Alloy and conventional NOES

Technical Innovation

Element	Data Range (wt%)	Dr (μΩ-cm/at%)	Alloying Behavior	Grain Growth Behavior	Mech--anical Strength	Ductility Effect	Cost per μΩ-cm	Other Barriers to Use
Si	0–2	5.8	α stabilizer	Moderate	Strong	Strong	Low	Embrittlement >3.5 wt%
Al	0–1	5.7	α stabilizer, +N	Moderate	Moderate	Strong	Low	Pyrothermic during solidification
Mn	0–2	4.7	γ stabilizer, +S	Moderate	Moderate	Weak	Low	Grain growth sensitive to S; challenging melt control
Cu	0–1	4.8	γ stabilizer	Strong	Strong	Moderate	High	Cost; precipitation at >1 wt%
Cr	0–2	5.9	γ stabilizer	Weak	Weak	Weak	Moderate	Cost
Mo	0–2	7.2	α stabilizer, +S, +C	Strong	Strong	Weak	High	Cost
Ni	0–1	0.9	γ stabilizer	Moderate	Moderate	Weak	High	Cost

All values determined using Fe – 3 wt%Si base alloy

Technical Approach – Phase 1, BP1

- Evaluate addition to 3.00-3.25 wt% Si to extend data >2 wt% Cr/Mn/Mo/X

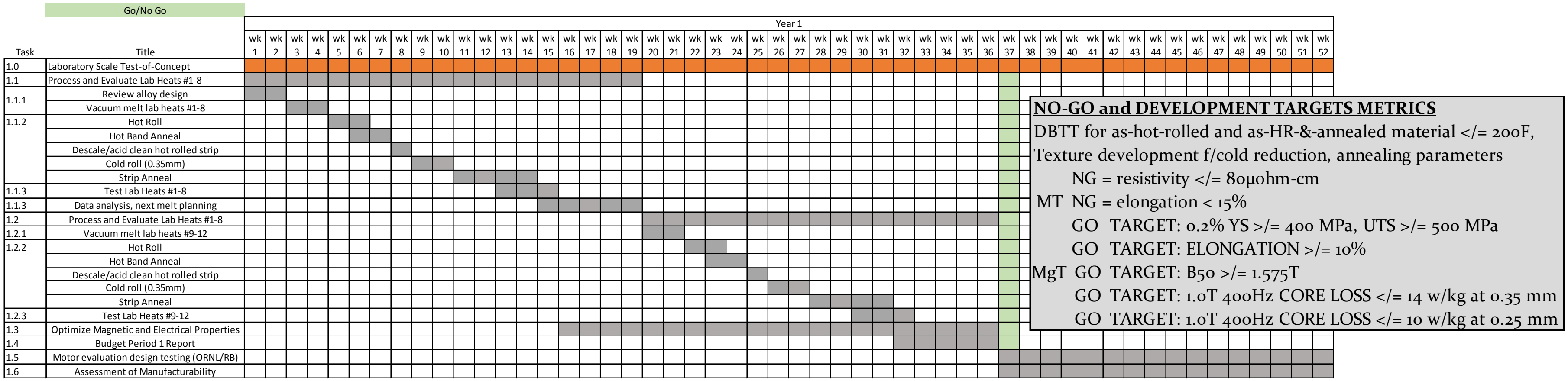
Alloy	Si (wt%)	Mn (wt%)	Cr (wt%)	Al (wt%)	Mo (wt%)	Fe (at%)	Resistivity (μΩ-cm)
Reference	3.25	0.23	0.20	0.85		91.7	61
3Cr 3Al	3.25	0.20	3.00	0.30		89.9	71
4.55Cr3Al	3.25	0.20	4.55	0.30		88.3	80
3.4Cr9Al	3.25	0.20	3.40	0.90		88.3	80
4.5Al9Al	3.25	0.20	4.50	0.90		87.2	86
2.25Cr15Al	3.25	0.20	2.25	1.50		88.4	80
3.4Mo	3.25	0.20		0.30	3.4	91.0	66
6.8Mo	3.25	0.20		0.30	6.8	88.9	80

- Determine physical, magnetic properties versus design expectations

				Mechanical Properties			Core Loss				Magnetic Permeability	
Steel	Thicknes s (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

Technical Approach – Phase 2, BPs 2-3

- Phase 1/BP1 work: Test concept alloy in laboratory



- BP2: If Phase 1 work is sufficiently encouraging, expand work to:
  A. Industrial scale manufacturing testing / demonstration (AK)
  B. Develop magnetic test data pursuant to design of 5HP induction motor testing / performance (ORNL, RBC)
- BP3: Build test motors, complete Life Cycle Cost/Benefit Analysis
  A. Material production feasibility and cost (AK)
  B. Potential energy savings (ORNL, RBC)

Transition (beyond DOE assistance)

- Will a substantial manufacturing investment be needed to capitalize X-Alloy production?
- Market acceptance depends on cost / performance of X-Alloy versus conventional NOES
- Will substantial machine redesign(s) be needed?
- Will machine characteristics be compatible with market need?
- Potential for thinner x-Alloy (0.25-0.30 mm) for >600Hz machines?

Measure of Success

- AMO internal calculations project energy savings potential of 2,143 GWhr/yr in the industrial sector and 9,721 GWhr/yr in the non-industrial sector.
  - Successful demonstration of cost-effective production of NOES having superior high frequency losses
  - Successful demonstration of cost-effective performance gains in 5HP induction test motors
  - Identification of motor design challenges/opportunities
  - Assess potential for broader application

Project Management & Budget

- Duration: 3 years
- Key milestone schedule

  BP1-M9: complete X-Alloy laboratory proof-of-concept, preliminary magnetic data needed for machine design

  BP2-M9: complete X-Alloy mill-scale testing, magnetic data development and preliminary machine design

  BP3-M9: complete machine design and testing
- Budget

Total Project Budget	
DOE Investment	$1,800,000
Cost Share	$520,141
Project Total	$2,320,141

Results and Accomplishments

- Conclude melting first series of laboratory test heats (May 31)