Soft Magnets to Achieve High-Efficiency Electric Drive Motors of Exceptional Power Density

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AMES LABORATORY
Creating Materials & Energy Solutions
U.S. DEPARTMENT OF ENERGY

Overview

Timeline

- Start: October 1, 2018
- End: September 30, 2023
- Percent complete: 60%

Budget

- Total project funding
  - $715K (Federal)
  - $0 K (Cost share)
- Funding for FY 2021: $150K

Barriers and targets

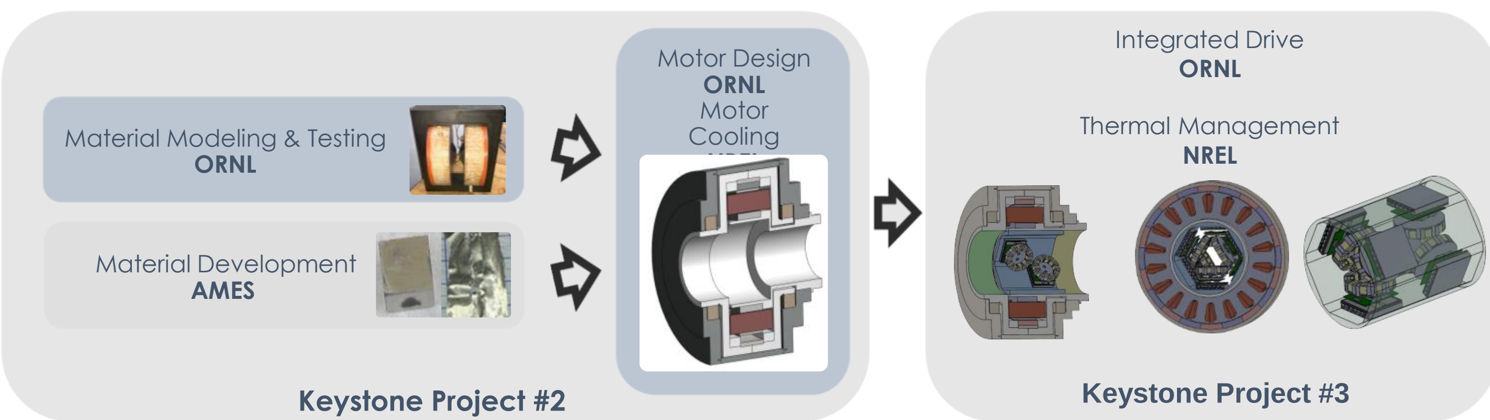
- Barriers addressed
  - Magnet cost and rare-earth element price volatility
  - Non-rare-earth electric motor performance
- Targets
  - Exceptional drive motor power density and reduced cost (50 kW/l at $3.3/kW).

Partners

- Oak Ridge National Laboratory
- National Renewable Energy Laboratory
- Sandia National Laboratory

Relevance

- Objective
  - Develop soft magnetic materials suitable for electric motors with exceptionally high-power density
- Impact
  - Reduces iron loss at higher frequency to maintain efficiency
  - Improve motor power density
  - Maintain system cost-effectiveness



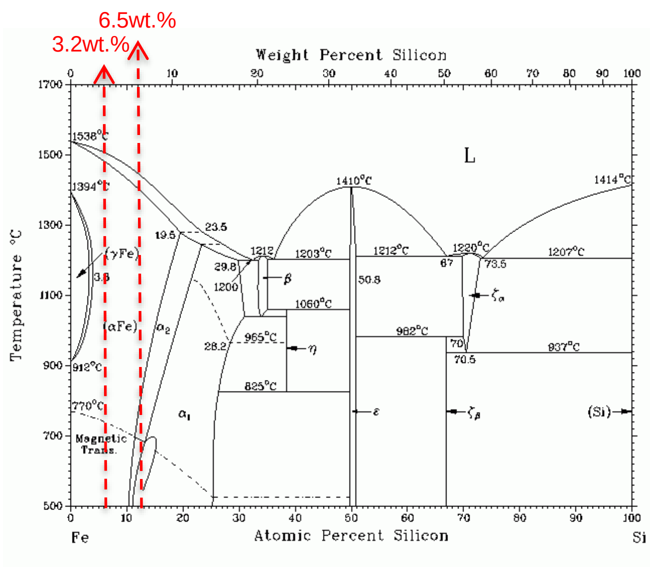
Milestones

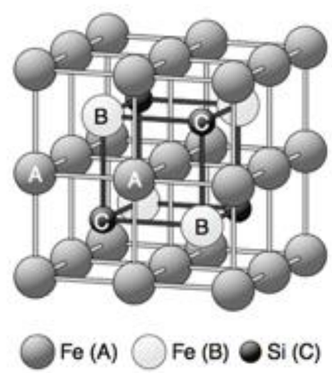
Tasks #	Description	Status
FY21-Q1	Develop a melt spin process for casting Fe-6.5% Si steel ribbon or wires, optimize post thermal-mechanical process for consolidation, and determine a bonding agent for electrical insulation.	100%
FY21-Q2	Develop insulating coating materials and processes. Prepare wire bundle rectangular prisms for testing (20x6x2 mm^3 active material loading >60%)	100%
FY21-Q3	Develop warm/hot press processes for fabricating 6.5%Si steel wire composite core sector shapes. Evaluate its magnetic properties and compare with state of the art materials.	90%
FY21-Q4	Assemble a “motorette” section with three teeth using two ‘U’ shape 6.5%Si wire bundles. Compare the core loss to a similar motorette from conventional Fe-3.2%Si steel as a function of frequency and temperature in collaboration with ORNL.	10%

Challenges (6.5% Si Steel)

Advantages of 6.5% Si Steel

FeSi steels	Ms (T)	DC relative permeability	Electric resistivity (μΩ-cm)	Magnetostriction (ppm)	Core loss $W_{10/400}$ (W/kg)
3.2% Si	1.96	18,000	52	7.8	14.4
6.5% Si	1.80	23,000	82	0.1	5.7





Challenges of 6.5% Si Steel

Too brittle to be manufactured using conventional strip casting and hot/cold-roll processes

α- FeSi	A2	All sites are randomly occupied by Fe or Si
α_2- FeSi	B2	C, B sites are randomly occupied by Fe or Si
α_1- FeSi	$D0_3$	C sites are randomly occupied by Fe or Si

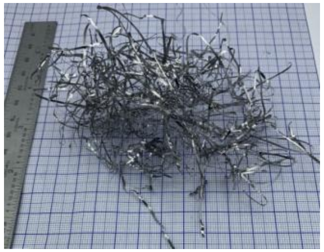
Approach (6.5%Si Steel)

6.5% Si steel exhibits superior electrical and magnetic properties, but it is too brittle to be cost effectively manufactured and used in motor. We approach the challenge with a novel thermal-mechanical process:

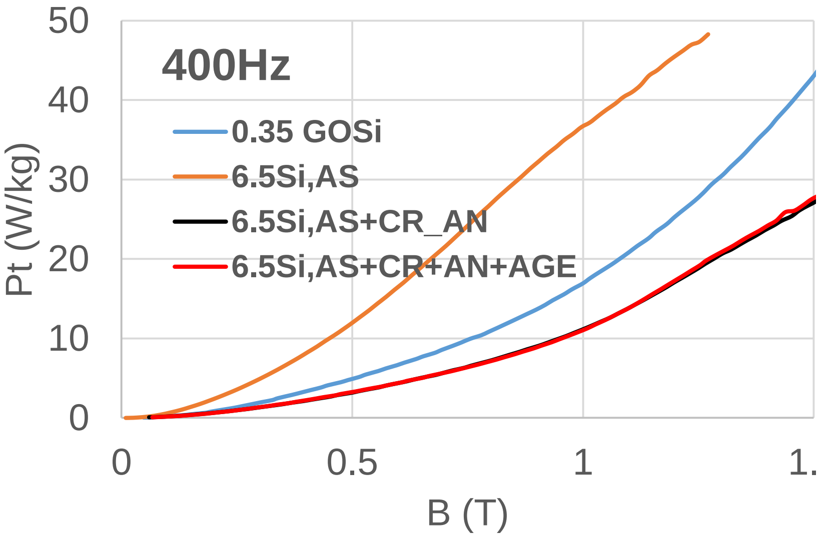
1. Use the rapid solidification process to suppresses the embrittling ordering phases, making it possible to produce ductile 6.5% steel in thin sheet form
2. Reduce the sheet width requirement for stator application. Abandon the conventional lamination approach, use bundled-wire form instead:
   – Further reduce eddy current.
   – Enable guided magnetic flux distribution
   – Enable near-net-shape molding of stator

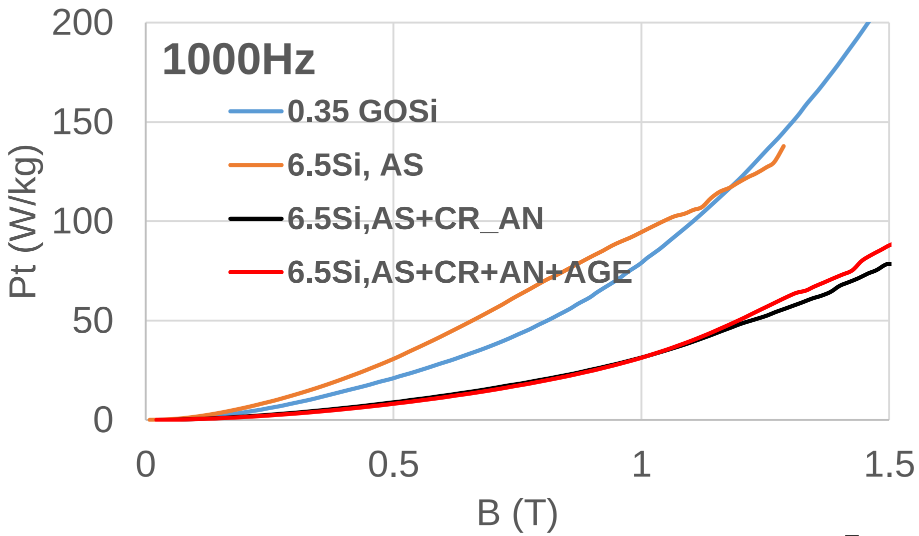
Technical Accomplishments

- Continuous Fe-6.5%Si ribbons prepared by melt spinning (cross section: 0.035x1 mm^2).
- The ribbons were cold rolled flat, and cut into strips (0.025x1x20 mm^3), mixed with epoxy and mold into a block.
- Annealed ribbon bundle showed much lower losses than conventional silicon steel at higher frequencies (>=400Hz).



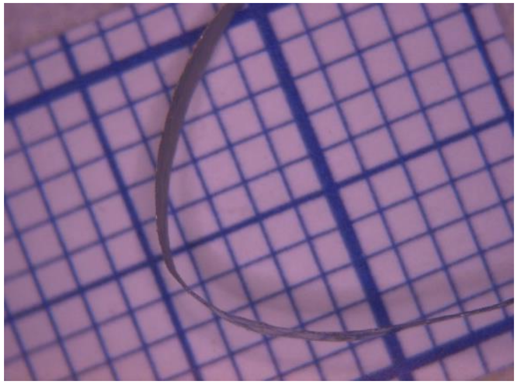
60mm x 20mm x 0.3mm





Technical Accomplishments

- Adjusting the quench wheel speed and post melt spun annealing will further reduce the core loss.
- Ribbons show excellent bending characteristic even after annealing, necessary for motorette bend radius requirement.



FeSi_10ms_CR_AN_bend

Sample	wheel speed	status	Hc	DC, µMax	DC coreloss	B8	B25	B50	W10/60	W10/400	W5/1k	W2/5k	W1/10k
			1T	1T	1T								
	m/s		A/m		J/m^3	Tesla	Tesla	Tesla	W/kg	W/kg	W/kg	W/kg	W/kg
Fe-3.2Si sheet	n/a	GOSi-Steel	9.3	12690	34.84	1.74	1.88	1.94	0.85	16.9	21	56.1	52.9
Fe-6.5Si ribbon bundle	20	AS+CR	159.9	1032	650.1	0.66	0.95	N/M	N/M	36.7	30.7	33.2	17.6
Fe-6.5Si ribbon bundle	20	AS+CR+AN	43.4	3849	187.4	1.16	1.31	1.43	1.5	11.1	8.8	11.8	7.3
Fe-6.5Si ribbon bundle	20	AS+CR+AN+AGE	43.1	4921	189.8	1.15	1.29	1.41	1.47	11	8.1	12.2	7
Fe-6.5Si ribbon bundle	10	AS	62.6	3295	241.6	1.16	1.37	1.49	1.93	14	11.5	14.9	8.5
Fe-6.5Si ribbon bundle	10	AS+AN	35.0	4424	144.8	1.17	1.33	1.45	1.19	**9.4**	**8.1**	**13.2**	**9.5**

GOSi-Steel: Grain oriented silicon steel; W10/60: loss as B = 1T, f = 60Hz; B8: flux density at H = 800 A/m.

AS: 20 m/s as spun; CR: cold roll (30.5% reduction); AN: 1100°C 2h annealing; AGE: 650°C ordering aging; N/M: not measured.

Responses to Previous Year Reviewers' Comments

Question 1 review 3 asked: …However, in the presentation it is not clear how this material compares with the state-of-the-art 0.27 millimeter (mm) or 0.25 mm Si steel in terms of flux density, core loss at different frequencies up to 1000 Hz, and mechanical properties. Without this comparison, it is not possible to claim that the cost barrier and performance barrier are addressed.

Ames response: when frequency exceeds 400 Hz, the advantage of Ames 'bundle' is obvious.

Sample	Sample thickness	Status	H_c 1T	DC μ_{Max} 1T	DC Coreloss 1T	B8 800A/m	B25	B50	W10/60	W10/400	W5/1k	W2/5k	W1/10k
	mm		A/m		J/m^3	Tesla	Tesla	Tesla	W/kg	W/kg	W/kg	W/kg	W/kg
Fe-3.2Si sheet	0.35	GOSi-Steel	9.3	12689.9	34.84	1.74	1.88	1.94	0.85	**16.9**	**21.0**	**56.1**	**52.9**
Fe-6.5Si ribbon bundle	0.30	AS+CR+AN+AGE	43.1	4921.1	189.8	1.15	1.29	1.41	1.47	**11.0**	**8.1**	**12.2**	**7.0**

Question 1 review 5 asked: It is not clear how the soft magnetic material developed in this project can compete with some existing material, such as Hiperco 50 in terms of saturation, permeability, and core loss. Hiperco 50 can easily go to 2.5 T. M19 can achieve more than 1.9 T. The material developed in this project targets to achieve 1.8 T, which is much lower than that of Hiperco 50. If the flux density of this material can only achieve 1.8 T, how can this material achieve better power density than Hiperco 50 or M19?

Ames response: 6.5%Si steel operates at higher frequency, less core loss than Hiperco50 or M19 at lower cost.

Materials	Bs (T)	Hc (A/m)	$10^3\mu_r$ 1 kHz	R ($\mu\Omega$-cm)	λ (ppm)	$W_{1.5/60}$ (W/kg)	$W_{10/400}$ (W/kg)
3.2% Si Steel, 0.35mm (AK Steel, M19)	2.0	32	8	50	8	3.2	14
Fe49**Co49**V2, 0.35 mm (Carpenter Hiperco 50)	2.4	40	19	40	60	2.0	13
6.5% Si Steel, 0.3mm (Ames Bundle)	1.4	43	5	82	0.01	1.5	11

Collaboration and Coordination

Oak Ridge National Laboratory

- Magnetic structure characterization of FeSi steel
- System level performance

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

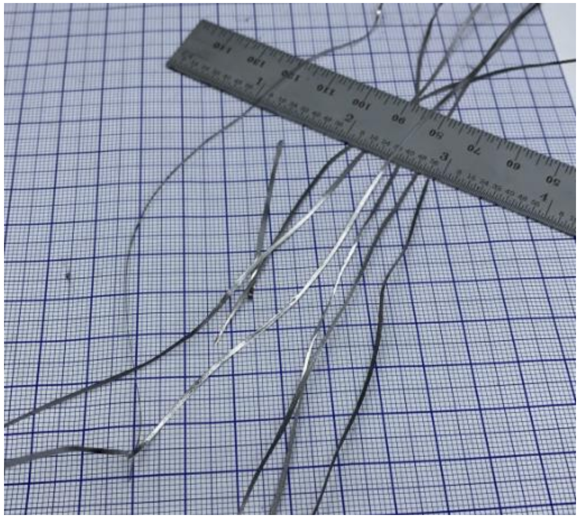
- Thermal mechanical properties

Sandia National Laboratories

- Nano-synthesis of soft magnetics for high frequency application

Remaining Challenges and Barriers

- A winding mechanism in needed to coil the continuous ribbon
- The ribbon bundle has to be consolidated into a net-net-shape with each ribbon coated and well-aligned
- The performance of a stator made of 6.5%Si steel wire bundle needs to be evaluated in actual motor



Invention disclosure filed

Proposed Future Research

- Optimize wire bundle consolidation process for higher magnetic properties
- Develop the hot-press setup for making U-shape near-net-shape stator teeth
- Incorporate into ORNL motor design

Any proposed future work is subject to change based on funding levels.

Summary

- Demonstrated a new approach to enable the high performance 6.5%Si steel for cost effective deployment.
  - Use rapid solidification to enable ductility and thin thickness, which leads to low eddy loss
  - Demonstrate the wire-bundle concept,
    - Reduced the ribbon width requirement from 200 mm to 2 mm, which dramatically reduces equipment and operation cost
    - Narrow and thin wire further cut down eddy current path
    - Demonstrated core loss less than the grain-orientated silicon steel

Technical Backup Slides