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

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Ames Laboratory

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Project ID: elt234

Overview

Timeline

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

Budget

- Total project funding
  - $715K (Federal)
  - $0 K (Cost share)
- Funding for FY 2020: $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

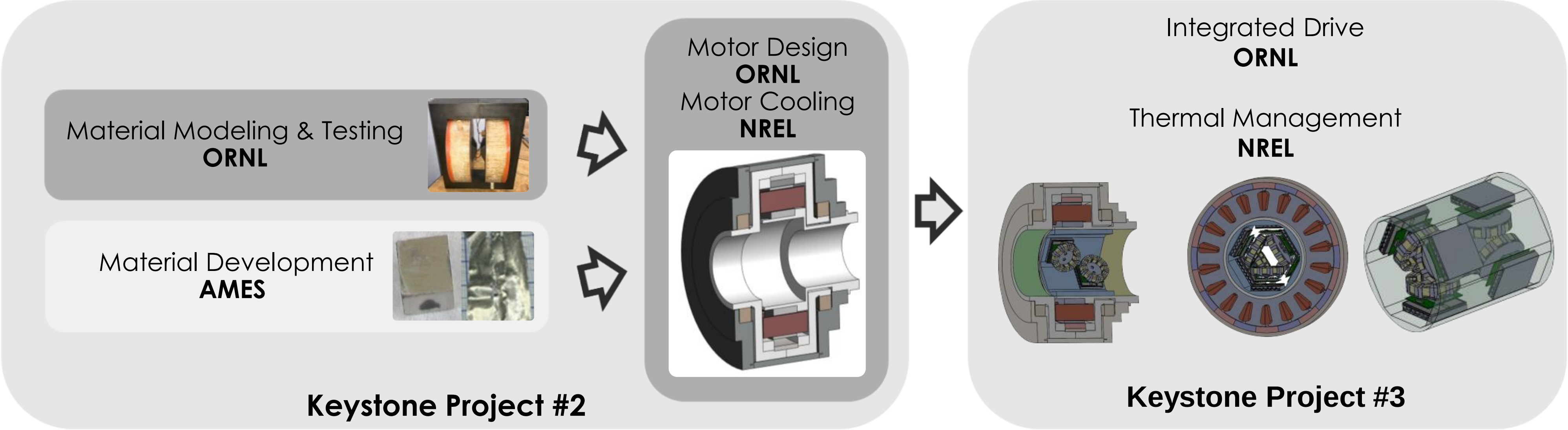
- Oak Ridge National Laboratory
- National Renewable Energy Laboratory
- Sandia National Laboratory

Milestones

Tasks #	Description	FY2019				FY2020				Status
	Soft Magnets to Achieve High-Efficiency Electric Drive Motors of Exceptional Power Density	1	2	3	4	1	2	3	4	
Yr1-Q1	Establish crucible design for adaptable sheet forming in new melt spinning system.									100%
Yr1-Q2	Initial demonstration of the planar flow casting system with a model alloy.									100%
Yr1-Q3	Demonstrate planar flow casting of 6.5% Si steel sheet with 25 mm width									95%
Yr1-Q4	Characterization of the fabricated sheet (microstructure, electrical and magnetic properties)									95%
Yr2-Q1	35mm ribbon									50%
Yr2-Q2	Heat treatment optimization, stamping									100%
Yr2-Q3	Stamping without spur									100%
Yr2-Q4	Motor sector stack, 3.5%-6.5%Si									0%

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



Approach (6.5%Si Steel)

- Rapid solidification suppresses deleterious ordering phases
  - Use the planar flow casting technique to produce wide and thin ductile sheet suitable for motor stator and rotor applications.
- Optimize sheet hardness for high speed stamping process
  - Post casting annealing

	Planned milestones and annual go/no-goes
2019	• Demonstrate the wide (>25 mm) rapidly solidified 6.5%Si steel sheet is viable for motor applications
2020	• Develop laminate material/insulation and stamping/stacking process for 6.5%Si steel sheet

1) G. Ouyang, X. Chen, Y. Liang, C. Macziweski, J. Cui, A review of Fe-6.5%Si alloy – a promising soft magnetic material for sub-kHz application. *Journal of Magnetism and Magnetic Materials*. 2019 July; 481: 234-250.
2) S. Cui, G. Ouyang, T. Ma, C. Macziewski, L. Zhou, M. Kramer, V. Levitas, J. Cui, Thermodynamic and kinetic analysis of the melt spinning process of Fe-6.5 wt.% Si alloy. *Journal of Alloys and Compounds*. 2019 January; 771: 643-648.
3) G. Ouyang, B. Jensen, Chad. Macziewski, T. Ma, F. Meng, Q. Lin, L. Zhou, M. Kramer, J. Cui, Characterization of ordering in Fe-6.5%Si alloy using X-ray, TEM, and magnetic TGA methods, Materials Characterization, 158, 2019,109973.

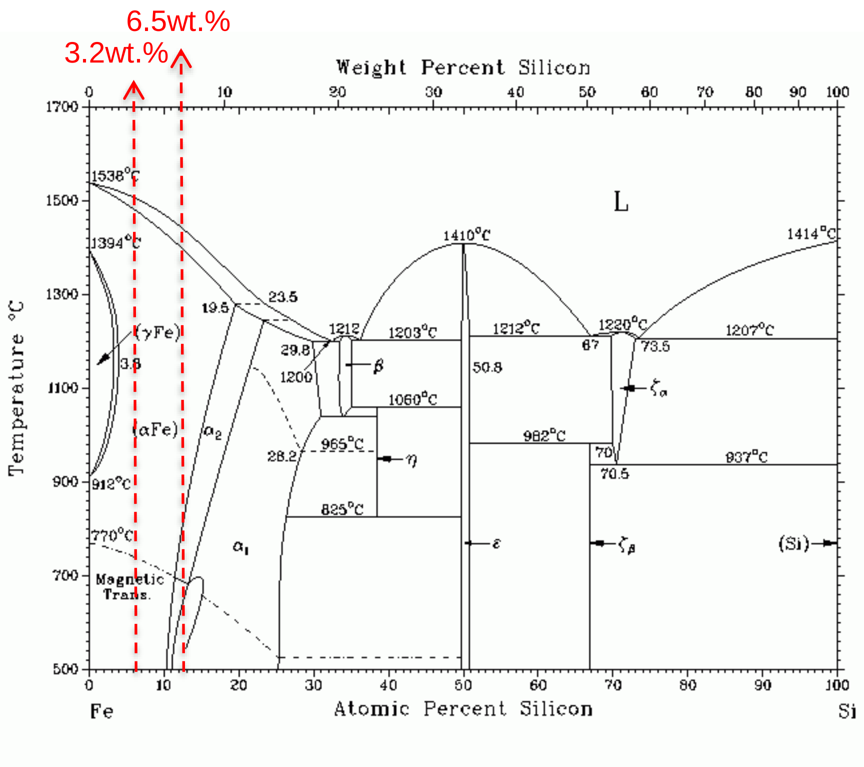
Challenges (6.5% Si Steel)

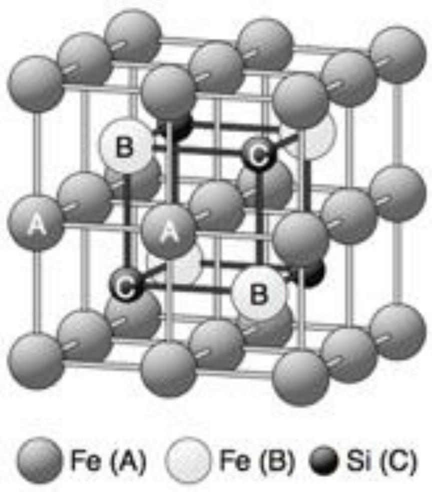
Advantages of 6.5% Si Steel

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

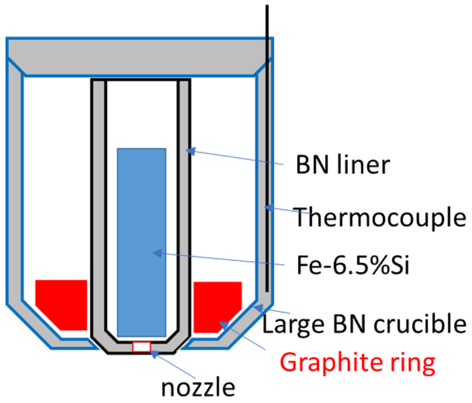


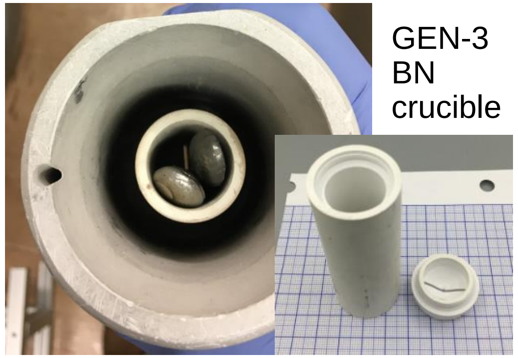


α- FeSi	A2	All sites are randomly occupied by Fe or Si
α_2- FeSi	B2	C, B sites are randomly occupied by Fe or Si
α_1- FeSi	$D0_3$	C sites are randomly occupied by Fe or Si

Technical Accomplishments

Fe-6.5%Si steel fabrication





GEN-3 BN crucible

Continuous ribbon

Trial ribbons, Fe-6.1wt%Si-3.5wt%B

T_m = 1136°C (by DSC)

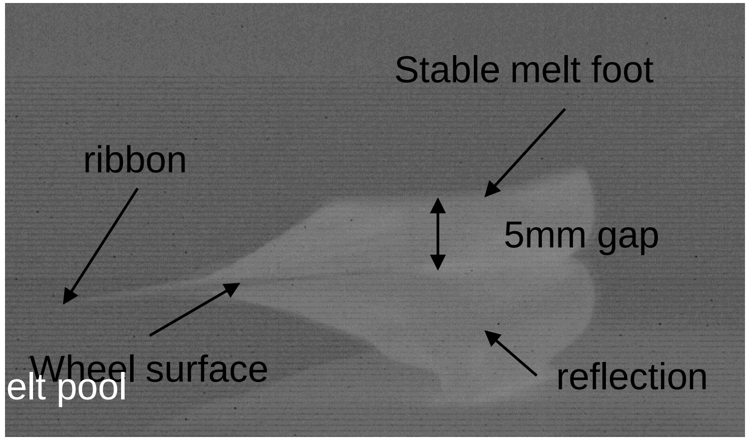
- GEN-3 BN crucible designed to facilitate higher super heat, melt temperature of 1700°C achieved.
- 10mm wide continuous ribbon prepared with good surface quality.

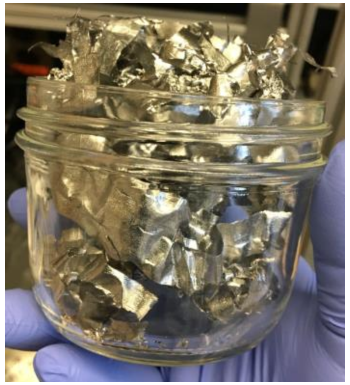
Technical Accomplishments

Instrument upgrades Parameters refinements

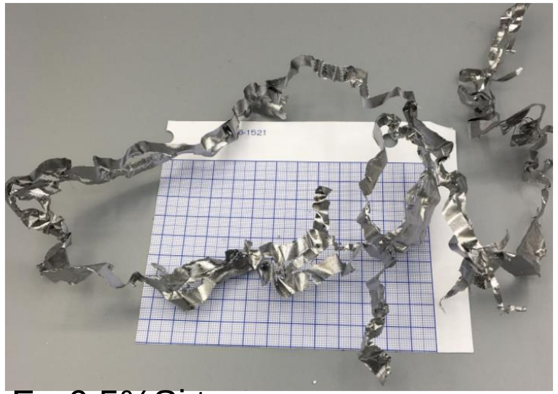
High speed camera footage showing unstable melt pool

Improved equipment heat management and cooling
New melt crucible, heater, and nozzle design
Refined super heat and injection pressure.

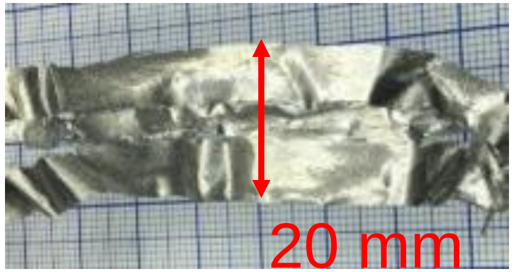




Fe-6.5%Si tapes



Fe-6.5%Si tapes

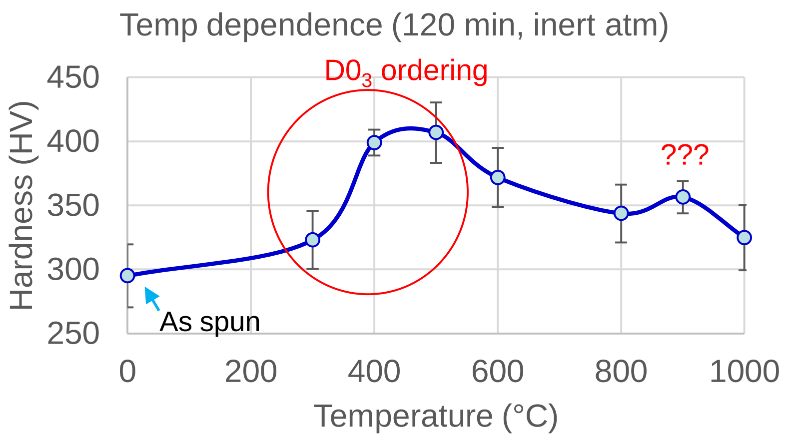


20mm wide Fe-6.5%Si tapes
$Tm_{Fe\text{-}6.5\%Si}$ = 1411°C (by DSC)

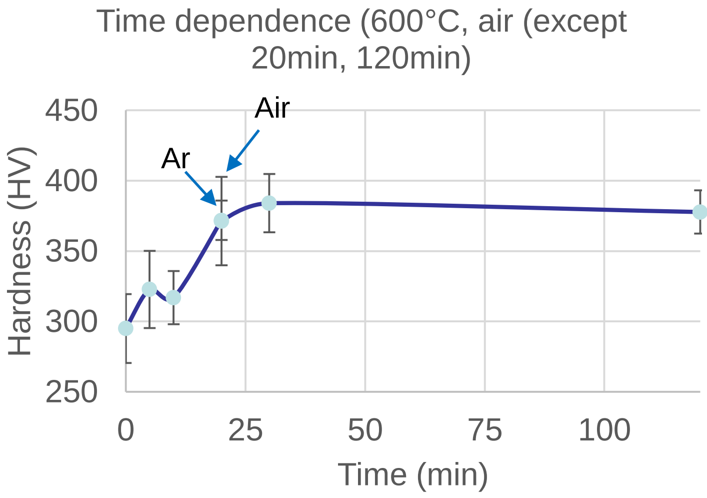
- The melt pool characteristic has been refined for wider and better quality ribbon.
- 20mm wide Fe-6.5%Si tapes prepared.

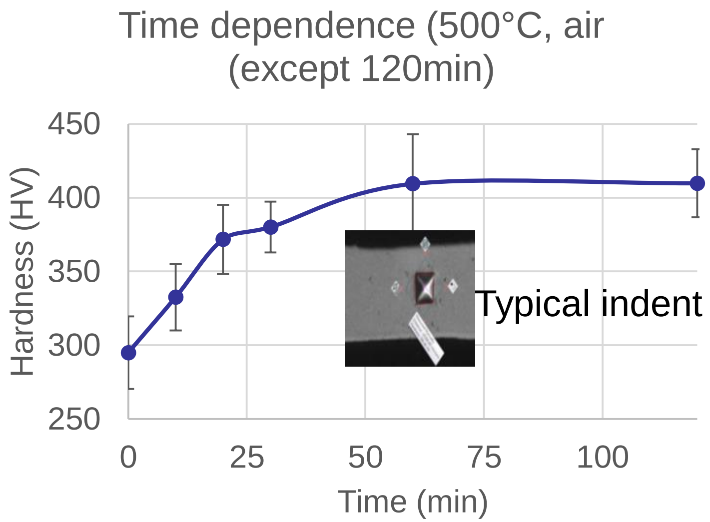
Technical Accomplishments

Fe-6.5%Si heat treatment, hardness

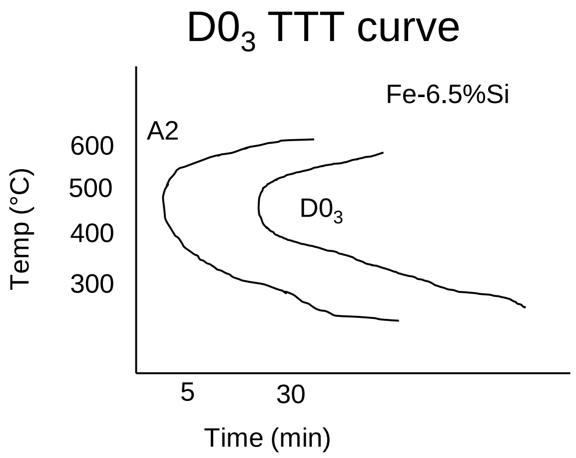


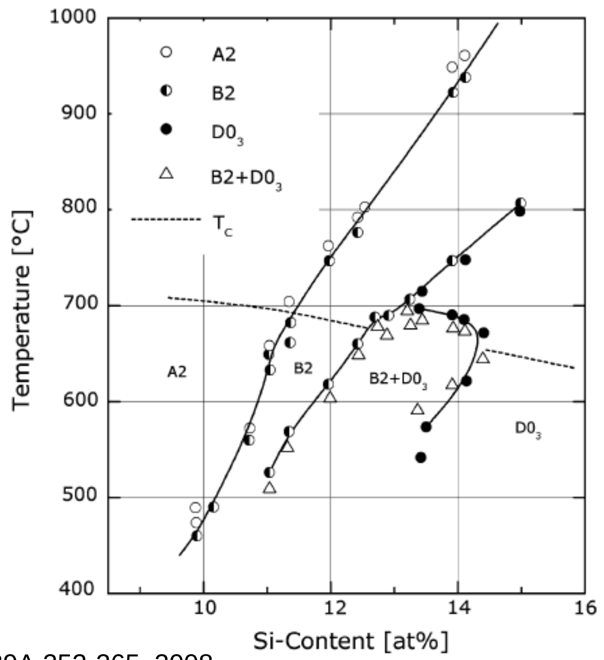
25gf,13s; 10 indents per sample.





- Good stamping ability when the hardness is ~380-420 HV.
- Significant hardness increase at 400-500°C relates to $D0_3$ ordering, consistent with literature.
- $D0_3$ TTT curve constructed based on hardness changes.





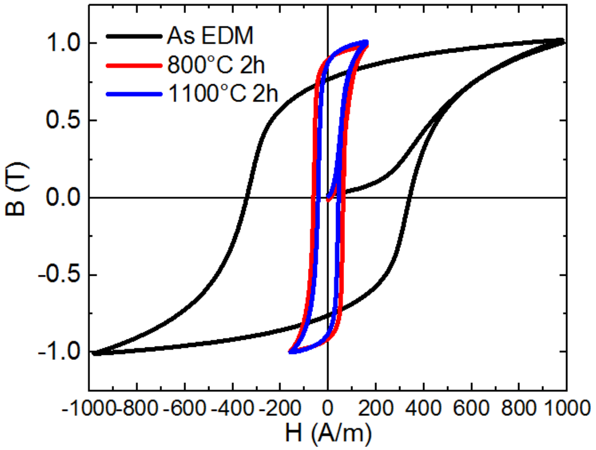
J. Witting and G. Frommeyer, Met. Trans. A, 39A 252-265, 2008

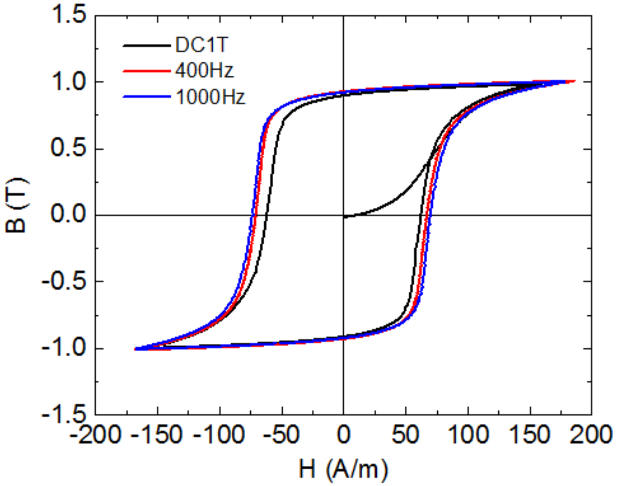
Technical Accomplishments

Fe-6.5%Si stacked laminates magnetic properties

OD: 22mm, ID: 18mm, h: 3.9mm

100 laminates, stack together, insulated by MgO powders





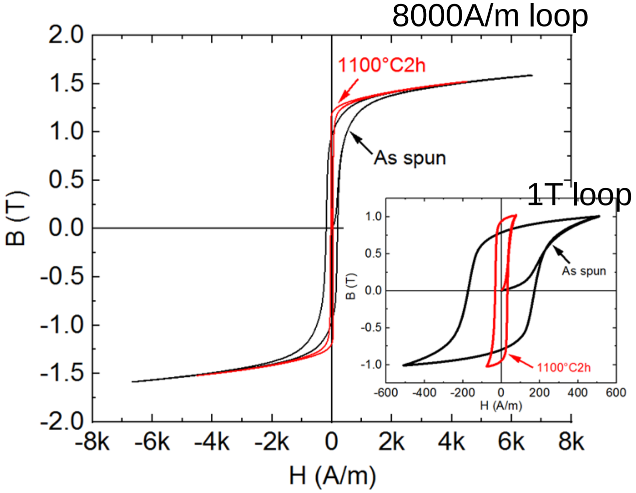
	thickness	Hc	DC,μMax	B8	B25	W10/400	W10/1k
	mm	A/m		Tesla	Tesla	W/kg	W/kg
Laminated core (as spun)	0.03	340.5	987.3			66.8	
Laminated core (800°C 2h)	0.03	62.2	6109.0	1.21	1.35	15.0	38.5
Laminated core (1100°C 2h)	0.03	42.9	7691.4			10.8	28.5

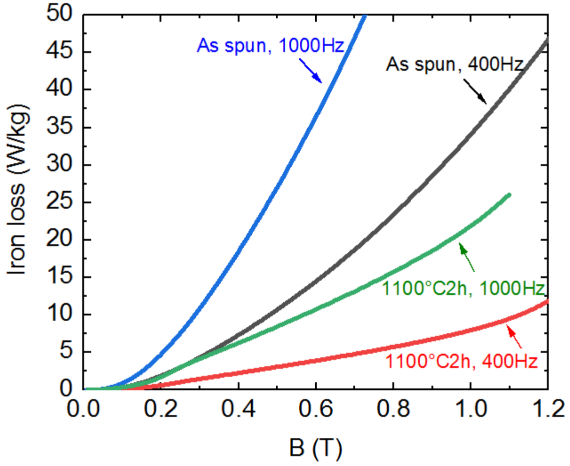
- W10/400 of 10.8 W/kg is achievable in annealed laminated core.
- Laminates' thickness less than skin depth (~0.3mm at 400Hz).
- Hysteresis loss plays dominate role in lowering W10/400Hz.

Technical Accomplishments

Fe-6.5%Si Tape wound core magnetic properties

OD: 32mm, ID: 25mm, h: 12mm
MgO powder lamination





	thickness	Hc	DC,μMax	B8	B25	W10/400	W10/1k
	mm	A/m		Tesla	Tesla	W/kg	W/kg
Tape wound core (1100°C2h)	0.03	49.2	12k	1.33	1.45	8.0	21.9
Tape wound core (as spun)	0.03	192.1	2k	1.19	1.43	33.3	84.5
JNHF, gradient	0.2		3.9k	1.09	1.47	14.5	29.1
JNEX, Fe-6.5Si	0.1		23k	1.29	1.40	5.7	18.7
NO Fe-3.2Si	0.35		18k			14.4	62.0

- Iron loss at 1T, 400Hz, W10/400 of 8.0 W/kg is achievable in annealed tape wound core.
- Annealing is necessary to lower the hysteresis loss for low W10/400.

Responses to Previous Year Reviewers' Comments

Question 1 review 2 asked: The major concern is if the process can scale beyond the proposed 25 mm width strip. For useful strip widths it will need to be wider even for segmented motor production. It would have been useful to measure some of the mechanical properties of the 6 mm before moving to the wider strip.

Ames response: For the FeSi project: the rapid solidification process (the one we are using to fabricate the 25 mm width strip) has been used to manufacture 200 mm width amorphous strip for transformer applications. Such wide strip requires large equipment beyond our lab equipment's capacity. We chose 25 mm because it is just wide enough for building a rotor section that can be tested for its actual core loss on relevant scale. Added benefit is we can learn the post casting treatment necessary for assembly and magnetic properties optimization. We will also be performing these mechanical properties in the future in collaborations with NREL.

We have recently reached an agreement with Metgals who will be performing a trial run on this composition using their pilot scale equipment.

Collaboration and Coordination

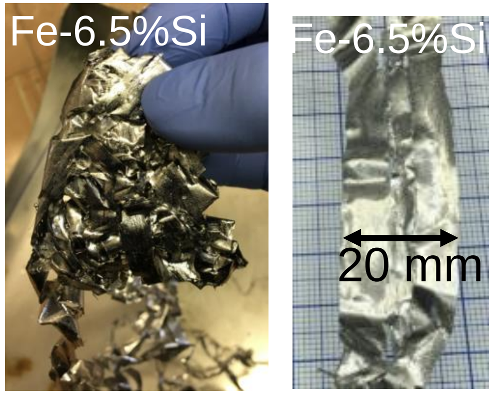
- Magnetic structure characterization of FeSi steel
- System level performance

- Thermal mechanical properties

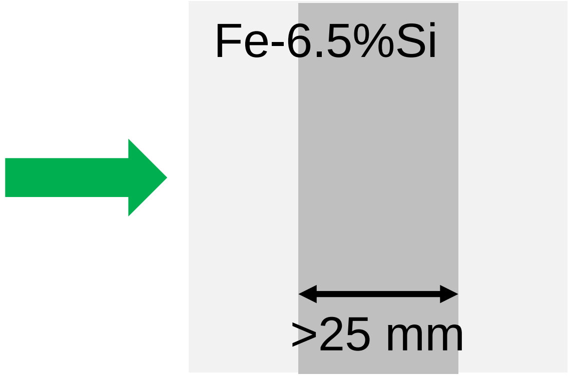
- Nano-synthesis of soft magnetics for high frequency application

Remaining Challenges and Barriers

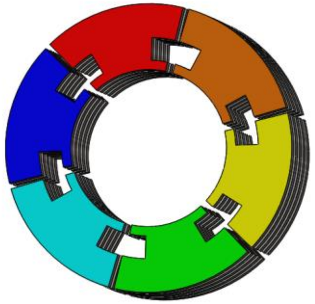
- Tape production
  - Width
  - Thickness
  - Surface finish
  - Processability
  - Heat management
- Effective use of materials for making stators
  - Modular (rotor sector) design
- Composition optimization
  - Manufacturability
  - Performance
    - Core losses
    - Increase induction



Fused due to limited flight path



0.03m to 0.1mm thick



Modular laminate teeth

Motor with High B_s, low eddy current loss Fe-6.5%Si motor laminates.

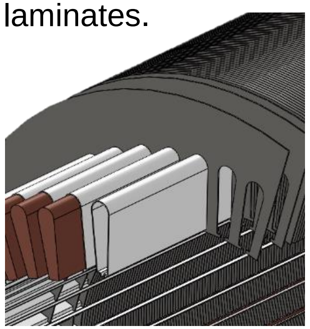


Photo Credits:
Doug DeVoto, NREL

Proposed Future Research

Key Challenges

- Demonstration of scalability for industry adoption.
- Optimizing core loses while maintaining manufacturability
- Casting at such high temperature requires advanced cooling technology for copper wheel.

Future work

- Partnership with Metglas Inc. for large scale Fe-6.5%Si manufacturing development.
- Minimize the crystalline anisotropy and increase the ductility through alloying additions.
- Develop refined heat treatment to improve magnetic properties of the melt spun tapes.
- Characterize mechanical and thermal properties with NREL
- Incorporate into ORNL motor design

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

Summary

- Modified traditional planar flow casting methods to simultaneously achieve disordered phase with larger grain size for the 6.5% Si steel.
  - Reduced core losses yet maintained formability

- Demonstrated planar flow casting system with Fe-Si-B alloy and Fe-6.5%Si.
  - continuous ribbons with 10 mm width were produced.

- System upgrade complete, developed 20 mm wide ribbons of 6.5% Si steel.
  - Melting point is ~300 ℃ higher than Fe-Si-B Metglas.

Technical Backup Slides