U.S. DEPARTMENT OF ENERGY
Office of Electricity

Microstructure Optimization of Electrical Steel Through Understanding Solidification Dynamics in Additive Manufacturing

August 14, 2019

TRAC Program Review
US Department of Energy, Office of Electricity

Presented at Oak Ridge National Laboratory
Oak Ridge, TN

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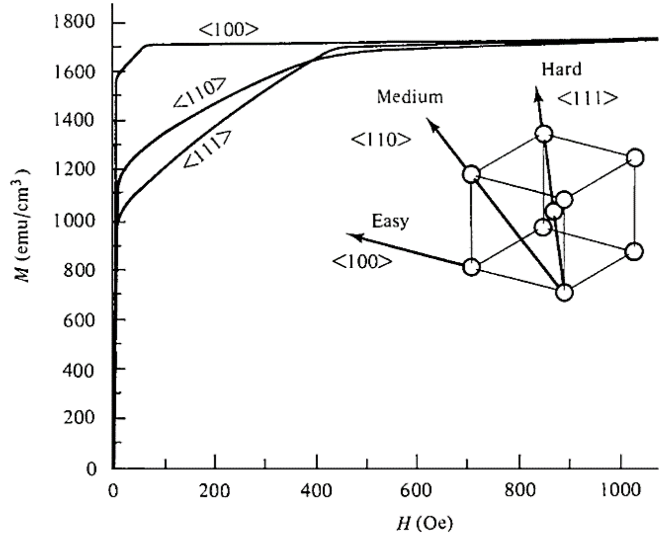
Project Overview

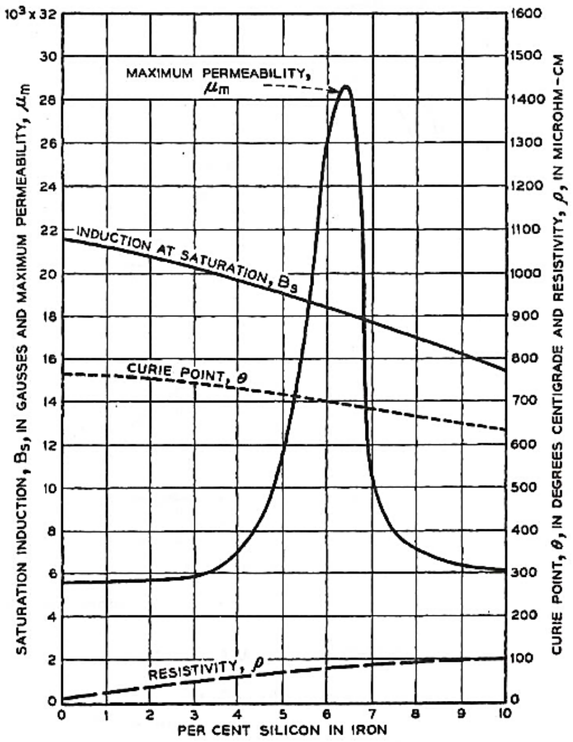
- Project Summary
  - Understand the potential for additive manufacturing in the production of electrical steels with tailored microstructures and composition for improved performance in transformer cores

- Budget: $1.2M
- POP: 10/1/17 – 9/30/19
- Project lead: Alex Plotkowski (ORNL)
- Project team:
  - Ryan Dehoff (Additive manufacturing)
  - Jason Pries (EM modeling and magnetic testing)
  - Keith Carver (Additive manufacturing and design)
  - Fred List (Additive manufacturing)
  - Jamie Stump (Heat transfer modeling)
  - Niyanth Sridharan (Ferrous metallurgy)
  - Peeyush Nandwana (Heat treatment)

Context and Motivation

- Additive manufacturing of Fe-Si transformer cores may be a future approach for rapid manufacturing in emergency situations
- **AM May offer a route for improved microstructure design and production of high-Si electrical steels for improved performance**
- Significant materials science and design challenged must first be addressed
  - Approaches for manufacturing brittle high-Si steels
  - Understanding and exploiting process-microstructure-property linkages
  - New component designs for AM



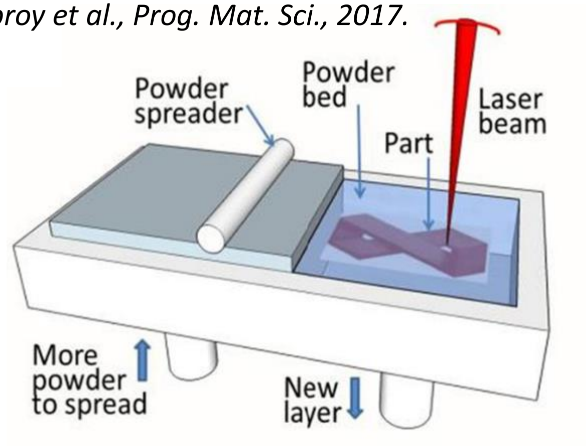


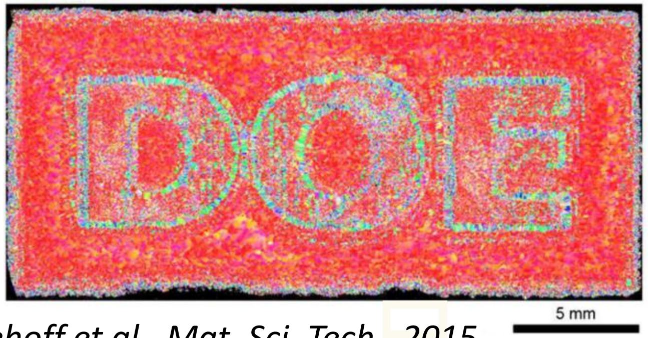
Bozorth, Ferromagnetism, 1993

State of the Art

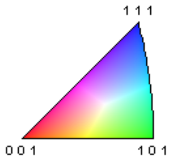
Examples of control over grain orientation in additive manufacturing of Ni alloys

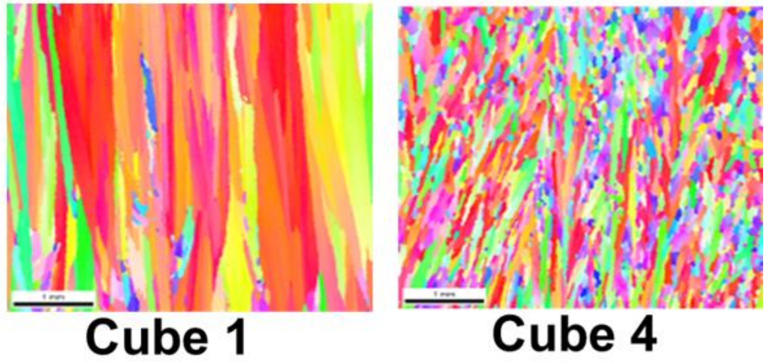
Debroy et al., Prog. Mat. Sci., 2017.





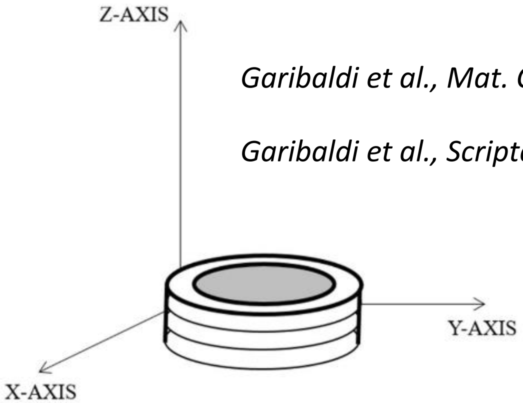
Dehoff et al., Mat. Sci. Tech., 2015





Raghavan et al., Acta Mat., 2017.

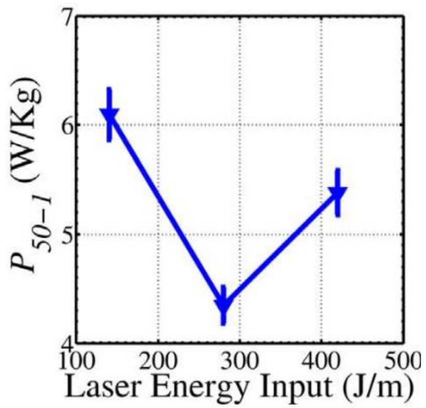
- Preliminary AM production of Fe-6.9Si
  - Simple B-H rings
  - Limited AC data

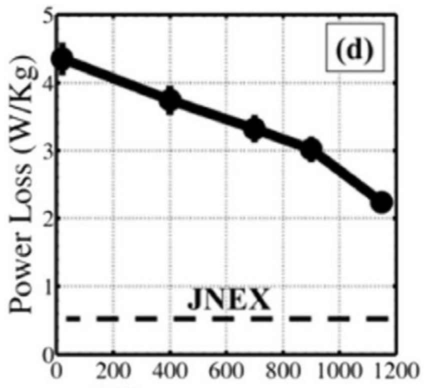


Garibaldi et al., Mat. Char., 2018

Garibaldi et al., Scripta Mat., 2018

1T – 50 Hz





Uniqueness and Significance

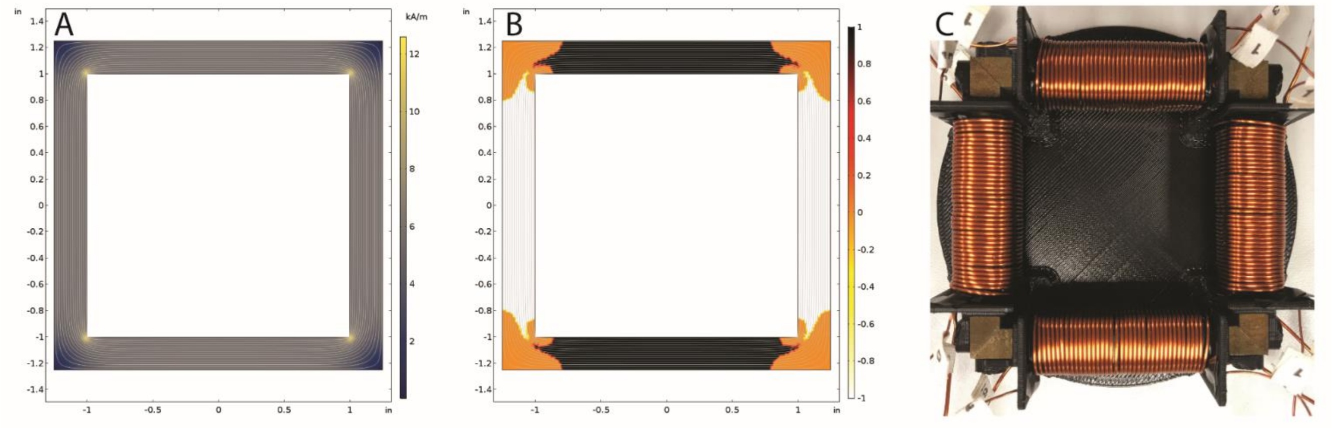
- **Technical Approach**
  - Microstructure optimization through manipulation of additive manufacturing process conditions
  - Fundamental understanding of process metallurgy
  - Consideration for influence of both material chemistry and structure enabled by advanced manufacturing
  - Unique designs enabled by additive manufacturing
- **Significance**
  - New production route for soft-magnetic materials
  - Roadmap for materials, process, and design considerations
  - Potential manufacturing route for rapid production of transformer cores

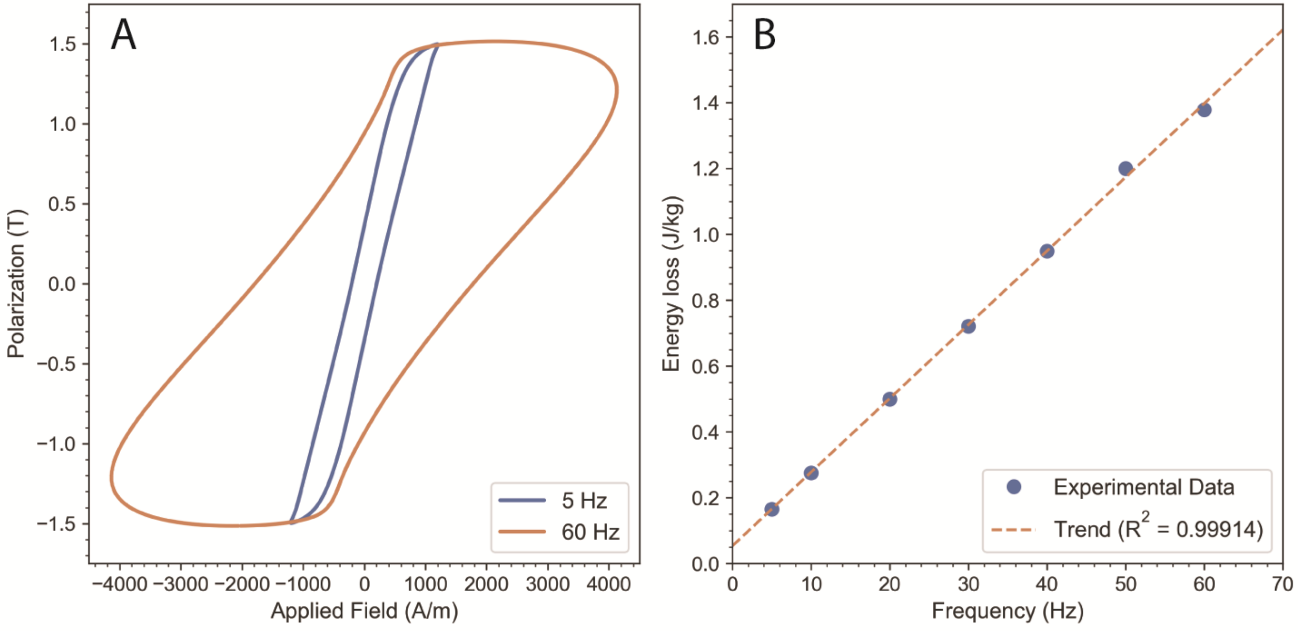
Test Setup and Loss Decomposition

- Isolate build direction
- Brockhaus MPG200 system used for automated measurement and data post-processing with good repeatability
- EM simulation of edge effects
- 6.35 mm sq. x 63.5 mm long
- Simple decomposition that assumes linear energy loss with frequency

$$P_{cycle} = c_{hyst}(B)f + c_{eddy}(B)f^2$$

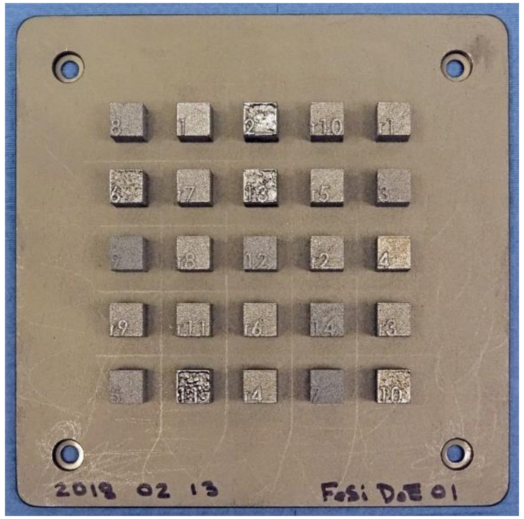
$$E_{cycle} = c_{hyst}(B) + c_{eddy}(B)f$$

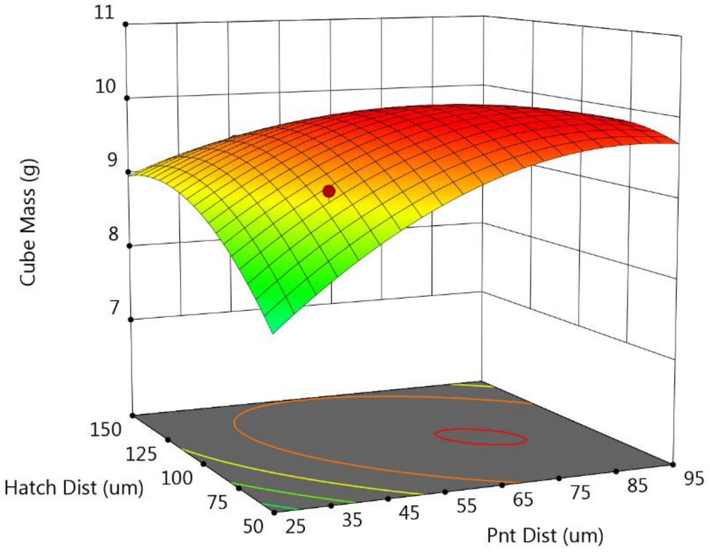




Additive Manufacturing

- Renishaw AM250
- Pulsed laser powder bed system

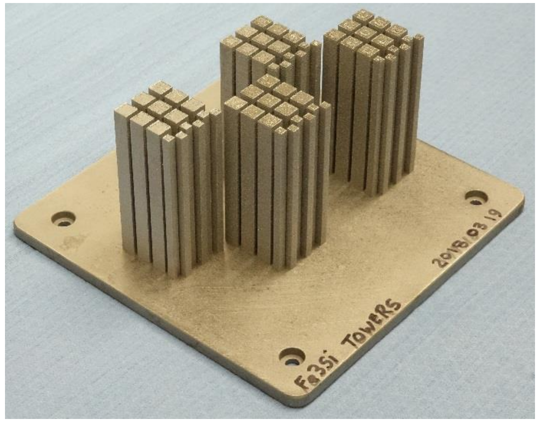




Fe	Si	C	N	O	Other
Balance	3.0 ± 0.3	0.04	0.001	0.027	<0.10

Parameter	Value
Hatch spacing (µm)	100
Point spacing (µm)	75
Exposure time (µs)	110
Layer thickness (µm)	50

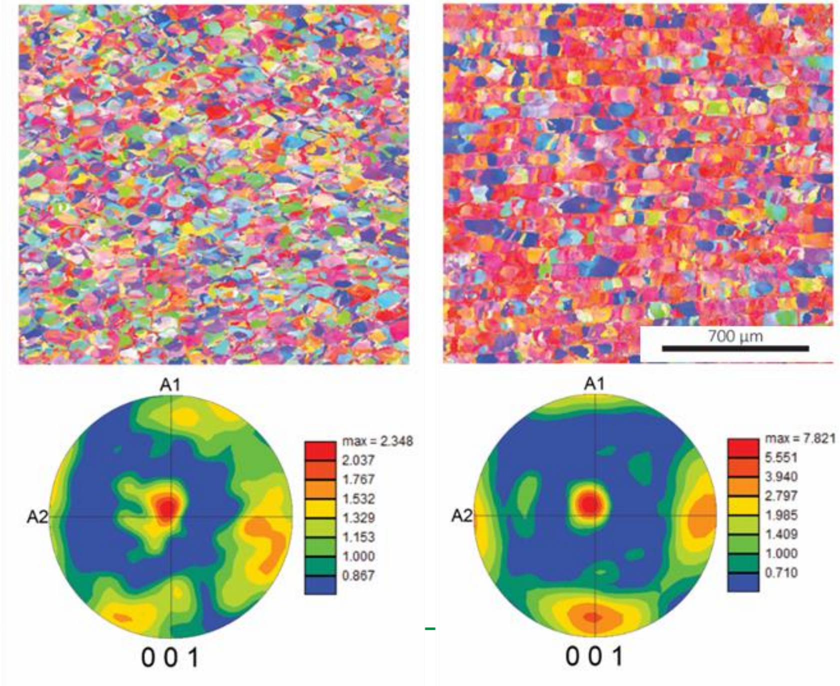
Fe-Si Processing with a Conventional Single-Laser System

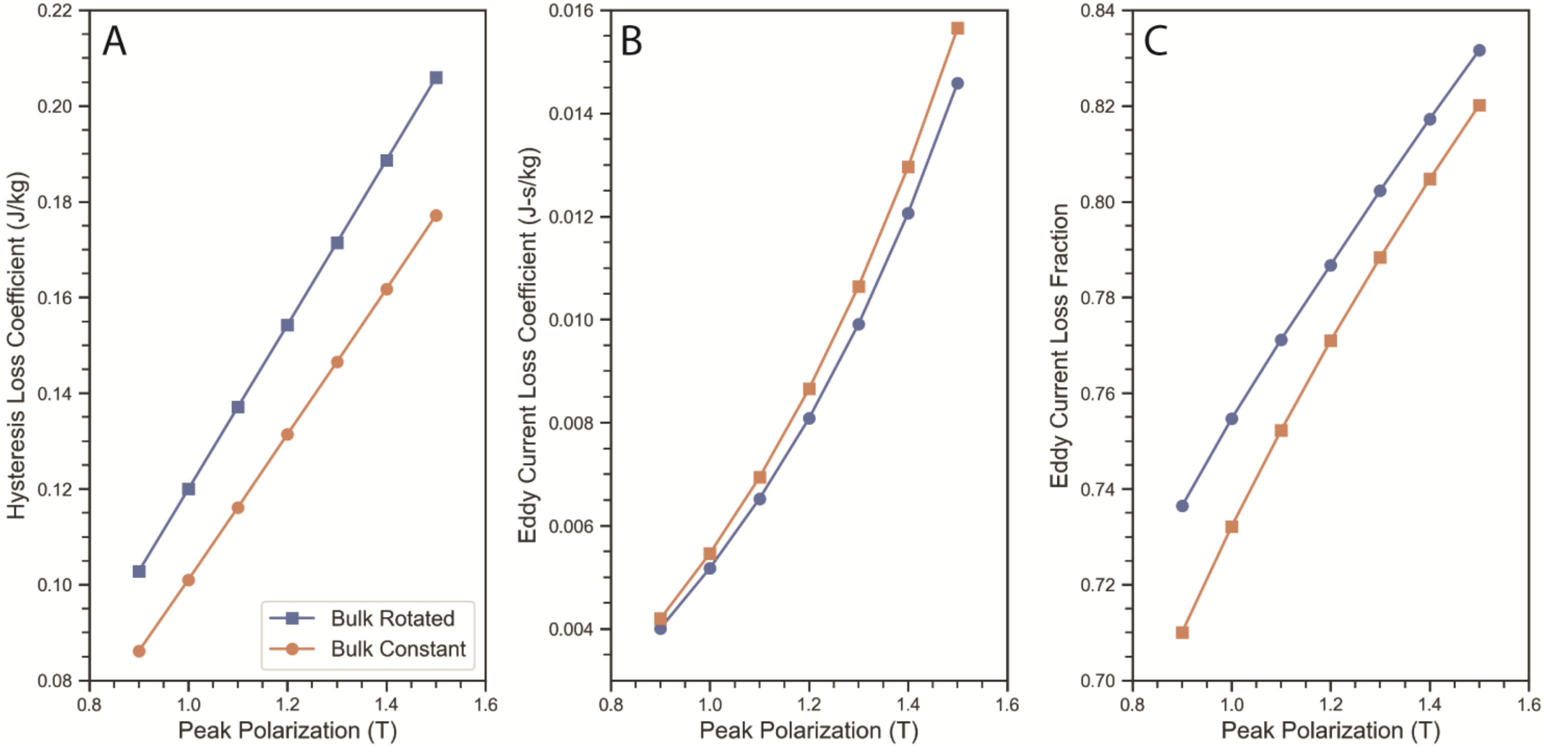


- Two scan patterns
  - Single scan (rotation)
  - Double scan with constant second pass

- Double scan shows lower hysteresis loss
  - Related to grain texture
- **Eddy currents account for 70-80% of power losses**

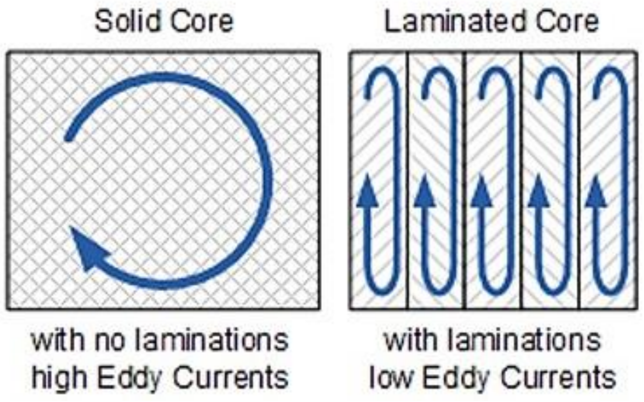
Single Scan　　Double Scan



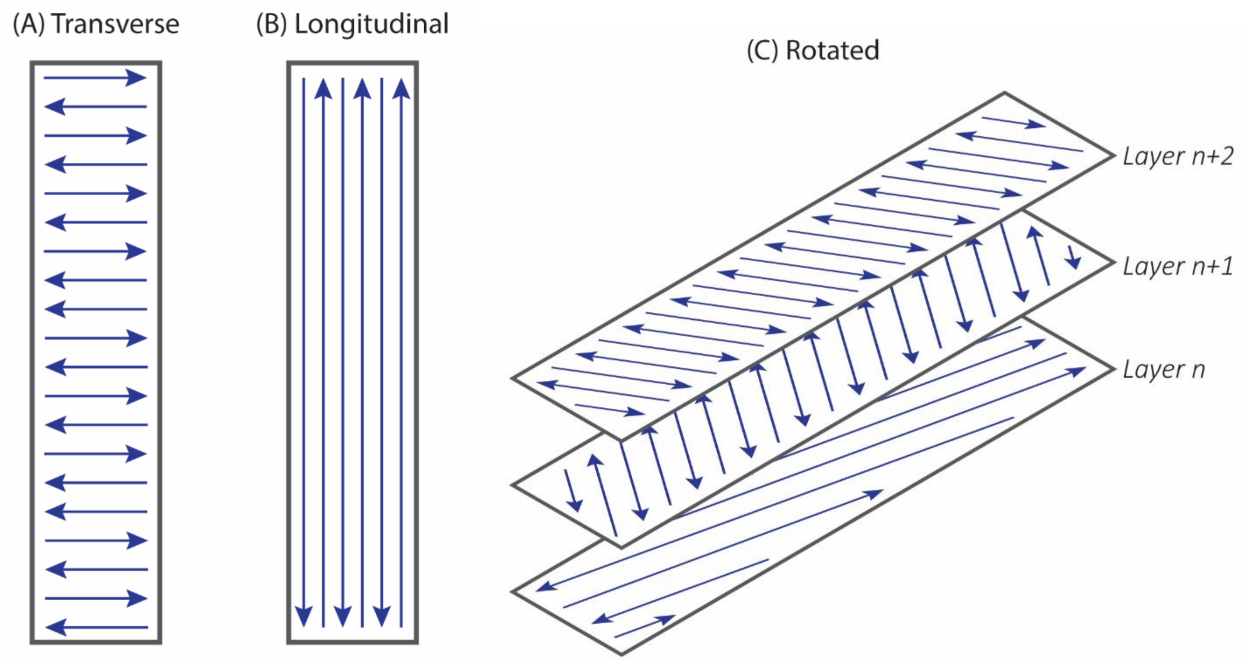


Thin Wall Structures to Reduce Eddy Current Loss

- Thin wall structures to confine eddy current development and significantly reduce power loss
- Dramatic variations in heat transfer depending on scan pattern

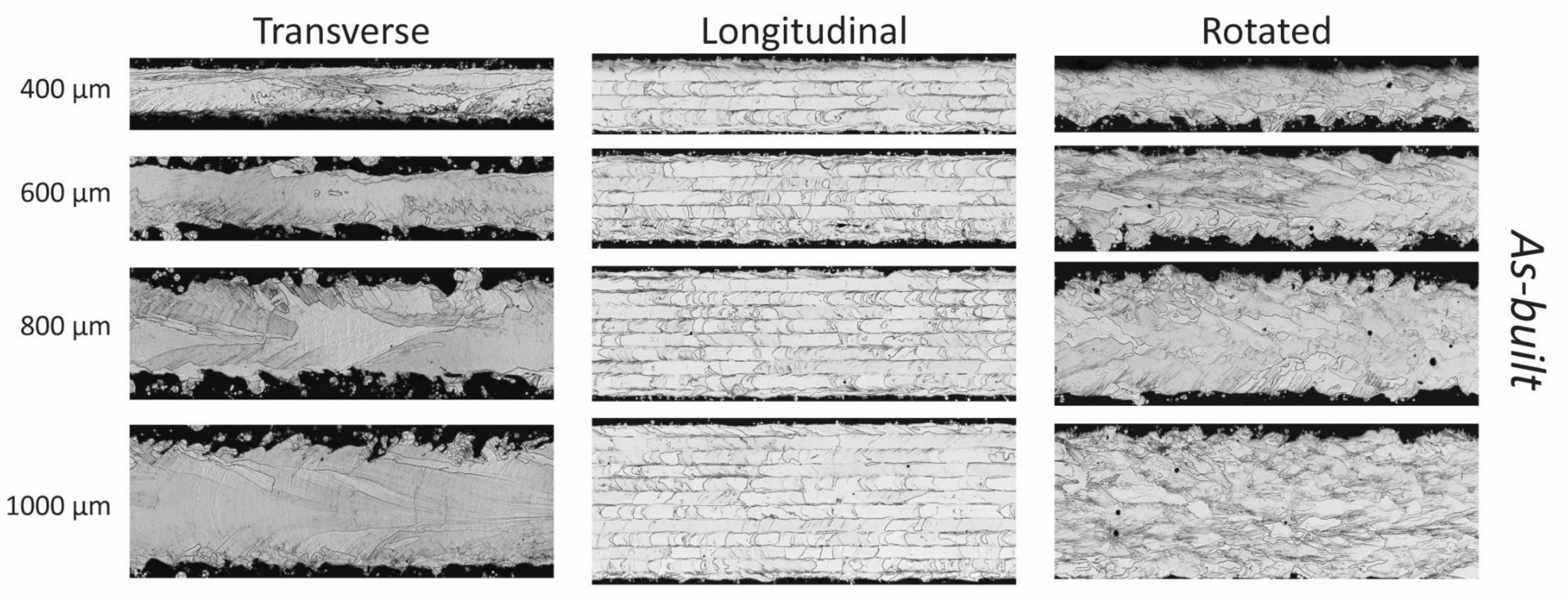


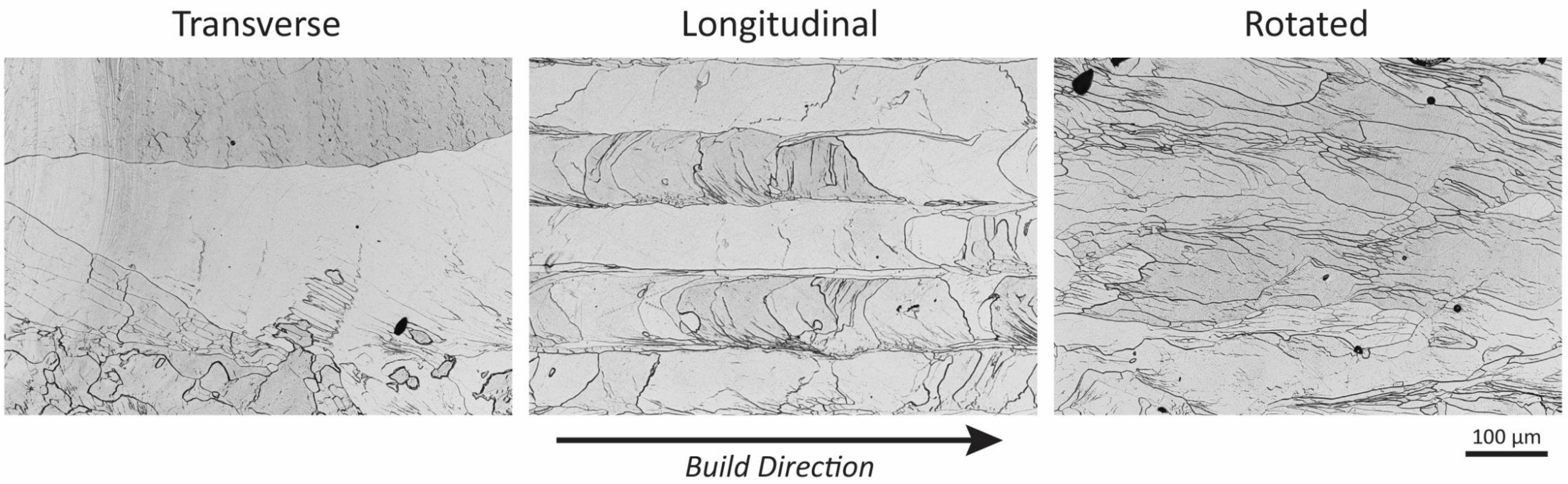
$$\delta = \sqrt{\frac{2\rho}{\omega\mu}} = 1.45\ \mathrm{mm}$$



Thin Wall Grain Stru

- Scan pattern orientation has dramatic effect on grain size
- Relate to process conditions?





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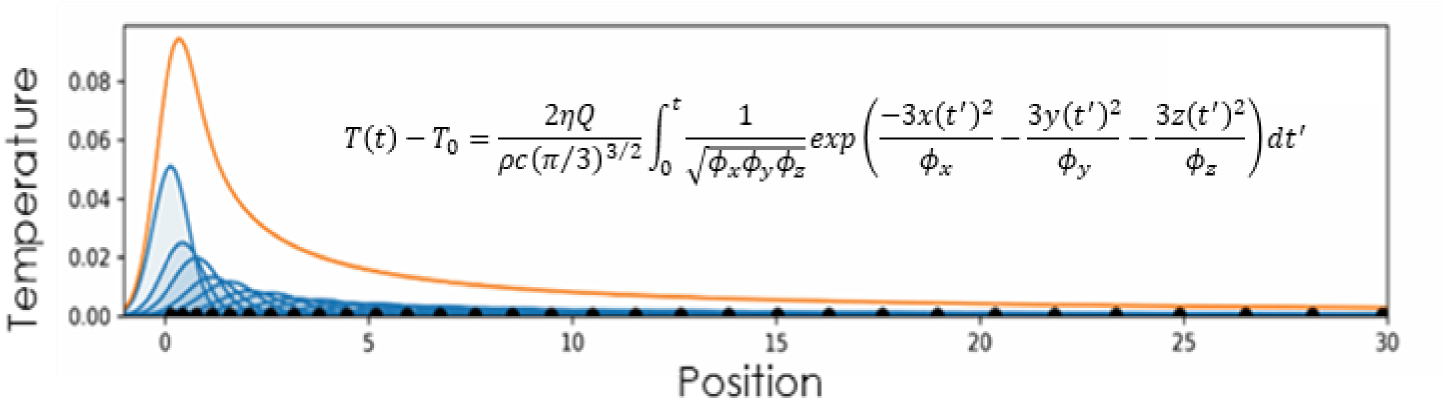
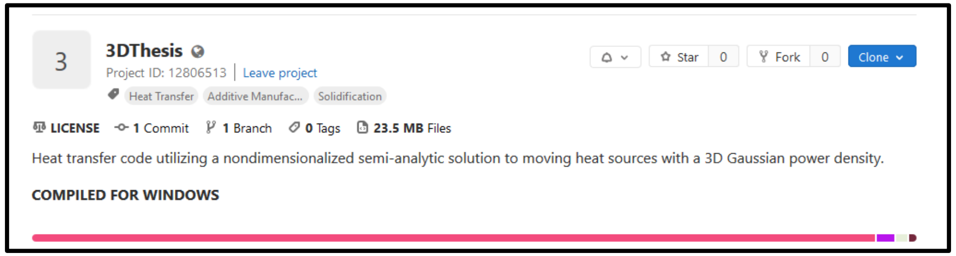
Simplified Thermal Process Model

- Green's Function solution for transient thermal field around a moving volumetric Gaussian heat source in a semi-infinite domain (Nguyen et al., Weld. Res. Supp., 1999)
- Neglects non-linear effects
- Adaptive quadrature technique for accurate and efficient numerical integration





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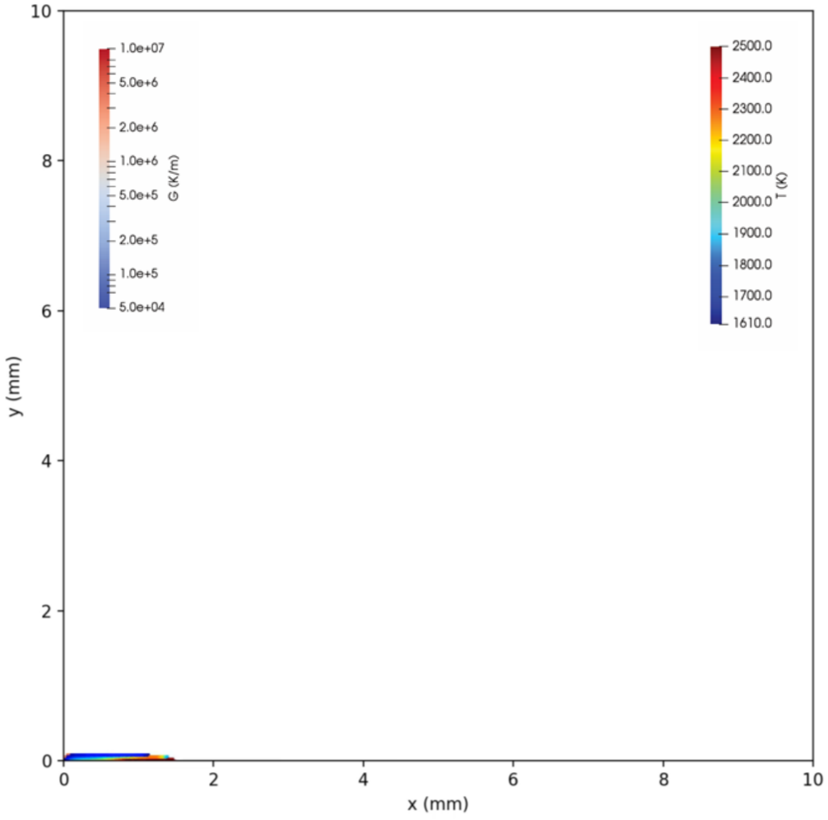
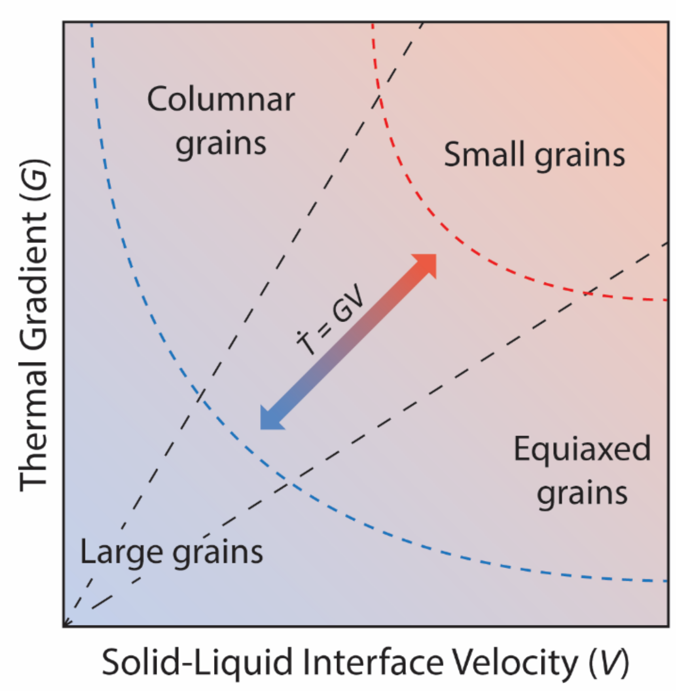
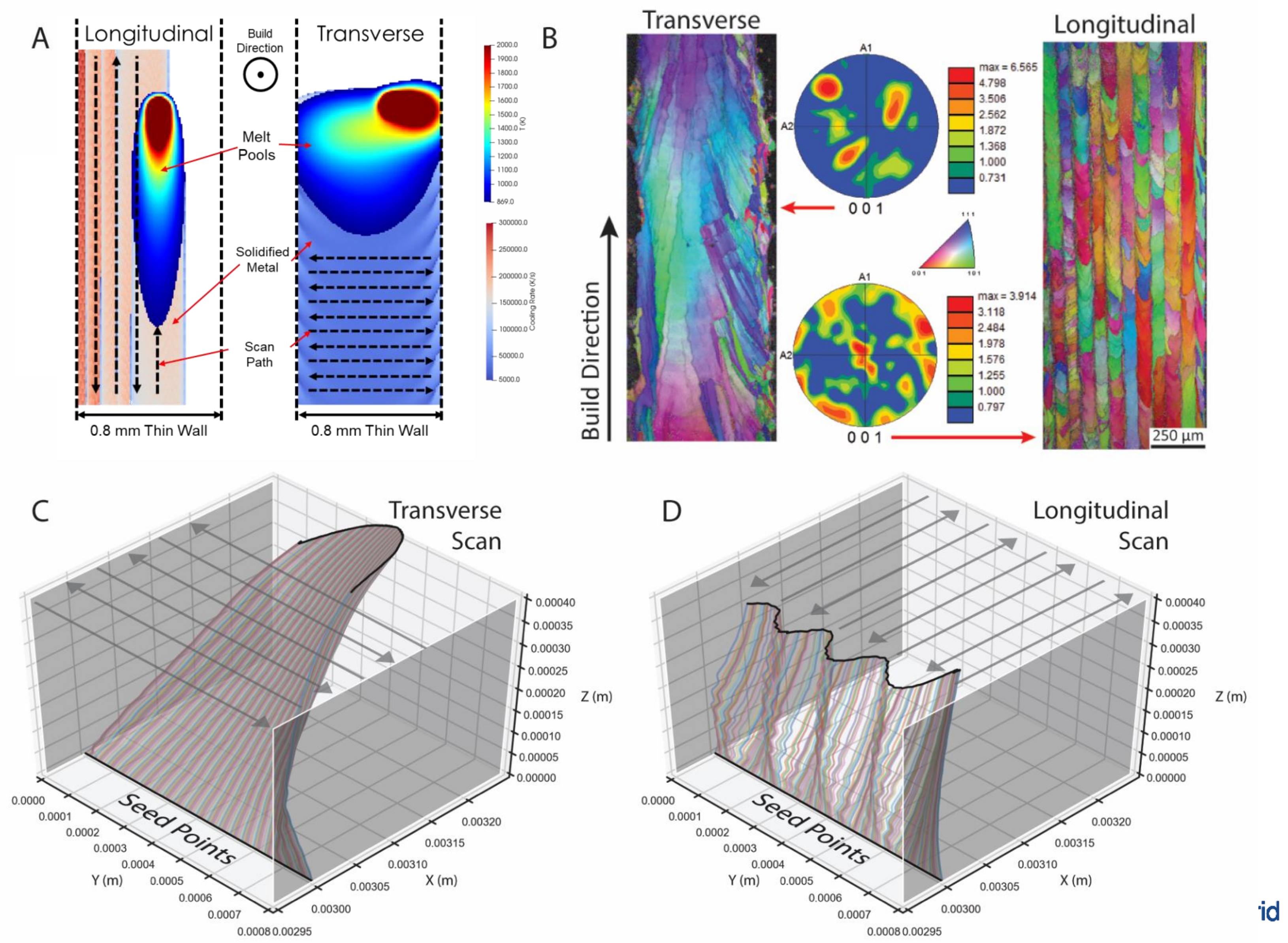


Stump and Plotkowski, Appl. Mat. Mod., 2019

Process Modeling of Thin Wall Structures

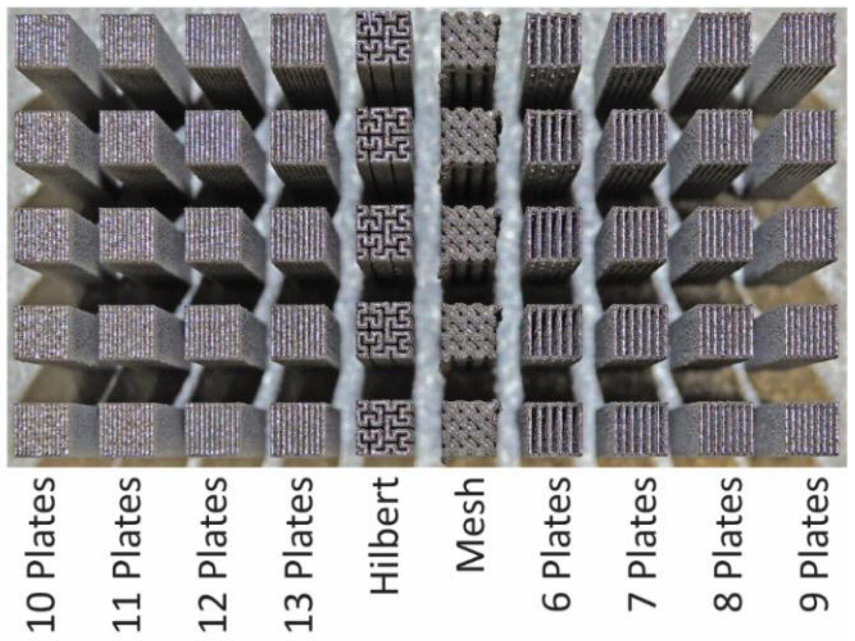
- Solidification conditions dictate grain structure
- Understood through statistics on solid-liquid interface and solidification pathways

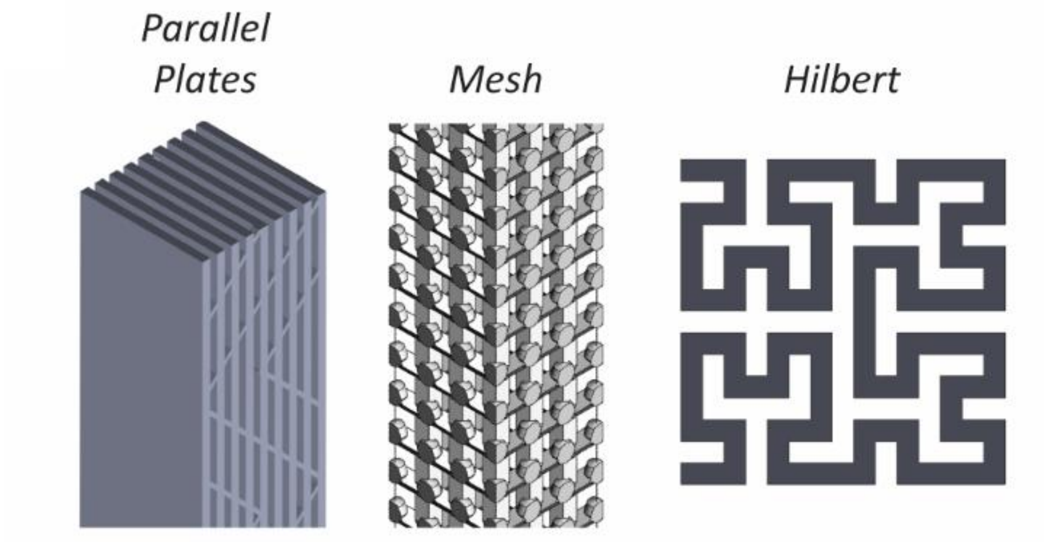


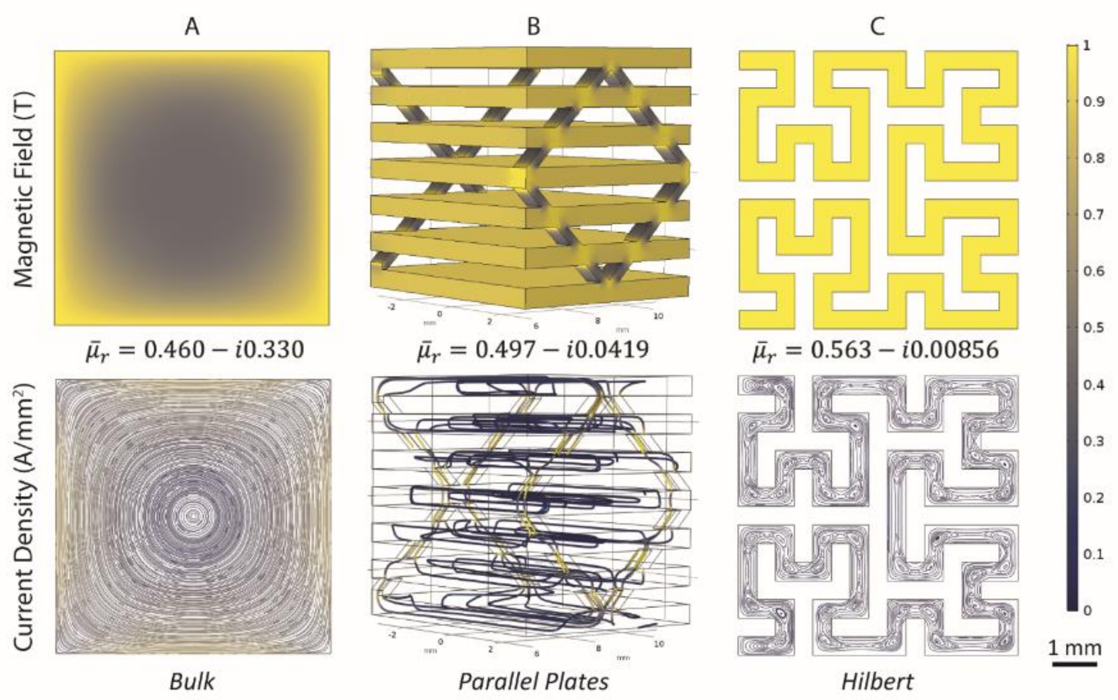


Design of AM Thin Wall Structures

- Not limited to planar laminations
- Unique geometries offer improved performance
- AC simulations of eddy-current development helps refine and down-select designs

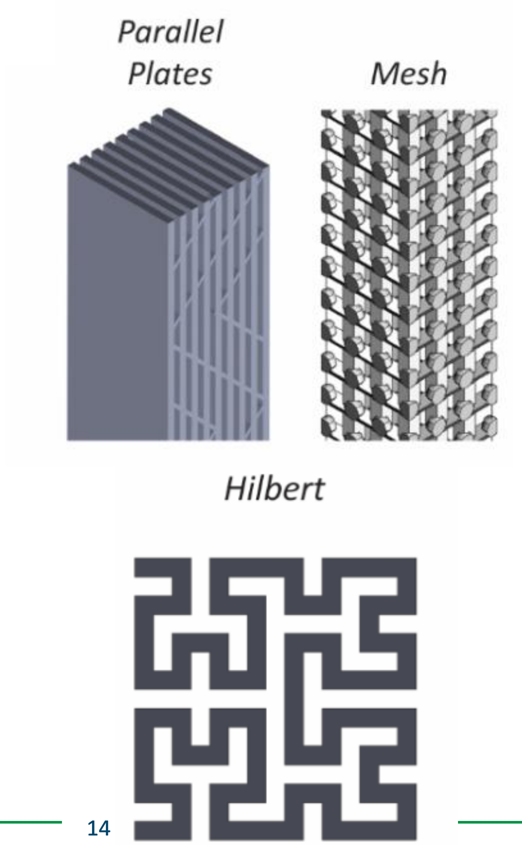


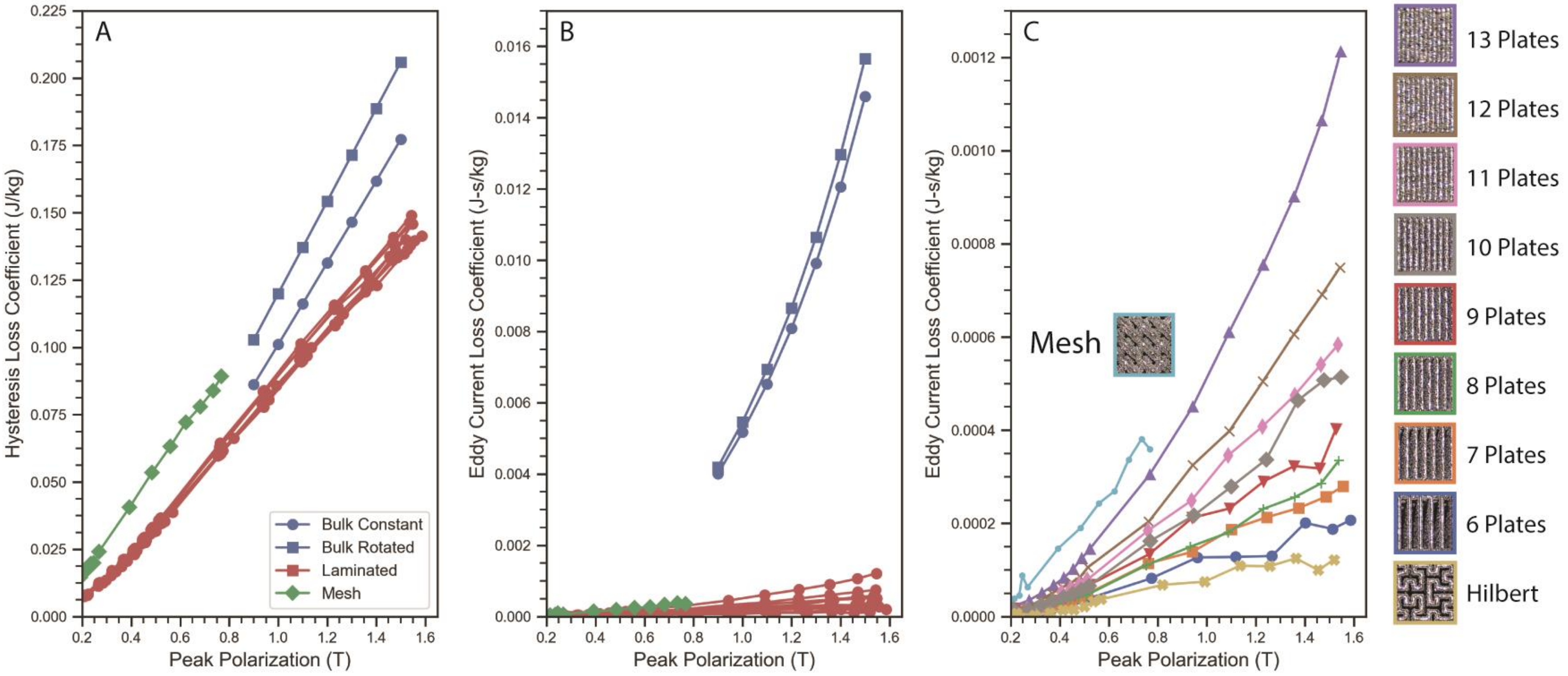




As-Fabricated AC Performance

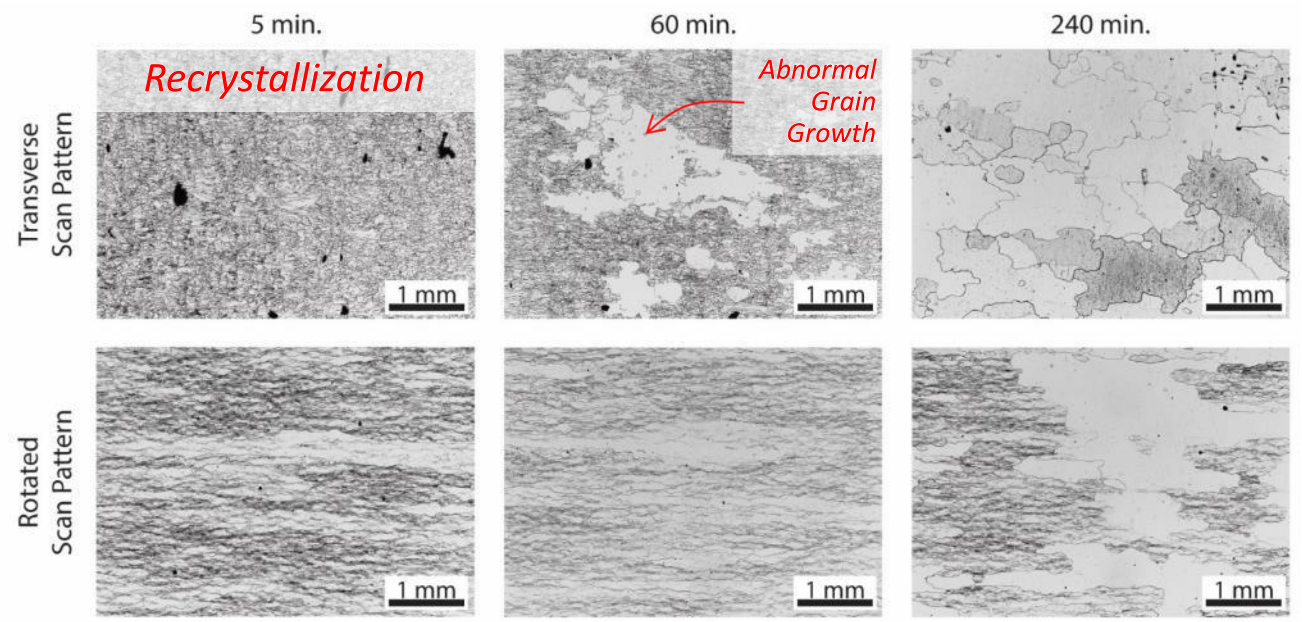
- Decrease in hysteresis losses with oriented thin wall grain structure
- Dramatic decrease in eddy-current losses
- Unique AM cross-section based on Hilbert curve shows best performance

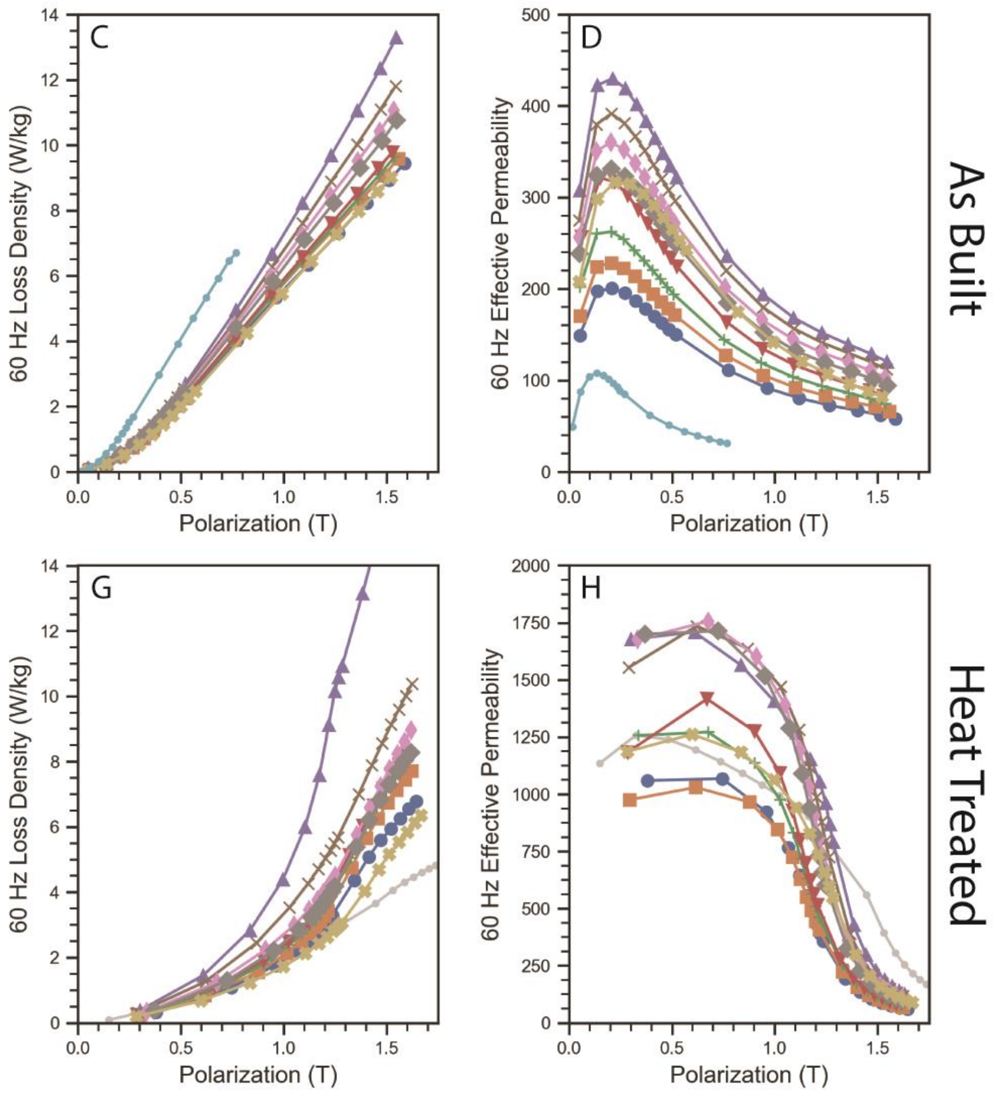




Influence of Heat Treatment

- Recrystallization and grain growth behavior depends on scan pattern
- Increased grain size reduces increases permeability and reduces power losses

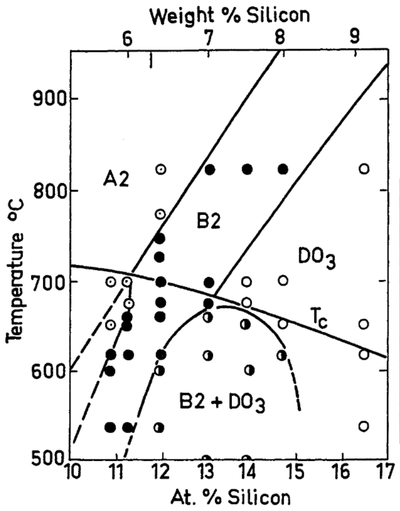




Additive Manufacturing of High-Si Electrical Steel

Materials Science

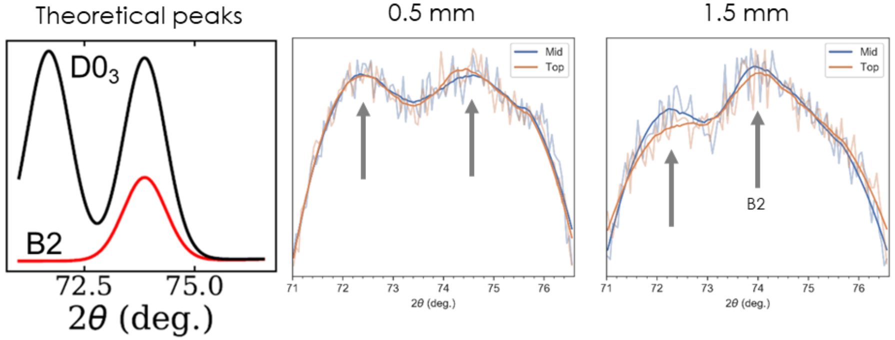
High-Si alloys are brittle due to the formation of ordered B2 and $D0_3$ phases



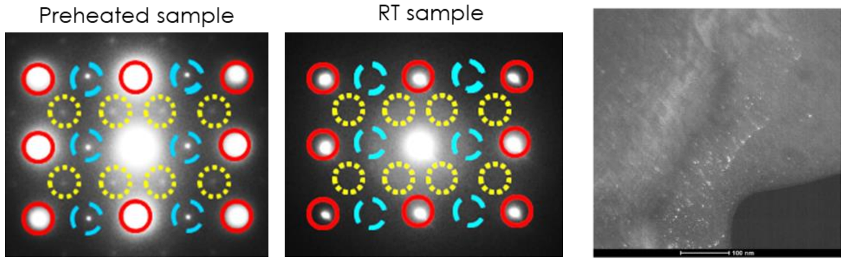
Cracking during rolling of Fe-6.5Si (Kustas, Purdue University, 2016)

Advanced Characterization

Combination of neutron diffraction (HFIR) and TEM to understand process-microstructure linkages



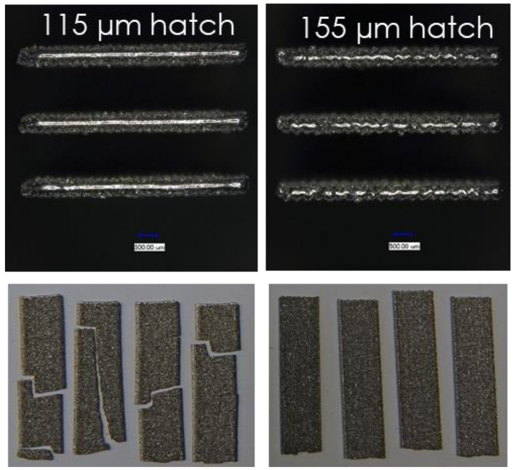
Neutron Diffraction



TEM Diffraction

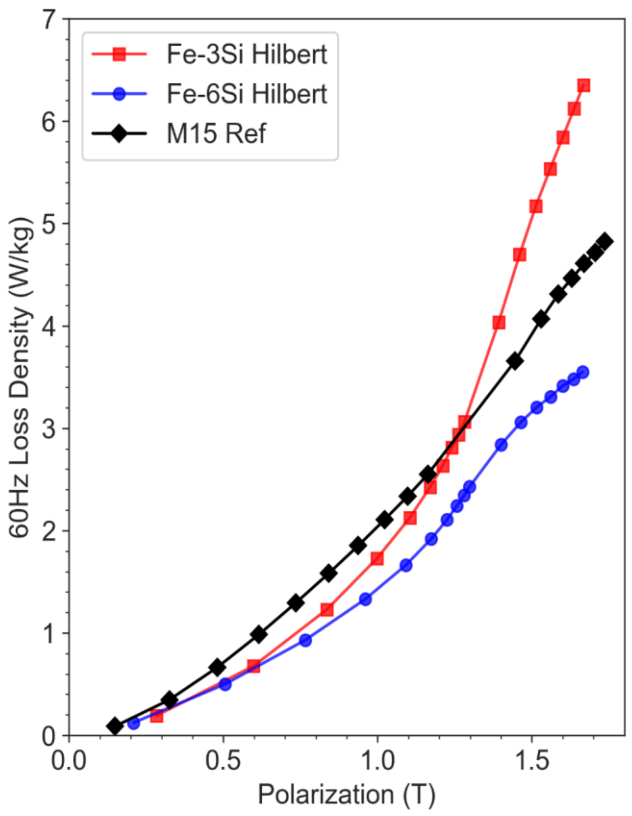
Process Optimization

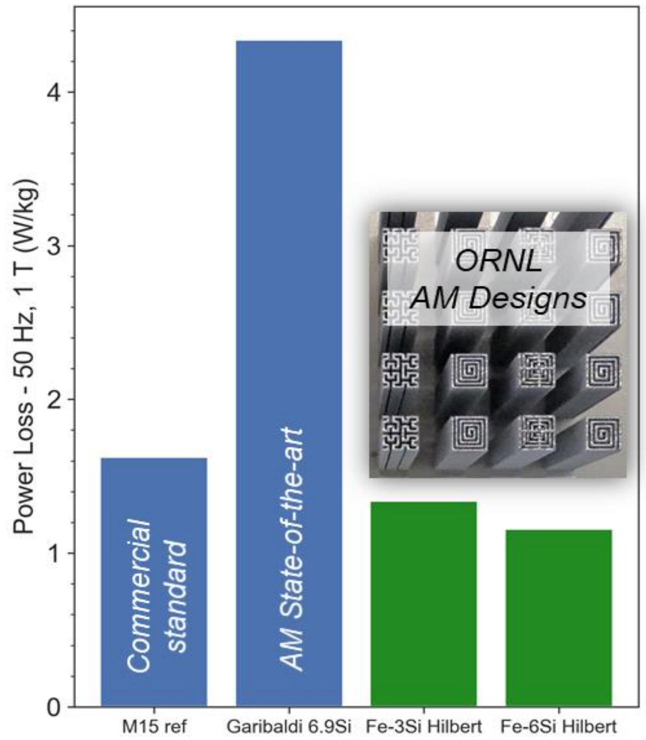
Successful manufacturing of Fe-6Si samples



Test Geometry Performance

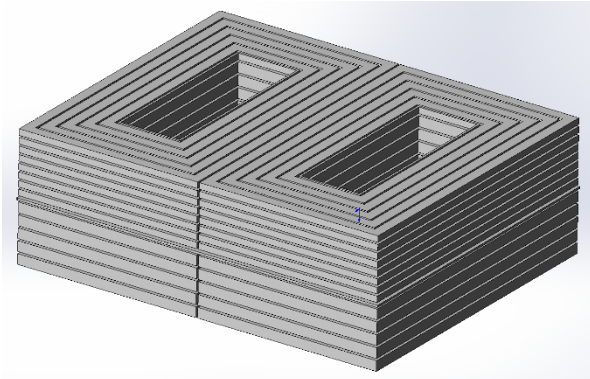
- Increase in Si content shows notable drop in power losses, especially at high polarization
- Additively manufactured Fe-6Si has lower power losses than benchmark non-oriented sheet at 60Hz
- ORNL thin wall designs show better performance than previous AM Fe-6.9Si steel from literature

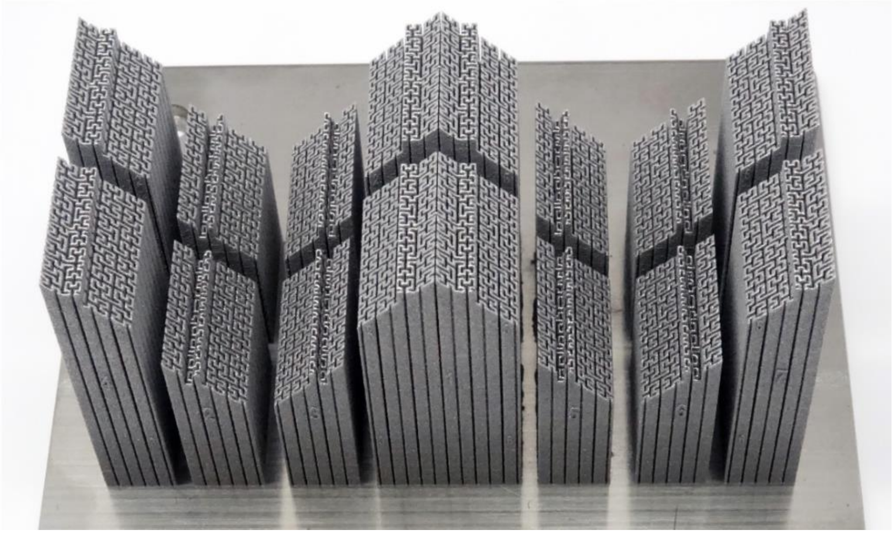




Transformer Core Design and Fabrication

- Produced with both Fe-3Si and Fe-6Si
- AM cross-section design based on a Hilbert space filling curve
- Currently undergoing heat treatment
- To be tested in August





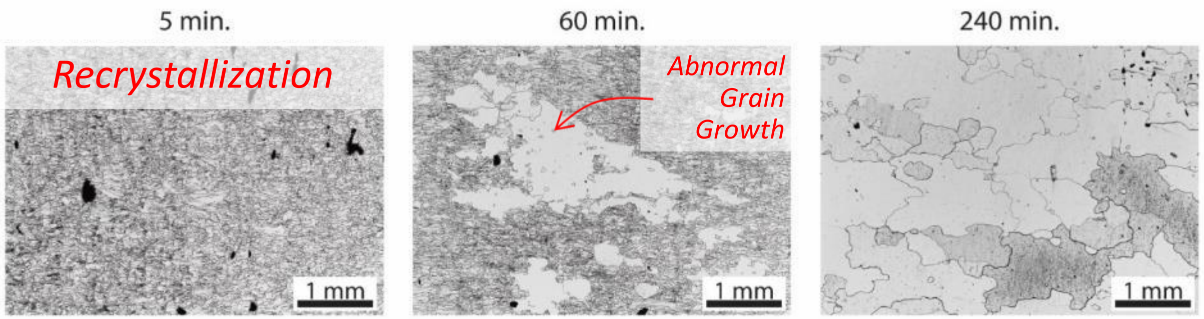
Project schedule, deliverables, and current status

- Total Budget: $1.2M
- Budget Remaining: $255k

- Project Status:
  - Benchtop scale transformer cores manufactured with Fe-3Si and Fe-6Si completed
  - Heat treatments recently completed
  - Final testing scheduled for August
  - Final reporting in September

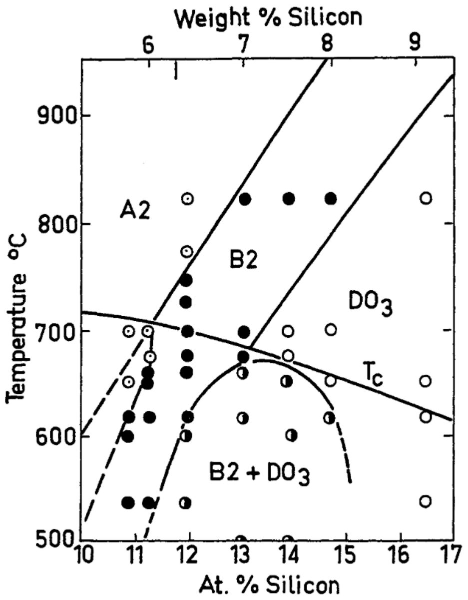
Task	FY18 Q1	FY18 Q2	FY18 Q3	FY18 Q4	FY19 Q1	FY19 Q2	FY19 Q3	FY19 Q4
Task 1: Preliminary feasibility of fabricating controlled grain structured electrical steel materials								
Task 1.1: Modeling of chemistry dependence on solidification behavior	✓							
Task 1.2: Determine optimal chemical composition and source powder		✓						
Task 1.3: Modeling of multiple scan strategies and preliminary fabrication of samples			✓					
Task 1.4: Preliminary material characterization				✓				
Task 2: Scan strategy optimization based on modeling improvements for fabrication of complex geometries								
Task 2.1: Reduced order analytical model for heat flow and thermal gradient direction and magnitude				✓				
Task 2.2: Preliminary feasibility study of in-situ reaction kinetics for creating laminate structures using powder bed AM technology					✓			
Task 2.3: Design of new scan strategies for controlling grain orientation in a cross section mimicking a transformer core						✓		
Task 2.4: Fabricate a transformer core with radially controlled grain structure								90%
Task 2.5: Final reporting								

Next Steps – Open Questions for Future R&D



Combined AM and HT optimization in Fe-Si

- Recrystallization and grain growth kinetics are influenced by scan strategy
- Opportunity for tuning final HT grain texture
- Fundamental materials science challenges requiring advanced processing, modeling, and characterization techniques



High-Si alloy design for AM

- Minor additions of ternary alloying elements can influence order phase formation kinetics
- Alloys must be designed specifically for AM processing
- Complex thermal histories in AM are key to solid-state ordering phenomena

Processing and Alloys for High-Frequency Operation

- State-of-the-art AM systems may enable lamination thickness below 200 µm
- High cooling rates in AM are suitable for nanocrystalline alloys and bulk metallic glasses
- Additional capabilities for geometric flexibility offer unique design opportunities

Broader Impact

- Publications
  - Stump and Plotkowski: "An adaptive integration scheme for heat conduction in additive manufacturing", Appl. Math. Mod., **75**, pp. 787-805, 2019.
  - Plotkowski et al.: " Influence of Scan Pattern and Geometry on the Microstructure and Soft-Magnetic Performance of Additively Manufactured Fe-Si", Additive Man., **29**, pp. 100781, 2019.
  - Sridharan et al.: "Effect of Heat Treatment on Texture Evolution in Additively Manufactured Fe-Si Components", In preparation.
  - Plotkowski et al.: "Atomic Ordering in Additively Manufactured Fe-6Si", In preparation.
  - Plotkowski et al.: "Design and Performance of an Additively Manufactured Fe-6Si Transformer Core", In preparation.
- Presentations
  - Plotkowski et al.: "Laser Powder-Bed Fusion of Fe-Si Soft-Magnetic Materials", 2019 TMS Annual Meeting & Exhibition, San Antonio, TX.
  - Plotkowski et al.: "Laser Powder-Bed Fusion of Fe-Si Soft-Magnetic Materials", Additive and Advanced Manufacturing of Magnetic Materials Workshop **(Invited)**, Albuquerque, NM.
- Open source software copyright claim
  - 3DThesis – Heat conduction process model for additive manufacturing (https://gitlab.com/JamieStumpORNL/3DThesis)
- Provisional Patent
  - Plotkowski et al.: "Additively Manufactured Laminate Structures for Soft-Magnetic Materials", filed 2/11/2019.
- Collaborations
  - Sandia National Laboratory – Ordered phase evolution
- Additional research funding
  - AMO project on system development for electric motor components

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