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

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TRAC Program Review
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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)
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 challenges must first be addressed:
- Approaches for manufacturing brittle high-Si steels
- Understanding and exploiting process-microstructure-property linkages
- New component designs for AM
State of the Art

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

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

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

Garibaldi et al., Mat. Char., 2018
Garibaldi et al., Scripta Mat., 2018

Raghavan et al., Acta Mat., 2017
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

\[
P_{\text{cycle}} = c_{\text{hyst}}(B)f + c_{\text{eddy}}(B)f^2
\]

\[
E_{\text{cycle}} = c_{\text{hyst}}(B) + c_{\text{eddy}}(B)f
\]
Additive Manufacturing

- Renishaw AM250
- Pulsed laser powder bed system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Hatch spacing (µm)</td>
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<tr>
<td>Point spacing (µm)</td>
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<tr>
<td>Exposure time (µs)</td>
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<td>Layer thickness (µm)</td>
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<table>
<thead>
<tr>
<th>Element</th>
<th>Mass Fraction</th>
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<tbody>
<tr>
<td>Fe</td>
<td>3.0 ± 0.3</td>
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<tr>
<td>Si</td>
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<tr>
<td>C</td>
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<tr>
<td>N</td>
<td>0.027</td>
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<tr>
<td>O</td>
<td>&lt;0.10</td>
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<tr>
<td>Other</td>
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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
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

\[ \delta = \sqrt{\frac{2 \rho}{\omega \mu}} = 1.45 \text{ mm} \]
Thin Wall Grain Structure

• Scan pattern orientation has dramatic effect on grain size

• Relate to process conditions?
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

\[
T(t) - T_0 = \frac{2\eta Q}{\rho c (\pi/3)^{3/2}} \int_0^t \frac{1}{\sqrt{\phi_x \phi_y \phi_z}} \exp\left(-\frac{3x(t')^2}{\phi_x} - \frac{3y(t')^2}{\phi_y} - \frac{3z(t')^2}{\phi_z}\right) dt'
\]
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 permeability and reduces power losses.

Recrystallization and Abnormal Grain Growth

As Built

Heat Treated
Additive Manufacturing of High-Si Electrical Steel

Materials Science
High-Si alloys are brittle due to the formation of ordered B2 and D0\textsubscript{3} phases

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

Process Optimization
Successful manufacturing of Fe-6Si samples

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

• Presentations

• Open source software copyright claim
  • 3DThesis – Heat conduction process model for additive manufacturing (https://gitlab.com/JamieStumpORNL/3DThesis)

• Provisional Patent

• Collaborations
  • Sandia National Laboratory – Ordered phase evolution

• Additional research funding
  • AMO project on system development for electric motor components
Contact Information

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