Presentation Submission Information

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- Organization(s): Pacific Northwest National Laboratory (PNNL)

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Manufacturing Near Net Shape High Flux Density Amorphous Magnets

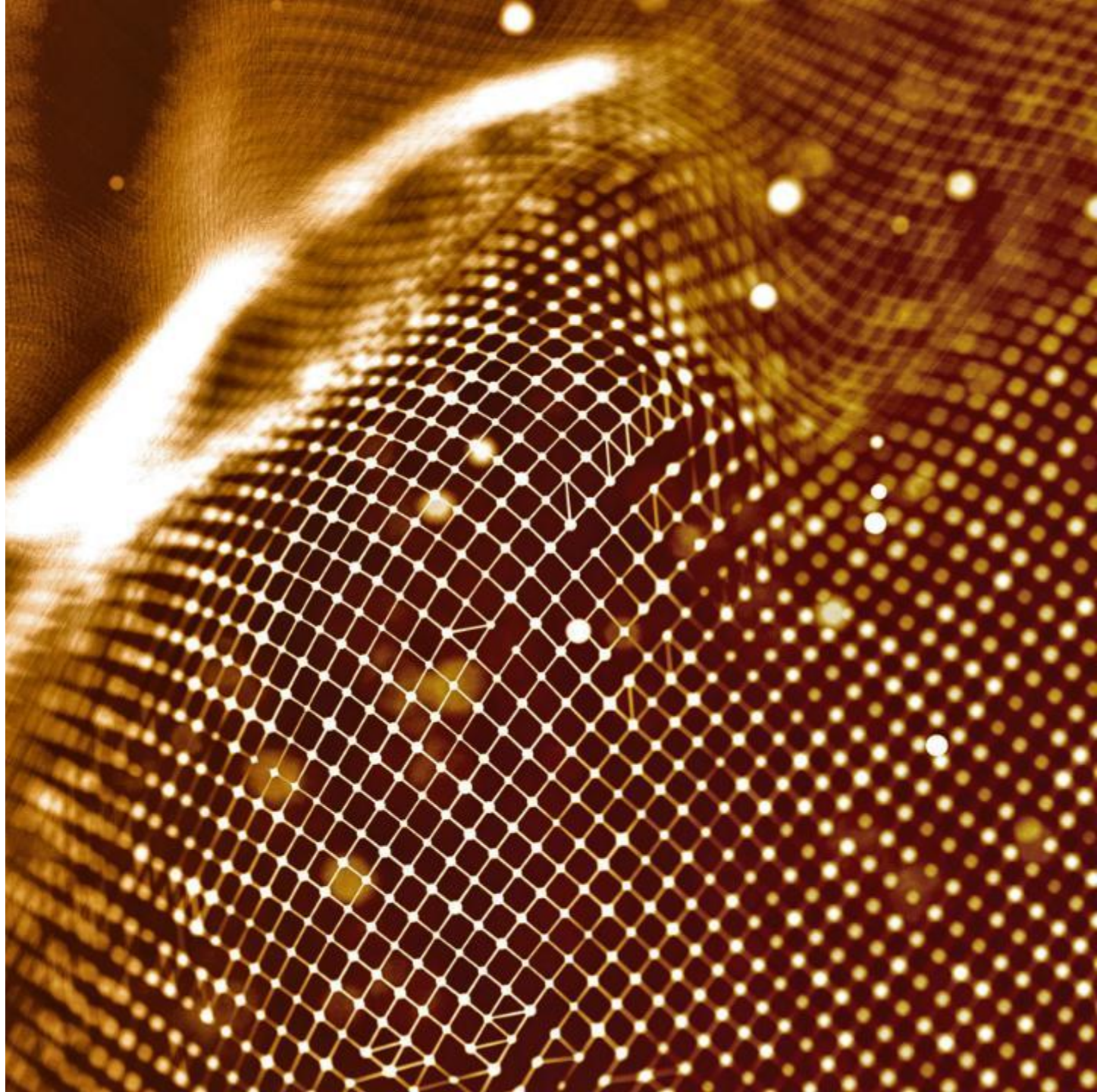
Hrishikesh Das

Pacific Northwest National Laboratory

Partner: University of Pittsburgh

U.S. DEPARTMENT OF ENERGY BATTELLE

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Project Overview

Project Description
Solid Phase in-situ friction stir forging (I-FSF) process: single-step, near-net-shape manufacturing from amorphous powders to cores.

Period of Performance
10/01/2025 to 09/30/2028 (3 years)

Award Amount
$750,000

Prime Awardee
Pacific Northwest National Laboratory

Partner
University of Pittsburgh

Technology Area
Transformer Materials

Alignment/Supports Strategic Pathway:
- Grow the grid by enabling innovation, advancing new technologies, and building capacity for a future-ready electricity system
- Advanced manufacturing process for soft-magnets
- Reduced core-losses
- Lowers manufacturing cost

Current Project Features:
- US-based technology-driven
- Leverages advanced manufacturing for high-performance core materials development

Problem Statement

- Escalating nation-wide power demand drives the need of higher-capacity transformers with reduced core losses

- Advanced manufacturing approaches essential for next-generation magnetic materials such as amorphous steels





Demand growth trends persist across system scales, from large urban grids (>100 MW) to rural distribution networks [1]

Amorphous & Nanocrystalline Soft Magnets: Beyond Current Manufacturing Limits

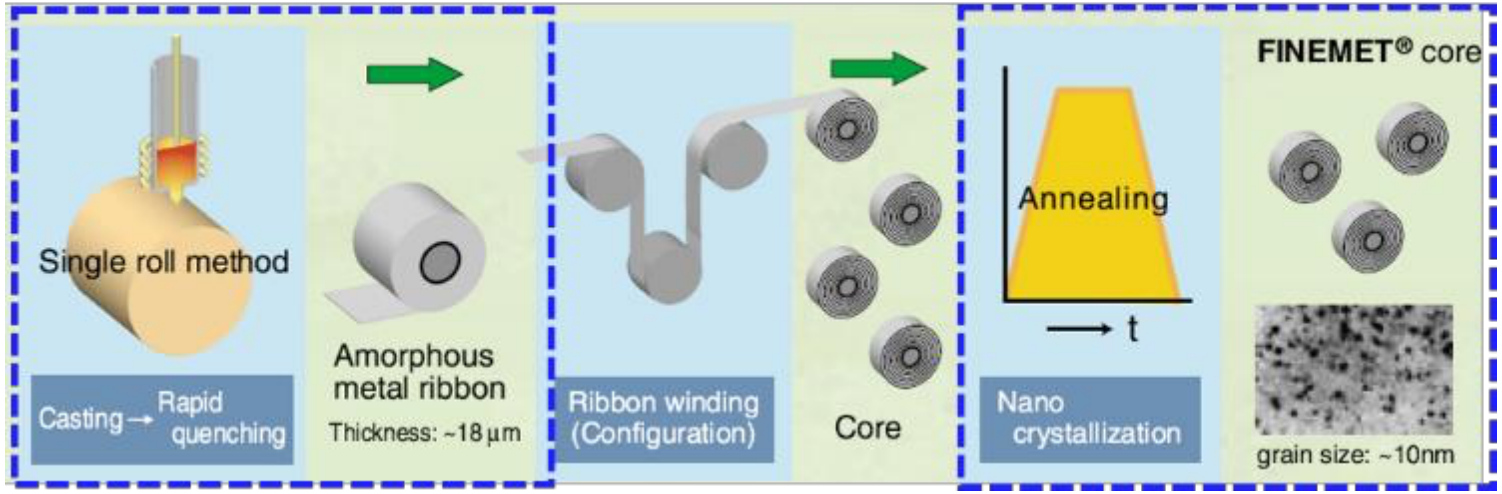
Materials	Composition	Coercivity (A/m)	Saturation Magnetization B_s (T)	Core Loss W (W/kg)
Amorphous/ Nanocrystalline	Finemet ($Fe_{73.5}$-$Si_{13.5}$-Nb_3-B_6-Cu_1)	**0.5-1.4**	1.2	**1.1**
	Metglass (Fe_{78}-Si_9-B_{13})	**3**	1.5	**2-5**
Crystalline (GOES)	Electric Steel (Fe-3.2%Si)	26	2.0	11

Why amorphous or nanocrystalline:
- Low core loss
- Low coercivity

Current state-of-the-art

Manufacturing challenges:
- Multi-step processing: rolling, annealing treatment

Manufacturing defects:
- Gapping, chipping, waviness
- Increased brittleness
- Poor formability



Schematic of manufacturing process for amorphous and nanocrystalline steel magnets [2]

Key Roles of Boron and Silicon Challenges in Manufacturing

Boron
Role: Amorphous Stabilizer

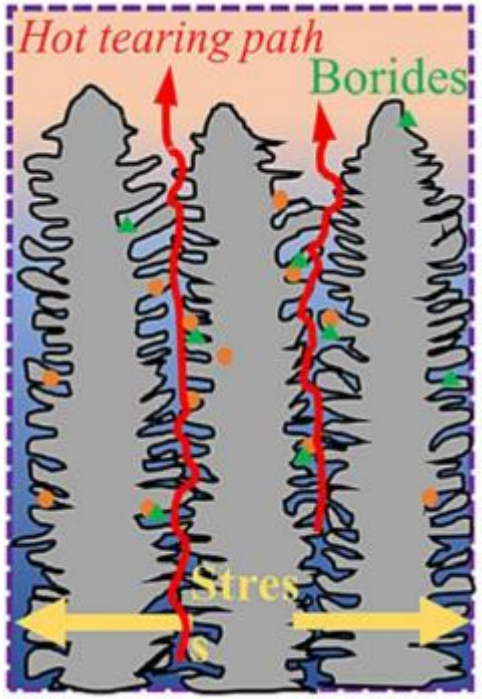
- Glass forming ability
- Thermal stability
- Diffusion barrier

Silicon
Role: Structural Director

- Nano-crystal formation
- Grain refinement

Manufacturing Challenges

- Extreme brittleness
- Highly reactive to oxygen
- Conventional rolling not possible
- Extreme cooling rate required
- Low packing factor
- Extremely brittle borides and dendrites formation

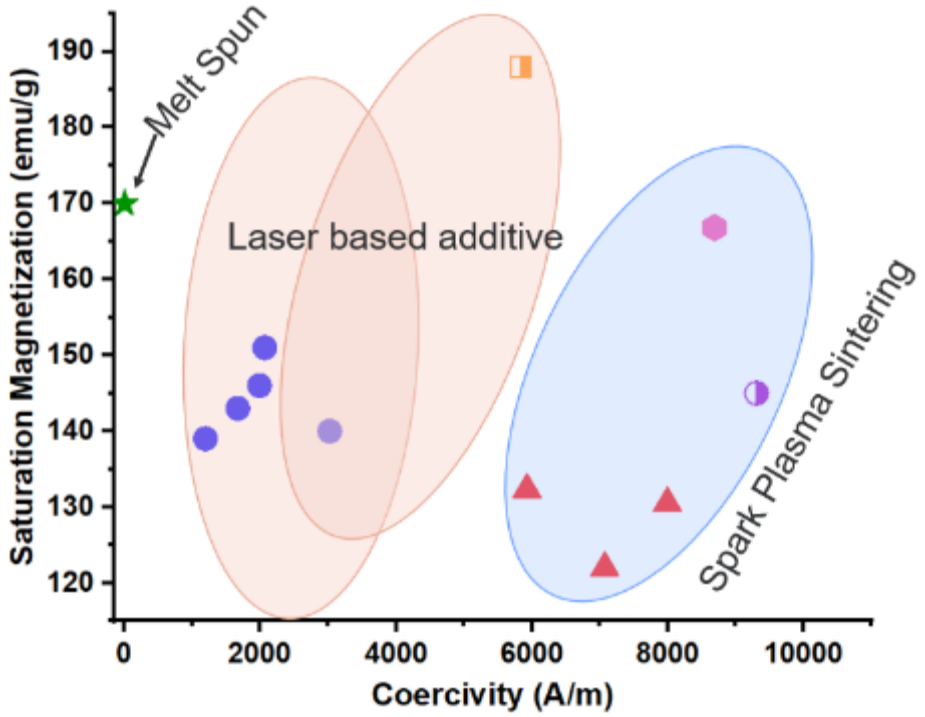


Schematic of dendrites and boride formation leads to hot tearing path



High silicon content in steels leading to sample cracking during processing

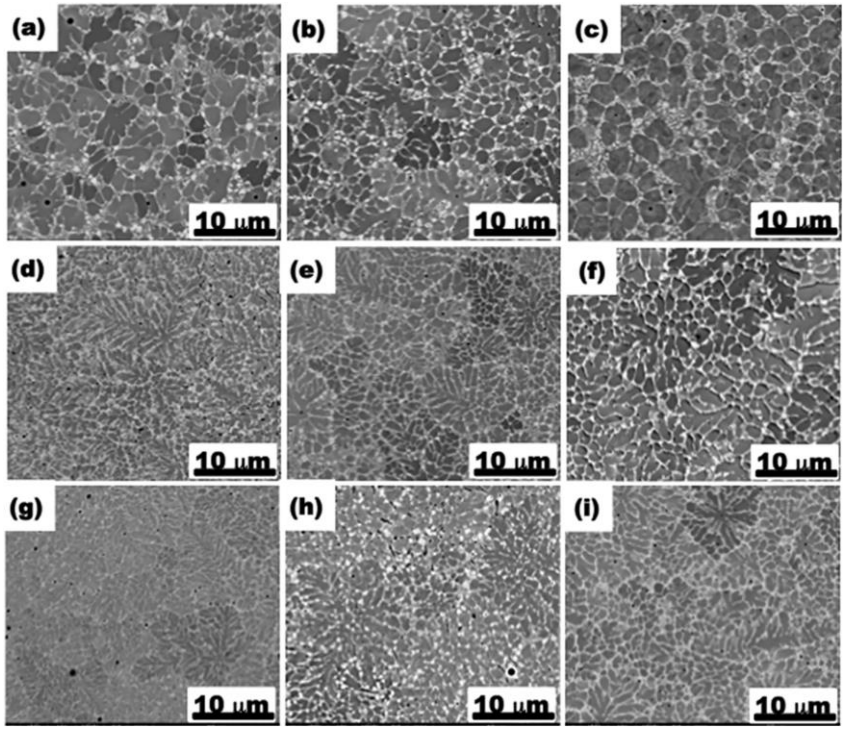
Advanced/Alternative Manufacturing
Melt-based Additive Manufacturing/Sintering



Comparison of coercivity and saturation magnetization between laser-based additive manufacturing [4,5] spark plasma sintering [6] and melt-spun methods.

Melt-based additive manufacturing is challenging

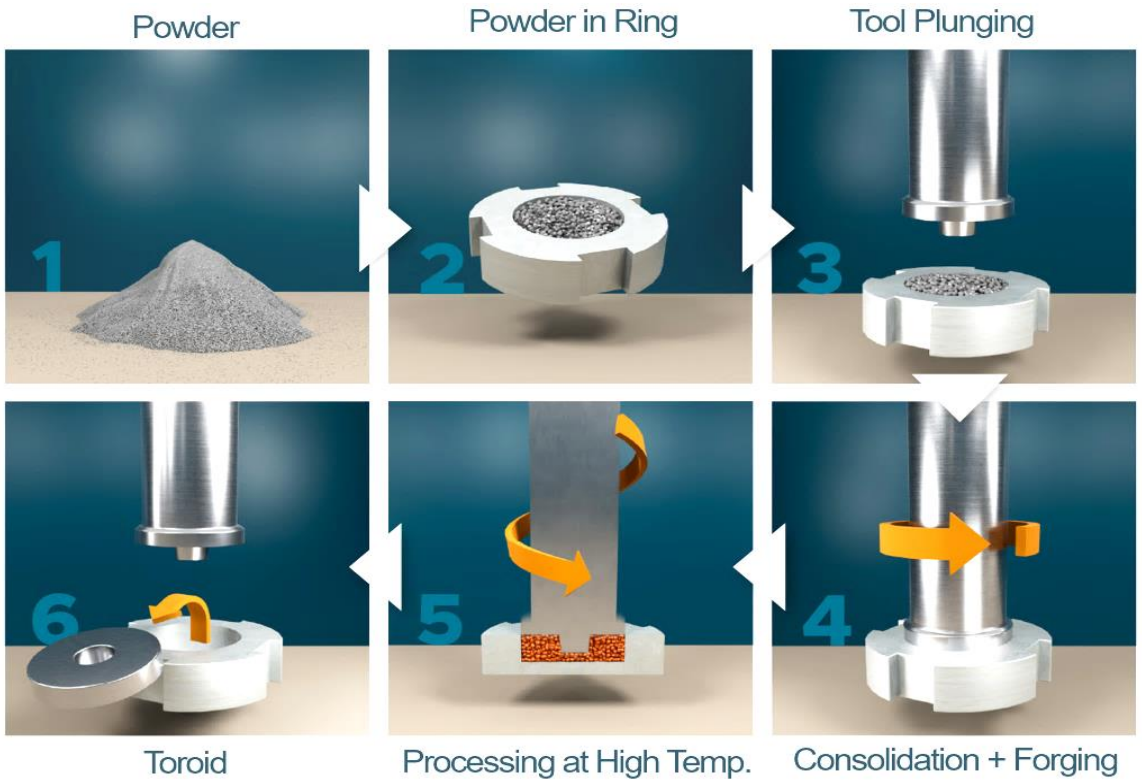
- Melting promotes dendritic cast structure
- Coarse grain size, porosity → detrimental for magnetic performance



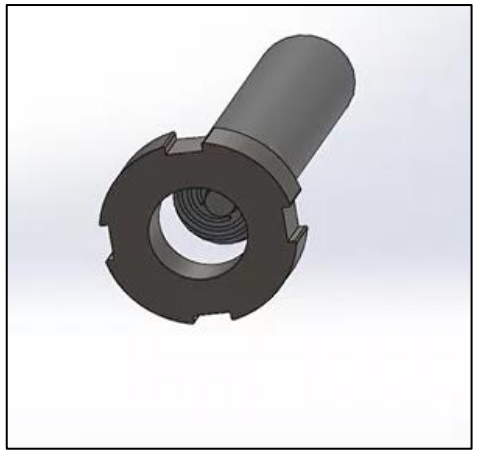
Microstructure image of Finemet alloy processed via laser-based additive manufacturing [4]

Project Objectives

Develop robust I-FSF process for single-step, near-net shape manufacturing from commercial amorphous powders with higher efficiency than current electric steel cores



In situ friction stir forging consolidates feedstock powders into near-net-final-shape parts through intense plastic deformation



I-FSF tool plunge animation

Year 1:
Process development for feedstock consolidation

Year 2:
Near-net final shape fabrication

Year 3:
High-performance amorphous steel core development

Project structure

Pacific Northwest
NATIONAL LABORATORY

Technical Accomplishments

Successful Consolidation of Amorphous Steel Powder using I-FSF process

Type	Powder	Si + B (wt.%)	Cu (wt.%)	Nb (wt.%)	Fe (wt.%)
Amorphous	Fe-Si-B	20-25	-	-	Bal.
Nanocrystalline	Fe-Si-Nb-B-Cu	20-25	0.5-1.5	2-4	Bal.

Feedstock powder



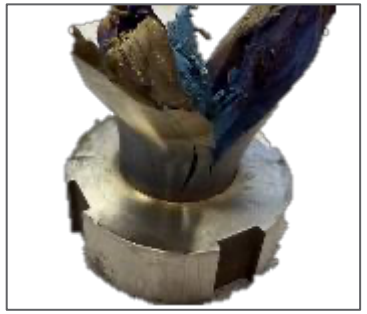
I-FSF



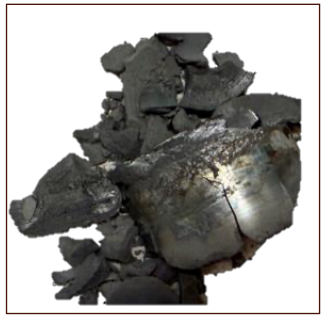


Images showing successful consolidation of amorphous steel powders into laminates via I-FSF

Observed challenges



Tool failure (due to force/torque spikes)

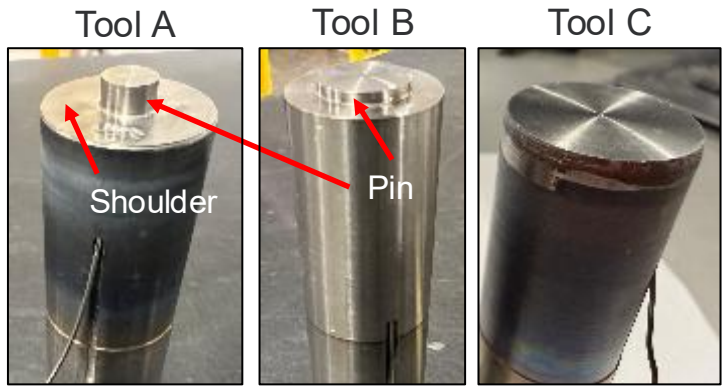


Unsuccessful consolidation (poor material flow due to high Si and B content)

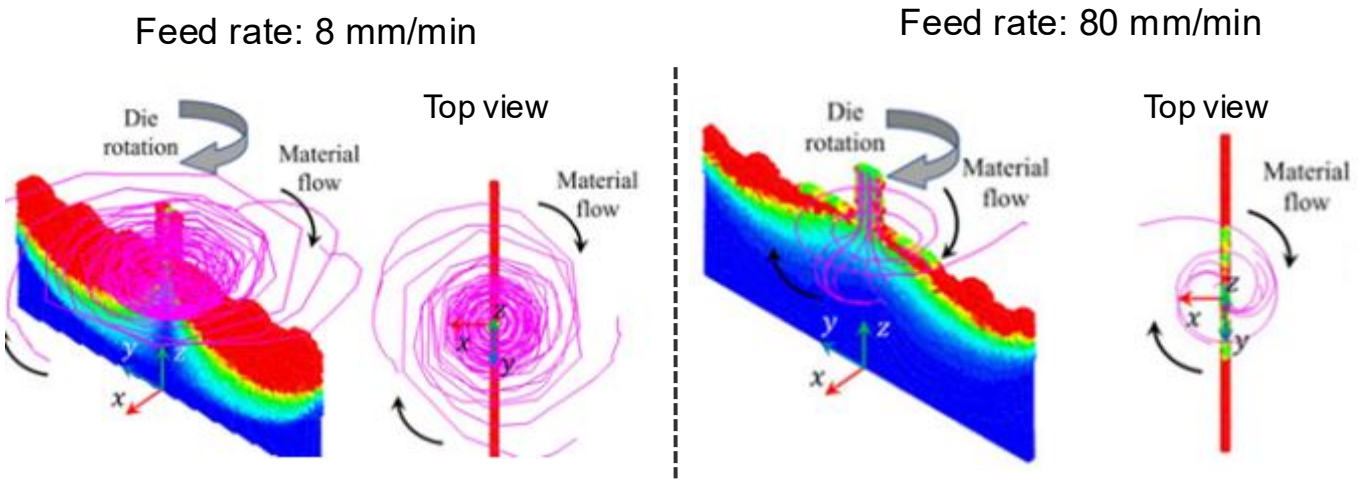
Initial I-FSF runs successfully consolidated amorphous and nanocrystalline powder feedstock into near-net-shape parts in a single step

I-FSF process parameter windows identified for successful feedstock consolidation

I-FSF Tool Design and Material Flow Hypothesis



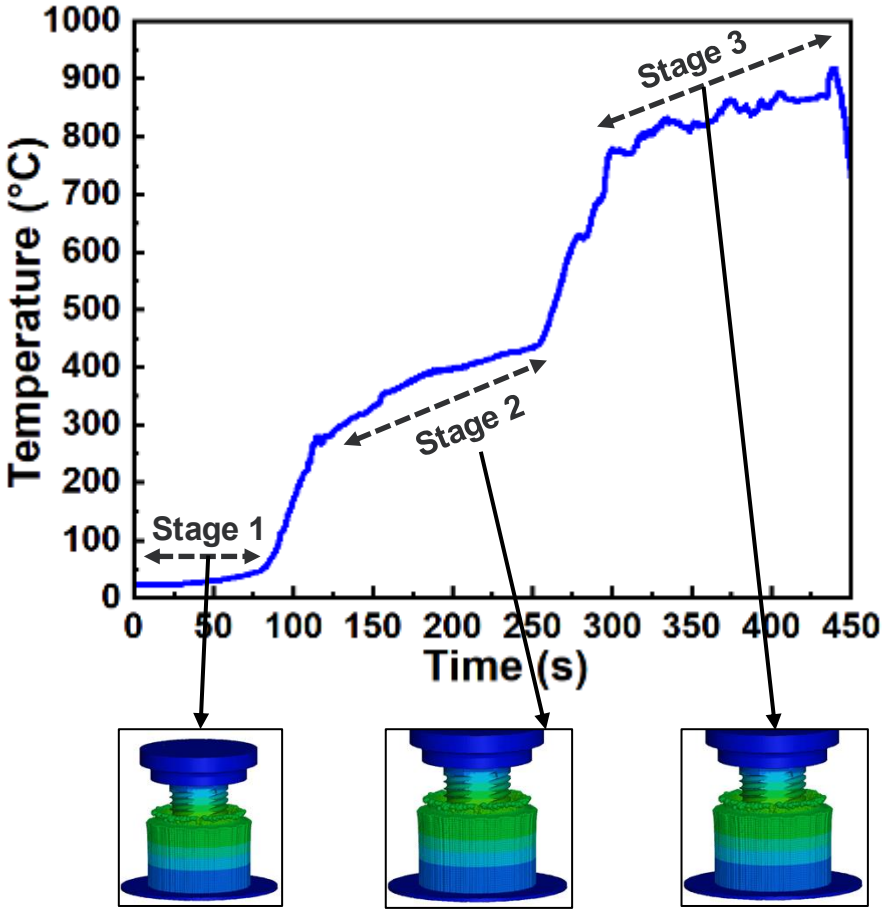
Tool ID	Shoulder Diameter (mm)	Pin	
		Diameter (mm)	Length (mm)
A	25	8	4
B	25	12	2
C	25	N/A	N/A



Increased feed rates (tool translational speed) substantially alter material flow (pink lines) and plastic deformation behavior [7]

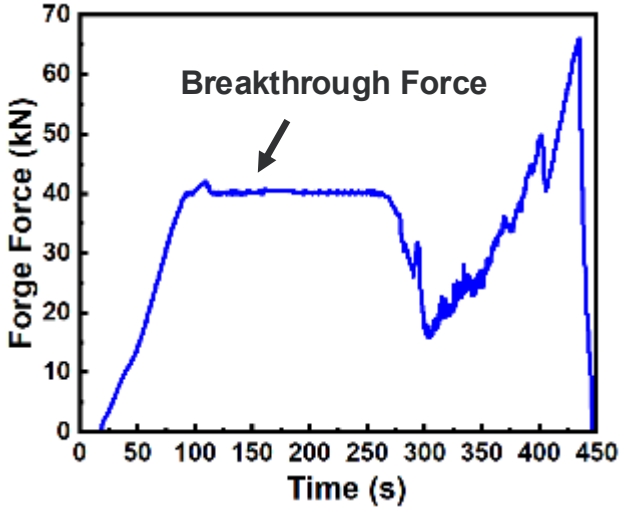
- Violent, complex material flow around the shoulder and pin regions
- Flow highly sensitive to feedstock materials flow-stress characteristics
- Tool rotational and translational speed combinations dictate general material flow and corresponding process outputs (forge force, torque, temperature) for successful feedstock consolidation
- Strain gradient across compacted feedstock controlled by generated frictional heat

I-FSF Process Mechanism
Tool A | Nanocrystalline Powder Feedstock

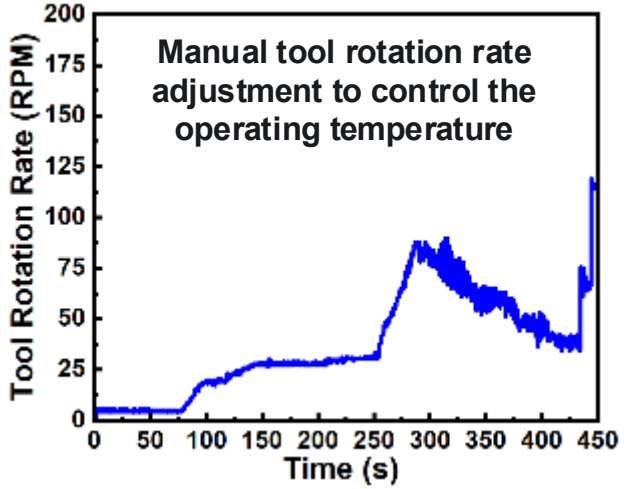


*animation from [8]

Three-different stages of I-FSF process with tool animations showing temperature variation



Forge force as a function of time during I-FSF



Tool rotation rate as a function of time during I-FSF

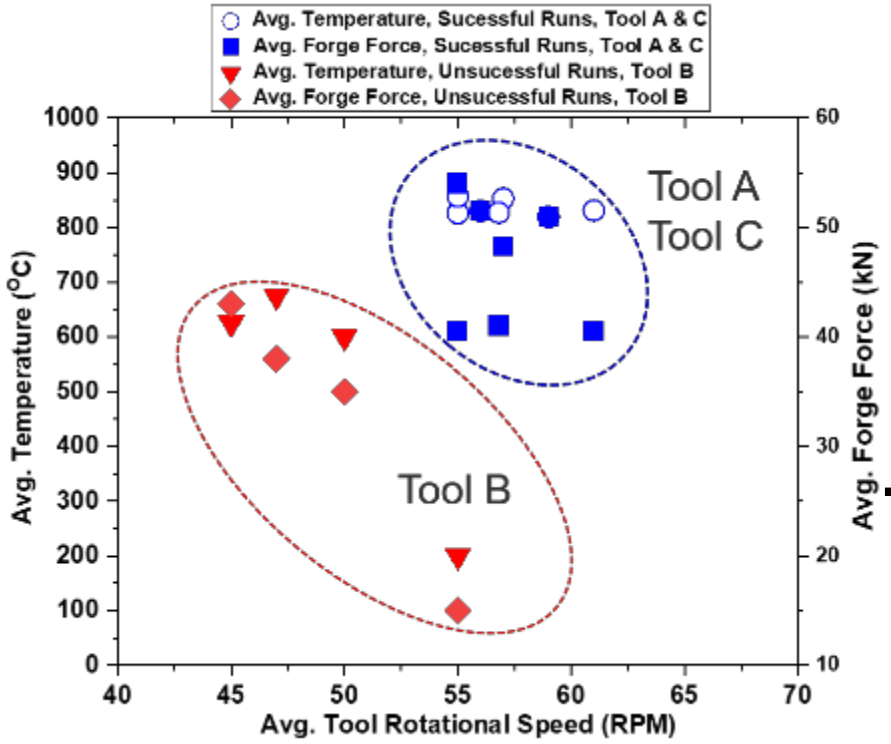
Stage 1: Initial plunging with high stress at low temperature
Stage 2: Intermediate heating with a signature breakthrough
Stage 3: Shoulder-driven heating and consolidation

High forge force and relatively steady temperature critical for effective consolidation of amorphous steel powders through simultaneous plastic deformation and metallurgical bonding

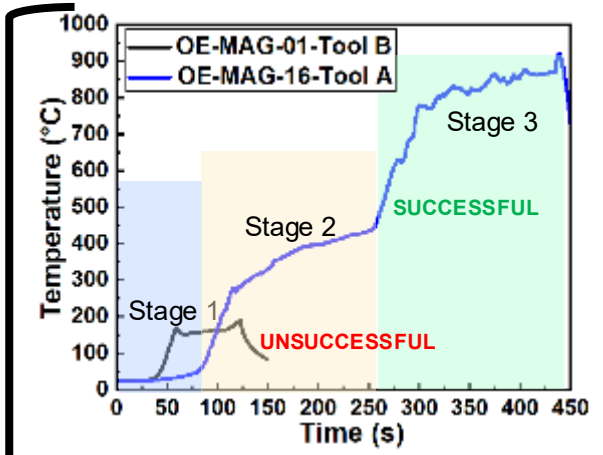
I-FSF Process Parameter Window Isolation

Initial trials established process window for successful consolidation

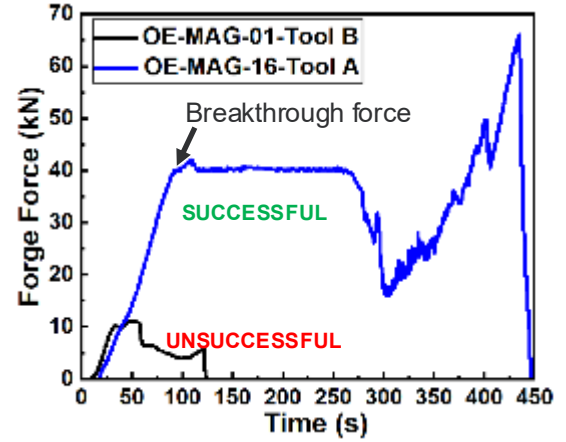
- Tool feed rate: 1 - 4 mm/min
- Tool rotational speed: 50-75 rotation per min
- Forge force: 40 – 60 kN



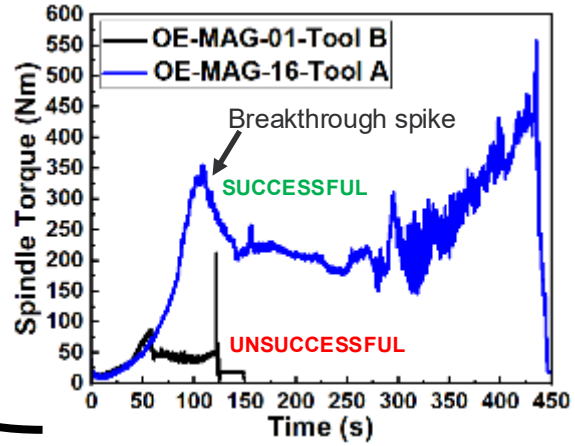
Process parameter window for Tool A, B and C resulting in successful and unsuccessful consolidations



Temperature vs. time plot for Tool A and B



Forge force vs. time plot for Tool A and B

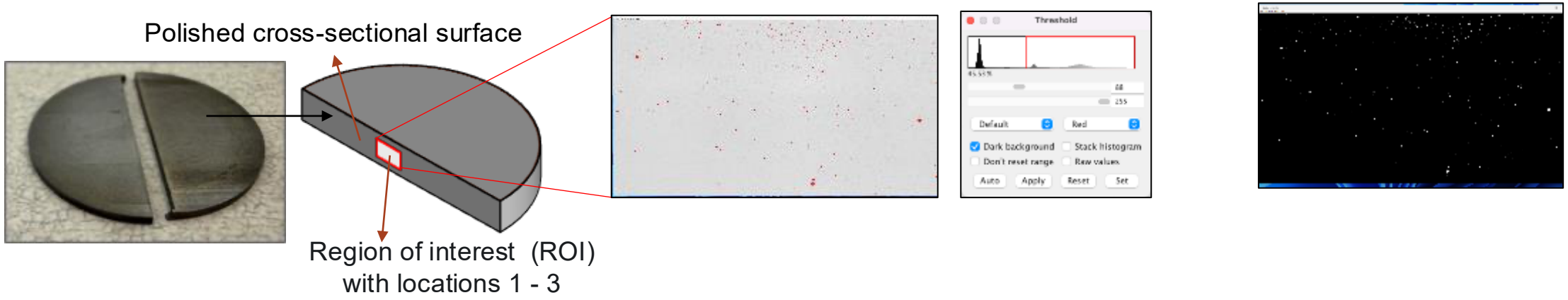


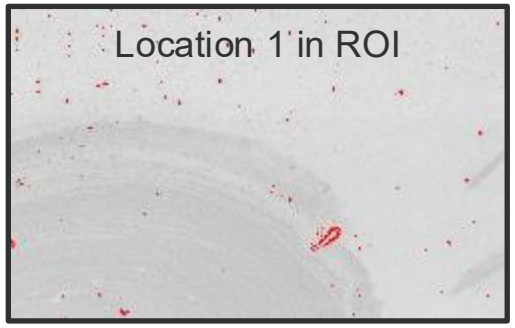
Spindle torque vs. time plot for Tool A and B

- Tool B's larger pin (12 mm vs. 8 mm in Tool A) facilities more powder displacement but does not impart sufficient plastic deformation, causing delayed breakthrough and instability: unsuccessful consolidation.

I-FSF achieving successful consolidation of amorphous steels with <1% porosity

Consolidated amorphous steel laminate sectioned and polished → **Region of interest (ROI) identified on the polished surface** → **Images of ROI captured via optical microscopy** → **Images of ROI imported into ImageJ software** → **Porosity identified through image pixel color differences by software**

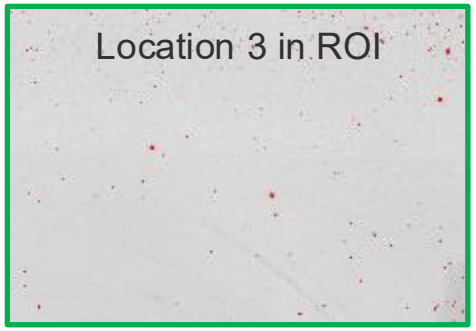




Porosity Fraction: 0.30%



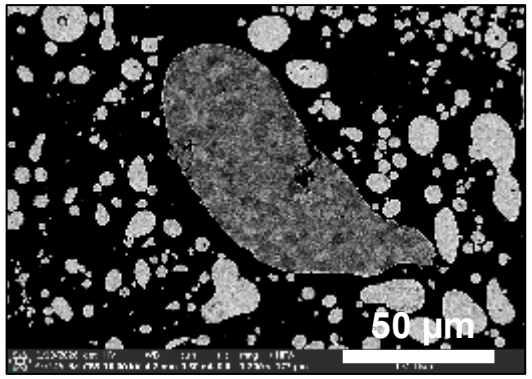
Porosity Fraction : 0.75%

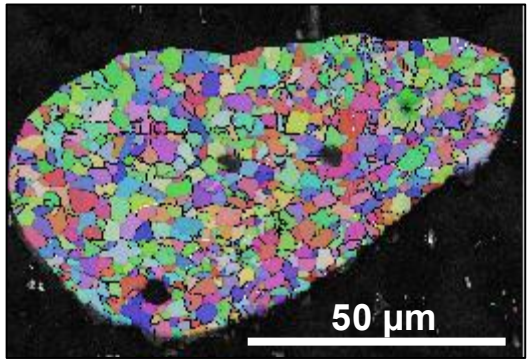


Porosity Fraction : 0.60%

Comparative Analysis: Feedstock vs. I-FSF Nanocrystalline Material Characterization

Feedstock powder
Mesh size: 44 ± 9 µm

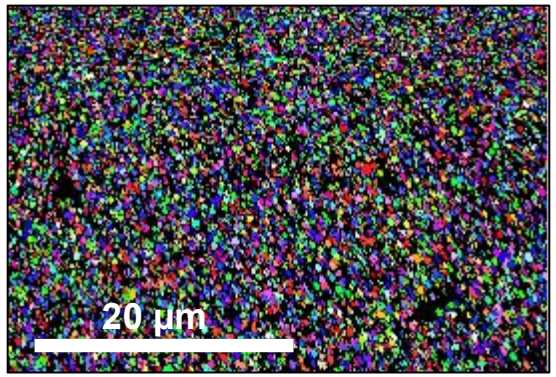


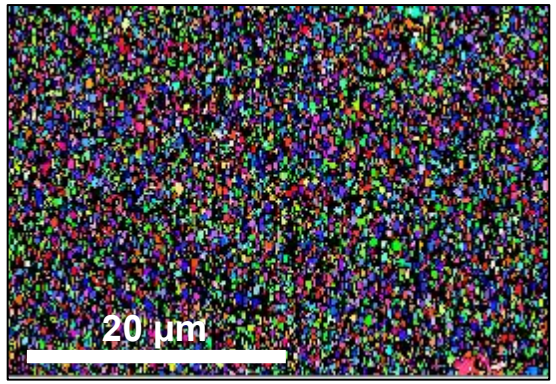


Avg. grain size: 2.3 ± 1.0 µm

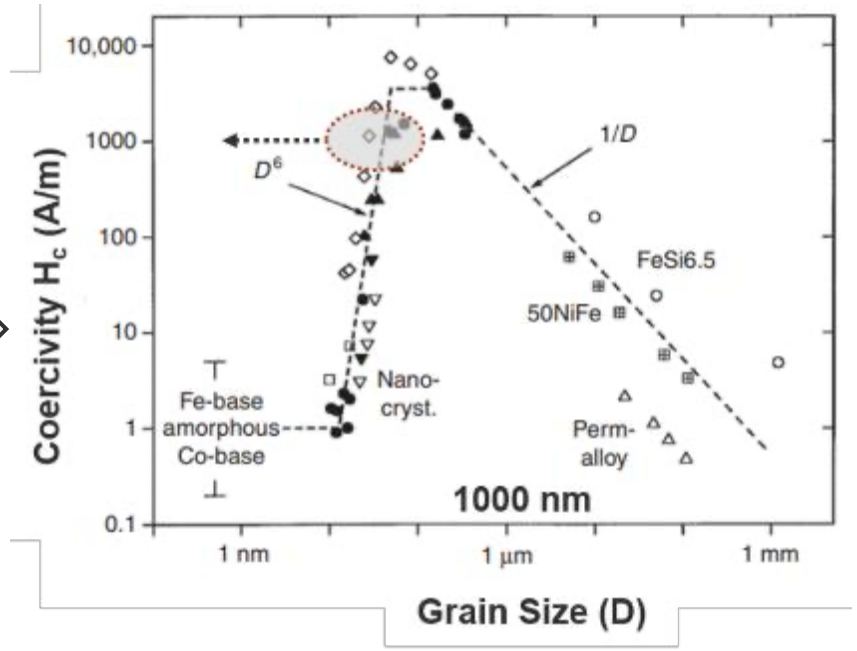
I-FSF

Avg. grain size: 354 ± 108 nm





Avg. grain size: 450 nm ± 90 nm



Grain size correlation in microstructure of magnets with soft magnet coercivity [10]

- I-FSF processed material grain size ranges from ~250 to 500 nm
- Further process development required to reduce the grain size to <100 nm

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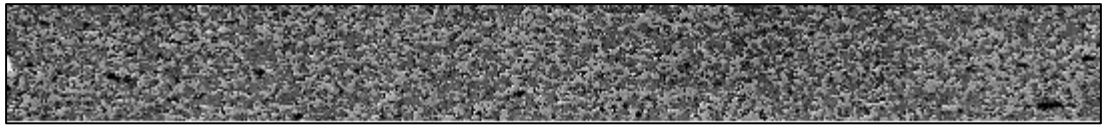
Conclusion | Impact | Next Steps

Conclusions and Impact



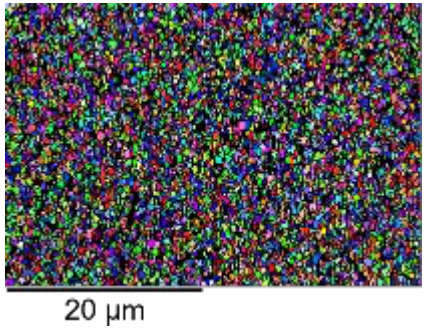
I-FSF consolidate

- Initial trials demonstrate successful single-step I-FSF consolidation from powder feedstock to laminates with <5% porosity.



SEM-montage of amorphous steel I-FSF consolidate

- Three I-FSF tool designs evaluated
  - Initial process window established for successful feedstock consolidation for two tool designs
    - Tool traverse speed 1 mm/min
    - Processing temperature 825-875 °C
    - Forge force ~40-60 kN



Grain size of amorphous steel consolidates after I-FSF

- Grain size consistently ~250-500 nm, for nanocrystalline-powders.

Invention Disclosure:
In-Situ Friction Stir Forging of Amorphous and Nanocrystalline soft magnet (iEdison No. 0685901-25-0378)

Future Directions

- Process parameters development for consolidation of amorphous/nanocrystalline feedstock into toroidal near net final shape
- Magnetic properties characterization of toroidal magnetic core materials
- Microscale and nanoscale microstructure characterization of magnet cores samples using scanning electron microscopy (SEM) and transmission electron microscopy (TEM)

I-FSF



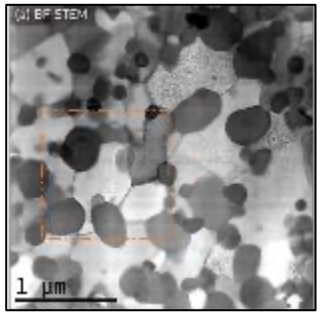
Toroid



Magnetic Property



Microstructural analysis



Acknowledgements

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Sponsor: Office of Electricity Transformer Resilience and Components Program
Leadership: Jordan Moree, Andre Perriera, David Howard



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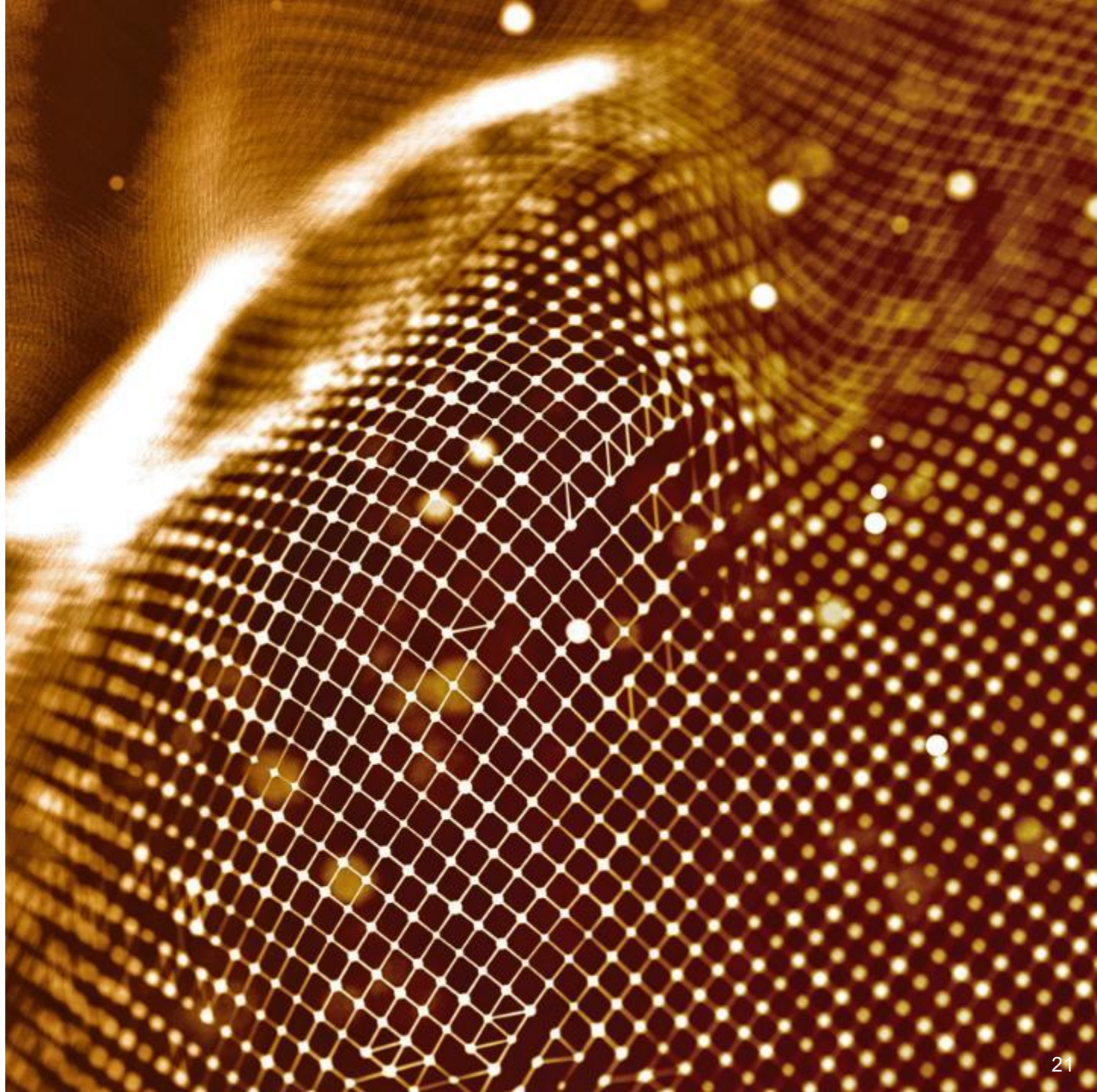
Paul Ohodnicki
University of Pittsburgh

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Thank you



Milestones
All The Milestones Were Accomplished On Time

Quarterly milestone

Due Date	Milestone (or Decision Point)	Verification Method (or Decision Criteria)	Status
12/31/2025	Friction stir forging tool design, amorphous steel composition selection	I-FSF tool design will be completed, and the tool drawings will be provided. Amorphous alloy compositions that will be used for magnet laminate development will be finalized based upon the discussion with project partner	Accomplished
03/31/2025	Procurement of tools and materials	Tools from external vendors, and amorphous steel powders from project partners and external suppliers will be procured.	Accomplished
06/30/2025	Preliminary material consolidation parameters identified	Process parameters needed for consolidation of amorphous steel feedstock using developed I-FSF tools (temperatures and pressures) are determined.	Accomplished
09/30/2025	Laminate properties determined	Electrical, mechanical, and magnetic properties of the amorphous steel laminates will be determined as possible and used to down select amorphous steel formulations for use in subsequent tasks.	On-track

Go/No-Go Decisions

Due Date	Milestone (or Decision Point)	Verification Method (or Decision Criteria)	Status
Sept 2025	Successful consolidation of amorphous materials feedstock using developed and selected tool design and process parameter	Successful demonstration of amorphous steel powder consolidation using I-FSF process by achieving < 5% porosity for the consolidated sample, confirmed using optical microscopy (OM) and scanning electron microscopy (SEM).	On-track