1467-1561 Amorphous and Nanocomposite Magnets for High Efficiency, High Speed Motor Designs

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Carnegie Mellon University/NETL/North Carolina State University

03/01/2017-03/31/2020

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Washington, D.C.
June 11-12, 2019

Overview

Project Title: Amorphous and Nanocomposite Magnets for High Efficiency, High Speed Motor Designs

Timeline:

Project Start Date: 04/01/2017

Budget Period End Date: 06/30/2019 (with NCE)

Project End Date: 03/31/2020

Barriers and Challenges:

Develop RE-free motors to address:
(a) metal alloy processing & core production;
(b) soft magnet & core post- processing;
(c) demo an efficient 2.5 kW motor.
(d) Transfer MANC casting technology to domestic production of high power density motor materials.

AMO MYPP Connection:

- AMO MYPP Mission: Transition DOE supported innovative technologies and practices into U.S. manufacturing capabilities.

Project Budget and Costs:

Budget	DOE Share	Cost Share	Total	Cost Share %
Overall Budget	$2,399,591	$774,471	$3,174,062	24.4%
Approved Budget (BP-1&2)	$778,016	$251,106	$1,029,122	24.4%
Costs as of 3/31/19	$284,688	$91,883	$376,571	24.4%

Project Team and Roles:

CMU (Alloys Development, Motor Design)

Team members and their role:

NETL (Ribbon and core post-processing)
NCSU (Motor controls & testing).
Fort Wayne Metals (Transition of Casting)
Carpenter (Evaluation of Stamping)

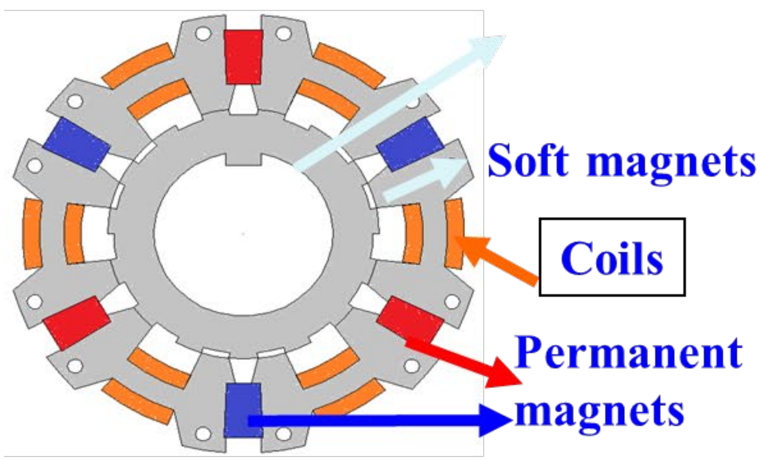
Project Objectives

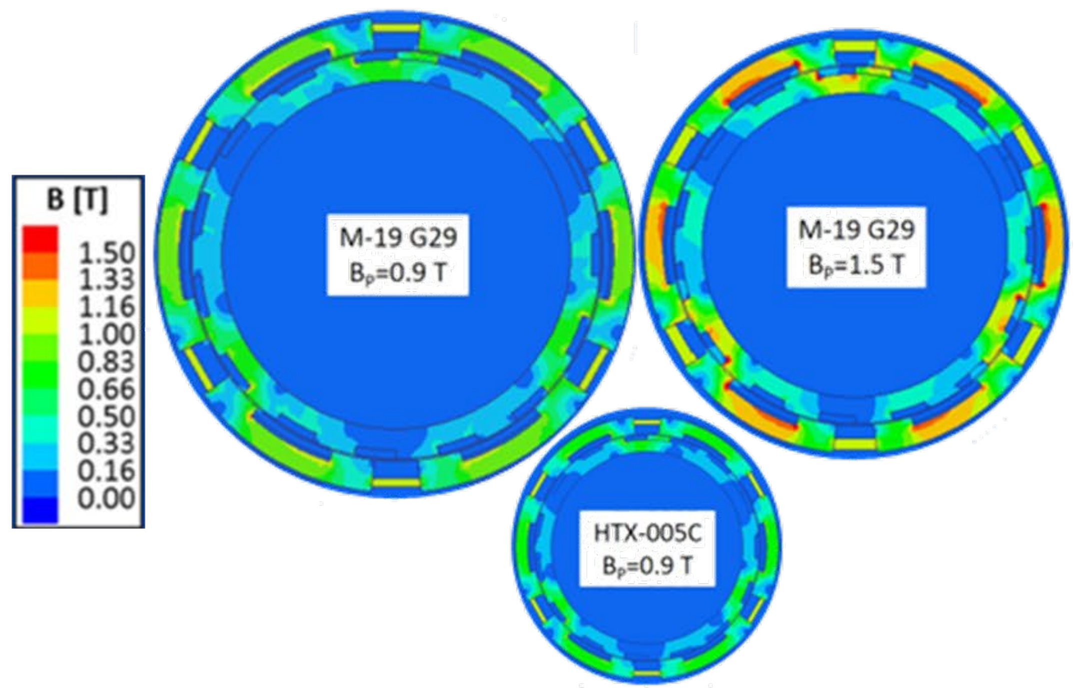
- CMU team will develop metal amorphous nanocomposites (**MANCs)** for a rare earth (RE)-free, 2.5 kW motor with 4% efficiency increase portioned between a) controller; b) Cu-; c) Fe-; & d) windage-losses. We address supply chain steps:
  - (a) metal to alloy processing & magnet core production;
  - (b) soft magnetic laminate & core post- processing; and
  - (c) demo a 2.5 kW motor showcasing superior efficiency of MANCs.
  - (d) Transfer **MANC** casting technology to domestic producers.
- Si-steels do not have resistivity and thickness required for low losses at magnetic switching frequencies > 1 kHz.
- New technology requires new topologies, processes & properties to leverage MANCs in motors.

Technical Innovation – MANC SMMs

- Current practice uses Si-steels that are limited by losses to f < 1 kHz. MANC technology adoption is hindered by: (a) limited US manufacturing; (b) materials limits for high f switching and (c) mechanical property constraints for certain motor applications;

- **Prior simulation:** P = Torque x speed. **Outrunner motor**





- **PPMT technology**
- **M-19 = Si-steel grade**
- **HTX-005 = MANC yields 70% size reduction**

Technical Metrics Enabling Applications: Power Losses.

$$P_{tot} = P_h + P_e + P_a$$

Hysteresis Losses

$$P_h = a f B^2$$

Random crystal anisotropy

(MANC H_c < 40 A/m)

Eddy Current Losses

$$P_e = b f^2 B^2$$

$$b = \frac{(\pi \cdot t)^2}{6 \cdot \rho}$$

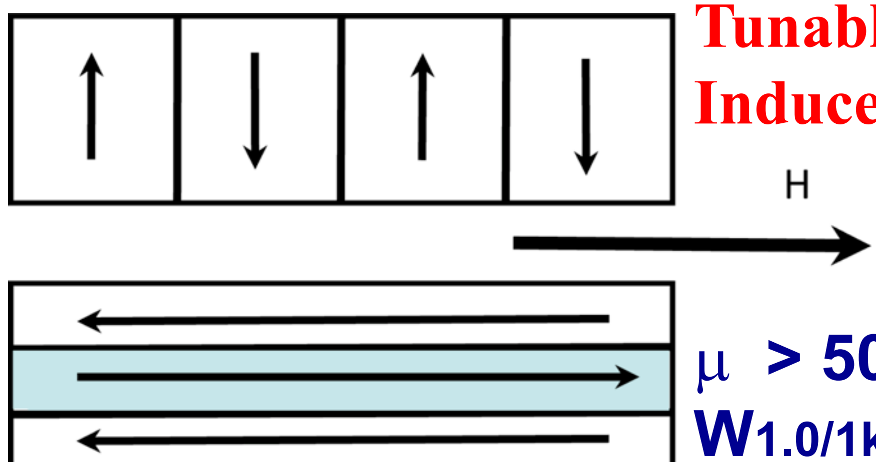
Resistivity, Thickness

ρ > 100 μΩ-cm

t < 25 μm

Anomalous Losses

$$P_a = e(f \cdot B)^{1.5}$$



Tunable (graded) Induced Anisotropy

μ > 5000,

$W_{1.0/1kHz}$ < 10 W/kg

DEPARTMENT OF
MATERIALS SCIENCE AND ENGINEERING

Technical Approach

- Technical Approach:
  - *Identify prototype FEA motor design for MANCs (CMU/NETL);*
  - *Solidification (RSP) & post-processing to tune permeability (CMU);*
  - *Post processing into rotor/stator components (CMU, NETL);*
  - *Winding techniques for use in new topologies (NETL),*
  - *Incorporate state of the art motor controllers (NCSU).*
  - *Measure loss partitioning between controller, Cu, Fe, & windage in 2.5 kW motor (CMU, NCSU).*

Project Risks:

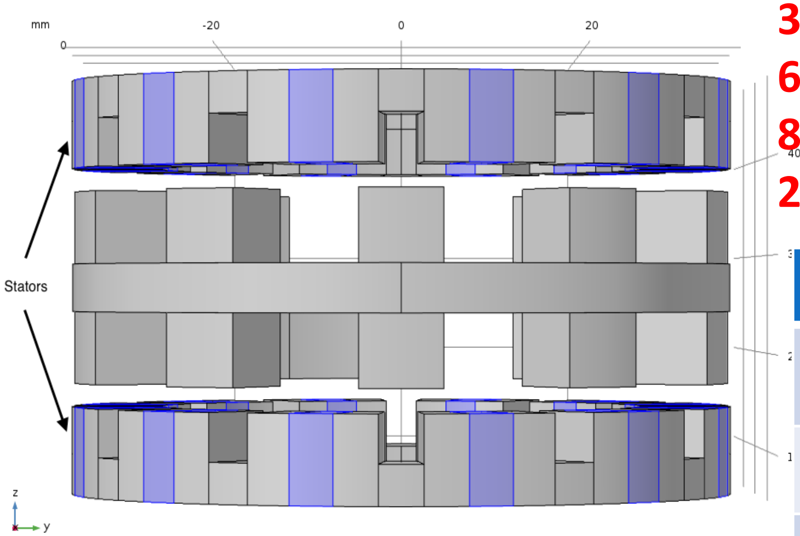
- Cutting/shaping technologies, Mechanical Properties.

Unique Advantages:

- (a) Commercial scale casting (b) US located companies, (c) ribbon processing (d) permeability tuning, (e) patented alloys.

Technical Approach

Novel Axial Motor Design: Flux Switching with Permanent Magnet (FSWPM) Motor



3-phase, Dual Stator & 14 Rotor Poles.
6000 rpm; 1.4 kHz switching; RE-free ferrite magnets.
80 mm outer & 50 mm inner radius
2.5 kW & 4.0 Nm torque.

	FeNi-MANC	3% Si-Steel
Fe loss: 2.5 kW	3.4 W	133 W
Cu loss (7.5 A)	27 W	27 W
Total	30 W	160 W
T-rise	27 °C	145 °C

Grey: Fe-Ni based MANC
Blue: Inexpensive Ferrite PM

Table I: Coercivity, saturation induction, thickness, losses at 1 T and 400 Hz, and losses at 1 T and 1 kHz for nanocrystalline $(Fe_{70}Ni_{30})_{80}Nb_4Si_2B_{15}$, nanocrystalline $Fe_{85}B_{13}Ni_2$, Fe-based Metglas 2605SA1, and non-oriented 3% Si-steel and 6.5% Si-steel. *H_c measured at 60 Hz and 1 T induction.

	H_c (A/m)	B_s (T)	t (µm)	$W_{1.0/400}$ (W/kg)	$W_{1.0/1k}$ (W/kg)
nc-$(Fe_{70}Ni_{30})_{80}Nb_4Si_2B_{15}$	7.0*	1.3	20	0.9	2.3
nc-$Fe_{85}B_{13}Ni_2$[38]	4.6	1.9	13.4	2.3	6.3
nc-$Fe_{89}Hf_7B_4$[39]	5.6	1.59	17	0.61	1.7
Fe-based amorphous[38]	2.4	1.56	23.9	1.6	4.7
3% Si-Steel[39,40]	55	2.05	100	8.5	27.1
6.5% Si-Steel[40]	18.5	1.85	100	5.7	17.2

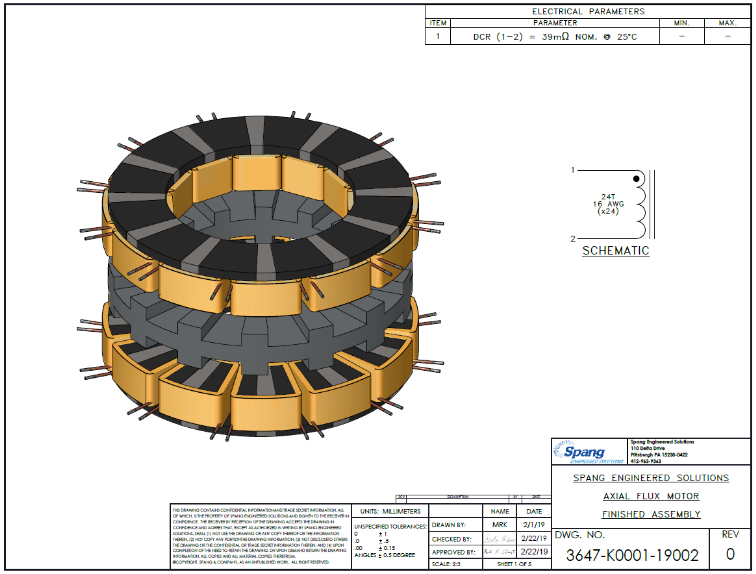
Patented CMU FeNi-based MANC

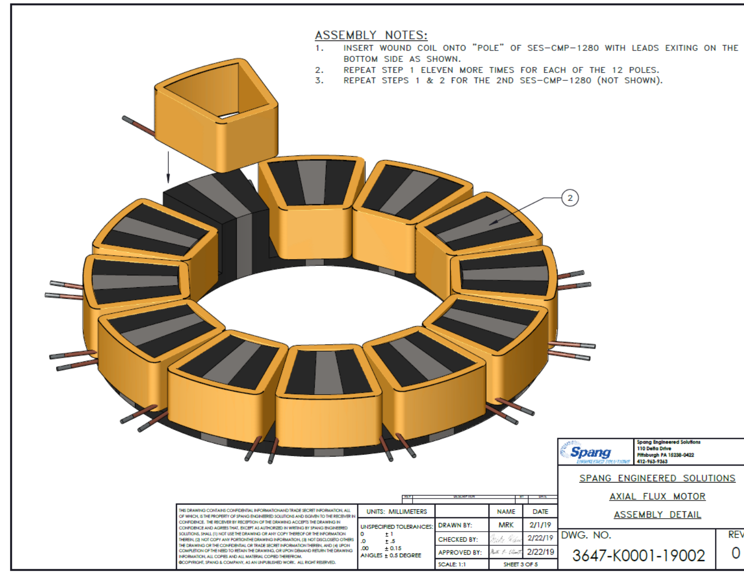
10x lower losses

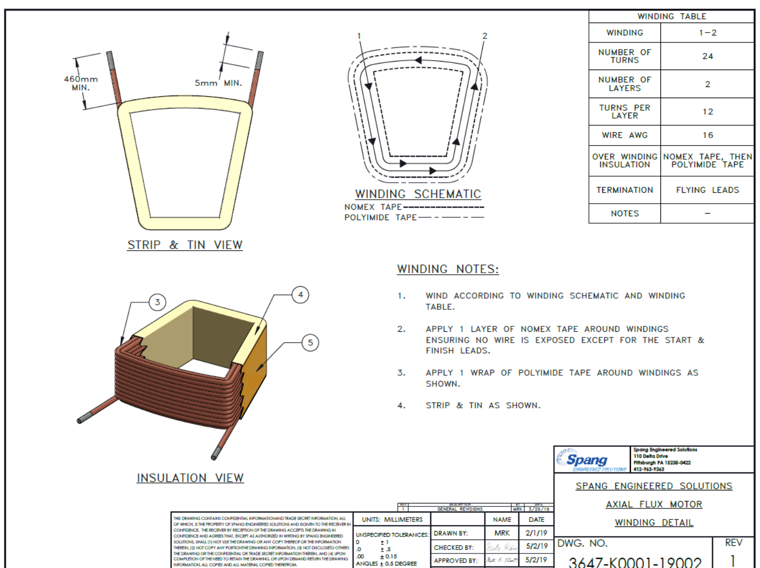
Results and Accomplishments 2018/19

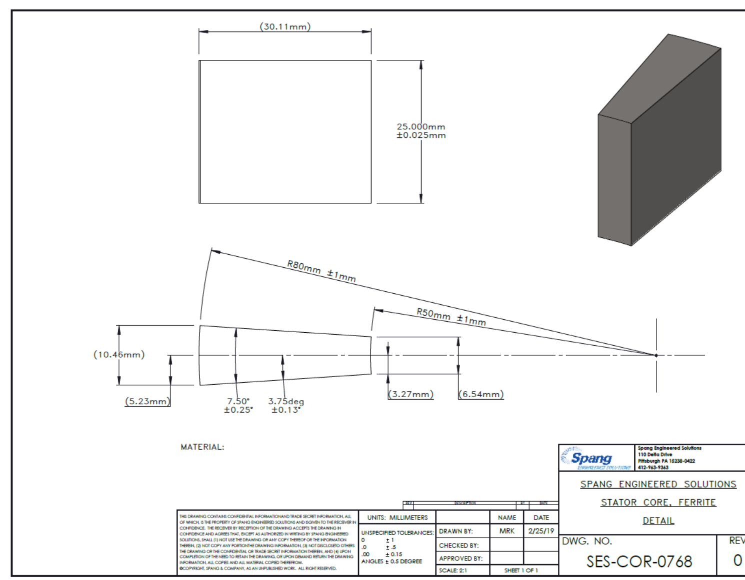
- **Modified FEA topology for gearless motors suitable for 1 kHz operation enabling 4% efficiency increase compared 0.35 mm non-oriented 3% NGO Si-steel, to reach 96% overall efficiency to accommodate dual stators.**
- **Produced Alloy at Pilot Lab Scale in Amounts >2 kg, sufficient for a 2.5 kW motor build. Confirmed the total core weight (stator + rotor) is < 2 kg.**
- **Core loss < 11 W/kg at 1kHz/1T after waterjet processing MANC Core (70 C).**
- **Assessed Glass Forming Ability for ring stamping of MANCs.**
- **Developed winding procedures for axial motor topology. Validated slot fill factor of at least 50% with Cu windings.**
- **Controller design is complete & awaits finished motor for BP3 testing in BP3.**
- **We have evaluated MANC microstructures by HRTEM.**
- **Stator permanent magnet cutting contracted. MANC rotor and stator waterjet cutting contracted.**
- **We anticipate motor machinability demonstrated ~June 30, 2019.**

Assembly and Component Drawings



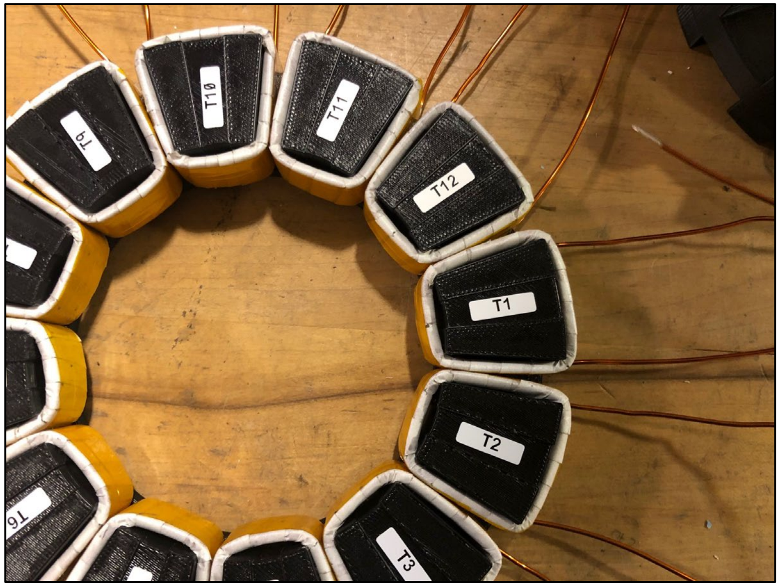




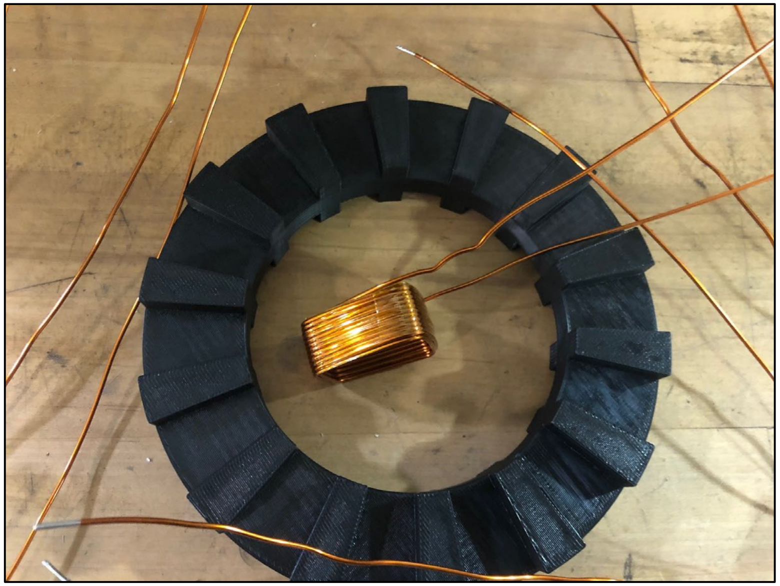


3D Printed Mock-Up: >50% Wire Fill Factor

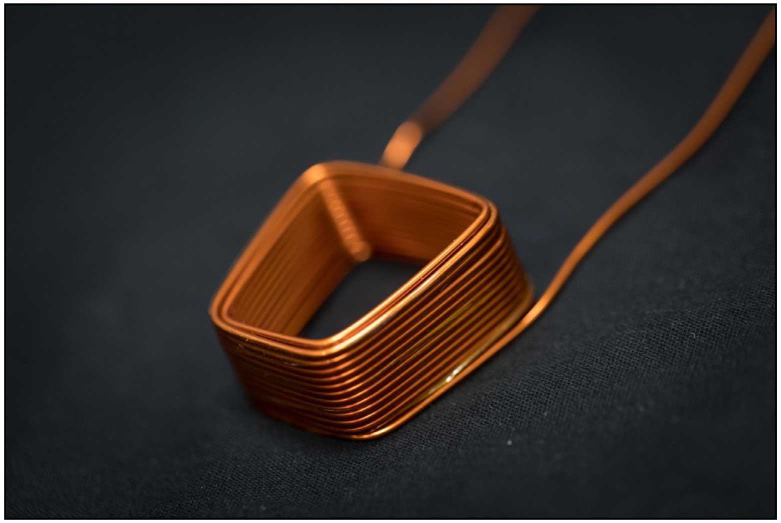
Wound Stator



Rotor



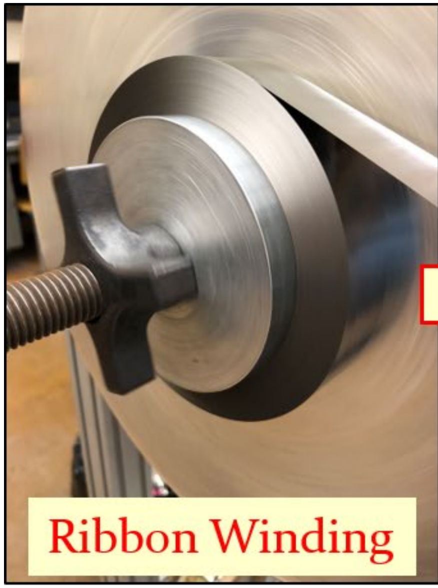
Bare Coil

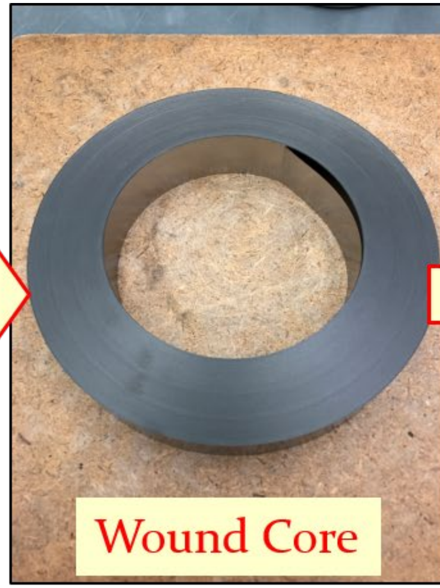


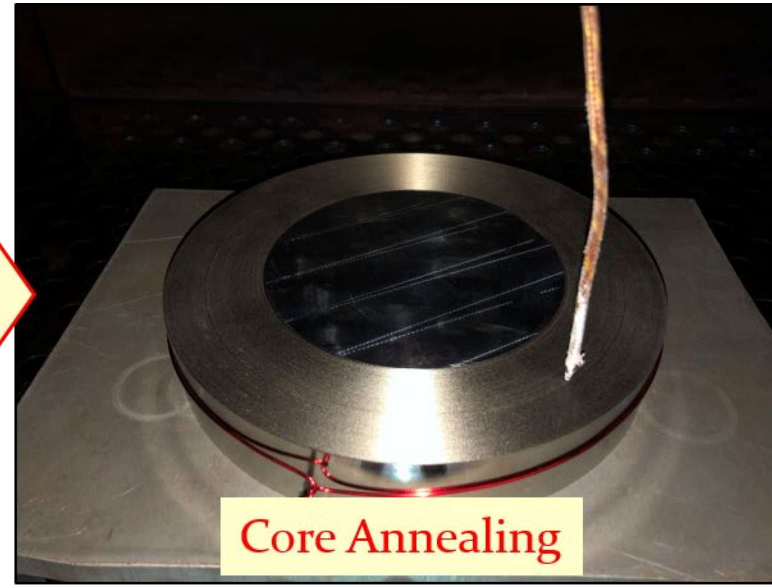
Rotor and Stators

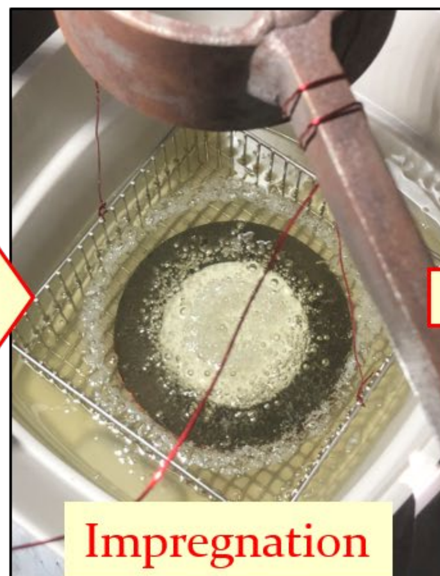
Core Fabrication for Water Jet Cutting

OMAX



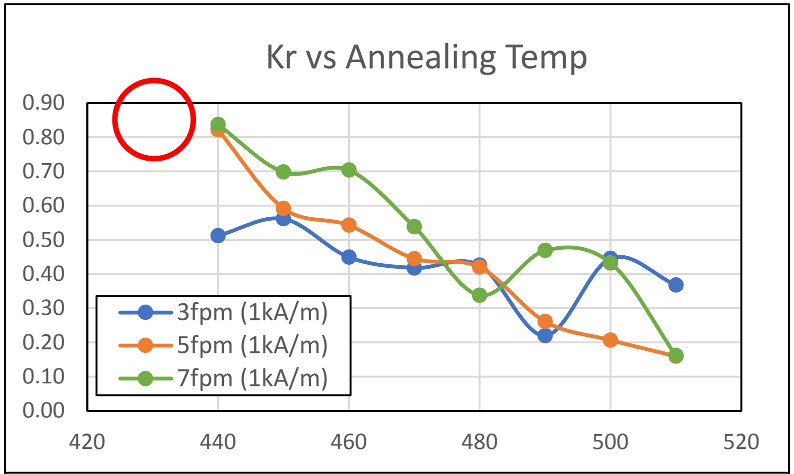


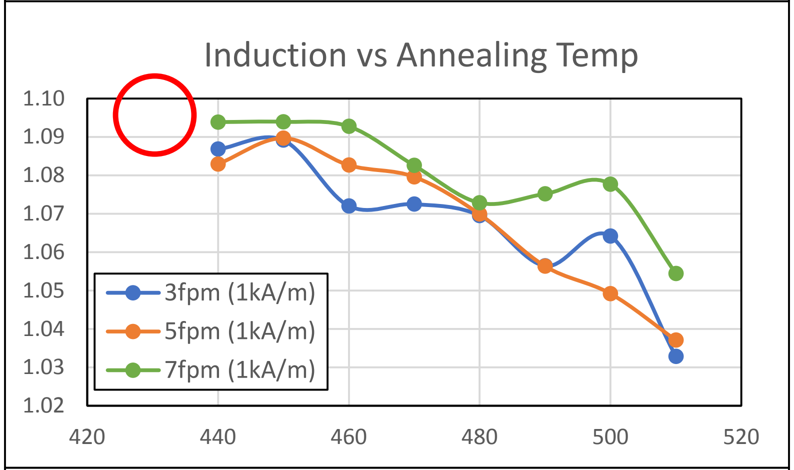


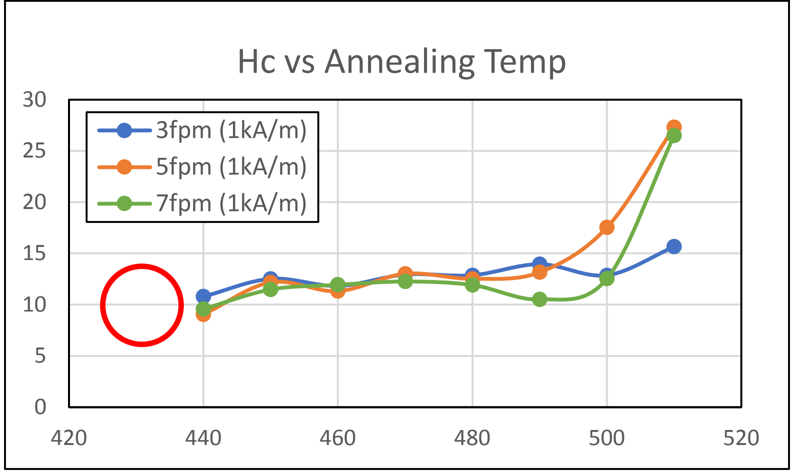


In-Line Annealing Trials: Fe-Ni Alloy at Scale

- 8 T's from 440°C to 510°C.
- 3 Materials speeds 3-7 ft/min.
- 440°C at 7 ft/min chosen for tension annealing 25 – 250MPa.

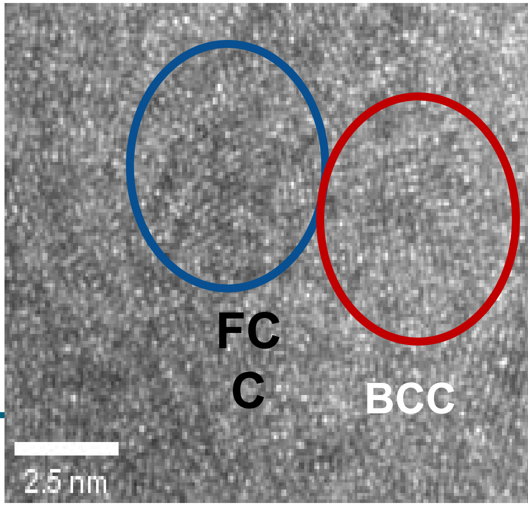


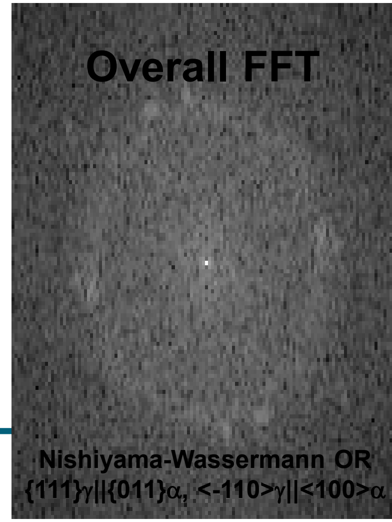


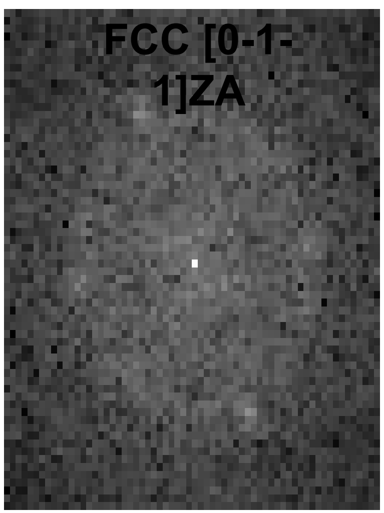


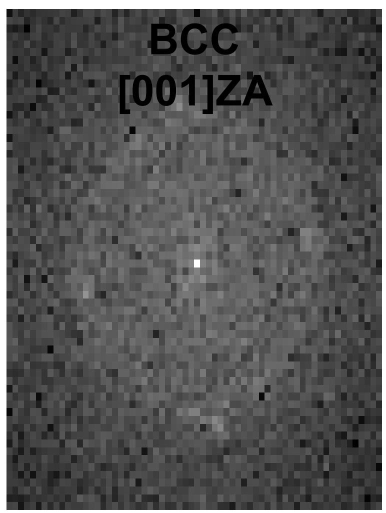
HRTEM in MANC Interior

Evidence of N-W, K-S, and Cube on Cube Orientation Relationships Between BCC and FCC Nanocrystals

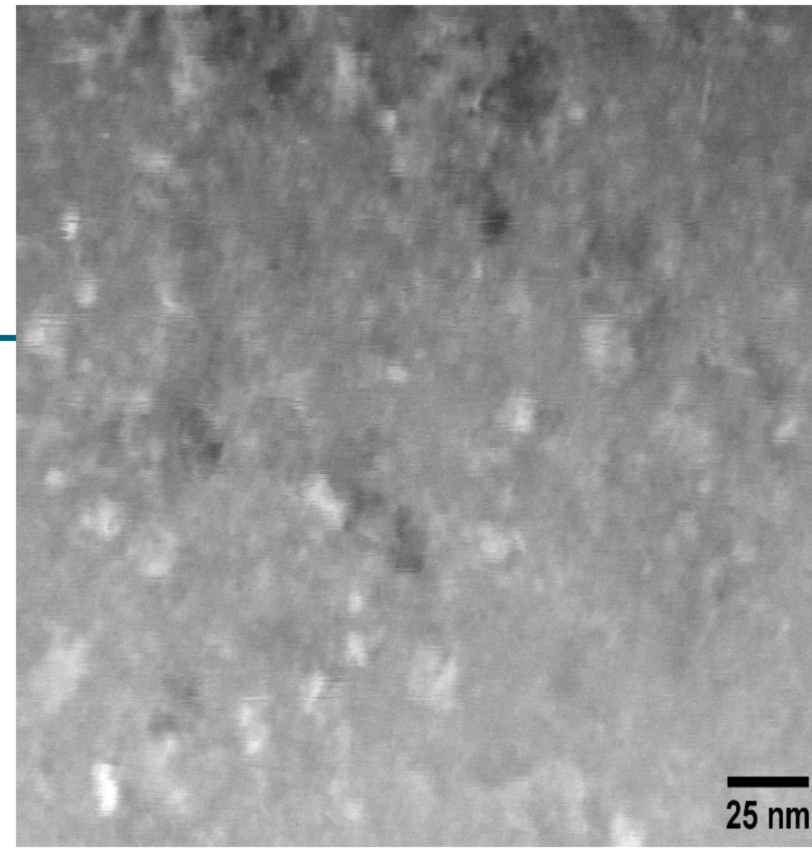








Bulk Nanocomposite



STEM HAADF (Dark Field)

Transition and Deployment

- Project demonstrates high speed motor efficiencies opening new markets for MANC ribbons.
- New MANC commercial production capabilities identified:

    Fort Wayne Metals has performed their 1st cast.

    Carpenter built a lab caster, id'd stamping equipment.

    Metglas has a license to test.
- Commercialization approach:
    - Technology transfer of casting technology to FWM
    - Investigate MANC stamping with Carpenter (BP3)
    - 2.5 kg Motor Demo in BP3
    - Concept paper for scaling to 20 kW motors submitted to VTO
    - Conversations with small appliance manufacturer initiated.