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

DE-EE0007867

Carnegie Mellon University/NETL/North Carolina State University

03/01/2017-03/31/2020

Michael E. McHenry & Carnegie Mellon University (PI & Presenter)

U.S. DOE Advanced Manufacturing Office Program Review Meeting
Washington, D.C.
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Overview

- 3 years beginning 03/01/17
- Partners: CMU (Alloys Development, Motor Design); NETL (Ribbon and core post-processing) NCSU (Motor controls and Motor testing)
- Project task and key milestone schedule
  - BP1 (ended 03/31/18): Staffed project, purchased computers, software M&S. Research included: (1) Finite Element Analysis (FEA) to propose a motor design, (2) alloy characterization to identify compositions for subsequent scaled lab caster runs and materials properties for models, (3) Identify practices for cutting, lamination bonding, and basemark switching losses.
  - BP2 (began 04/01/18):

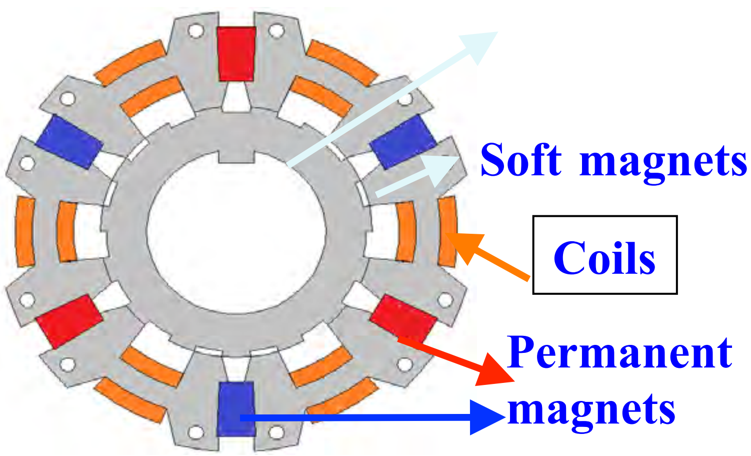
Total Project Budget (3 Yr)	
DOE Investment	$1,110,000
Cost Share	$230,566
Project Total	$1,340,566

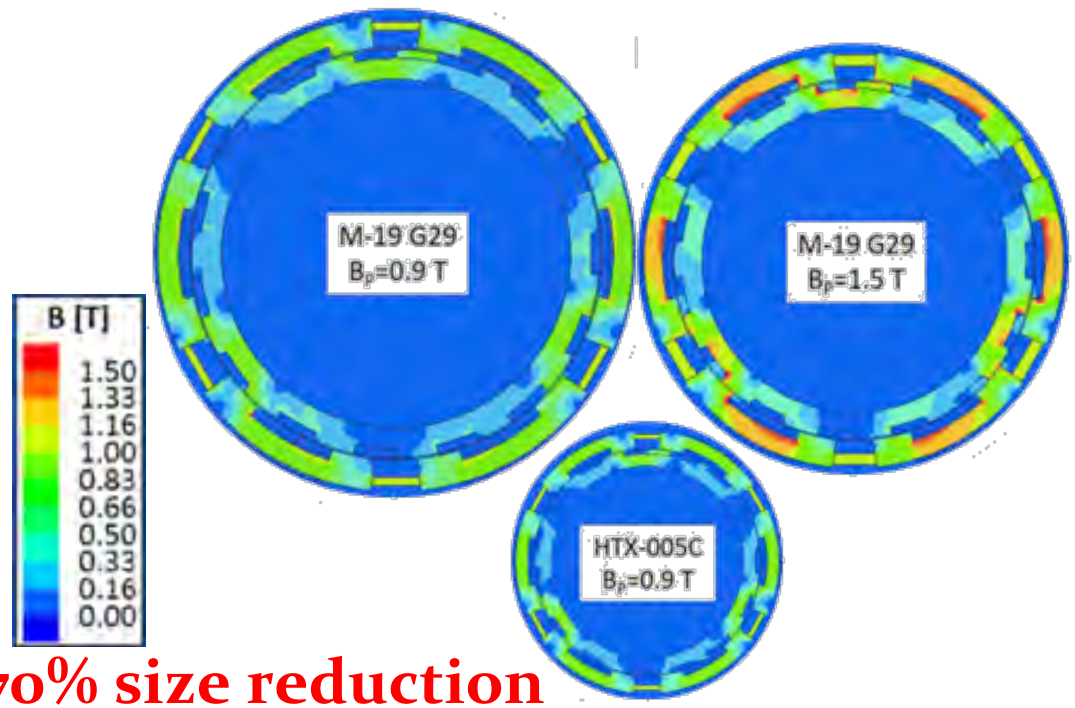
Project Objectives

- CMU team will develop metal amorphous nanocomposite (**MANC**) soft magnet materials (**SMMs**) 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 will model RE-free motors and 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. Transfer **MANC** casting technology to domestic production of high power density motor materials.
- Conventional Si-steels do not have combined resistivity and thickness required for tolerable losses at magnetic switching frequencies > 1 kHz targeted for the project.
- This new materials technology for motors and requires new topologies and processes to leverage MANC SMMs in motors.
- Mechanical properties must be investigated for high motor speed.

Technical Innovation – MANC SMMs

- Current practice for several kW motors use Si-steels which are limited by losses to switching f < 1 kHz. New MANC technology adoption is hindered by: (a) limited US manufacturing; (b) materials limits for high frequency 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

$$P_h = afB^2$$

Random crystal anisotropy
(MANC H_c < 40 A/m)

Eddy Current Losses

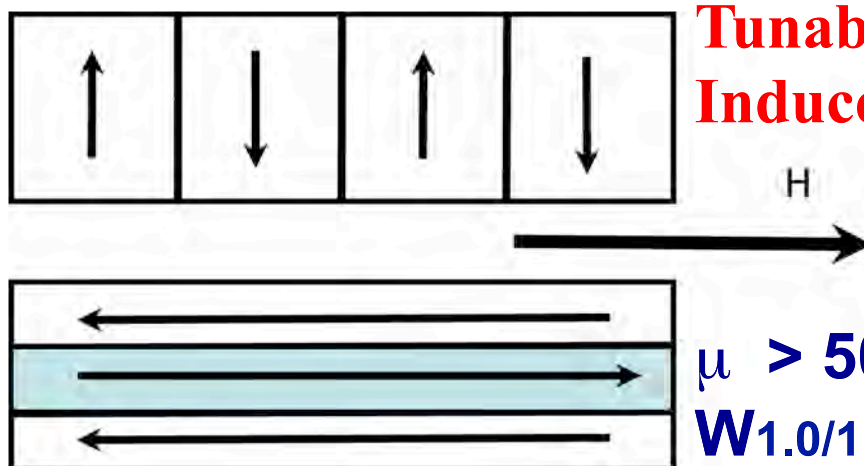
$$P_e = bf^2B^2$$

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

Resistivity, Thickness
ρ > 100 μΩ-cm
t < 25 μm

Anomalous Losses

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



Tunable (graded)
Induced Anisotropy

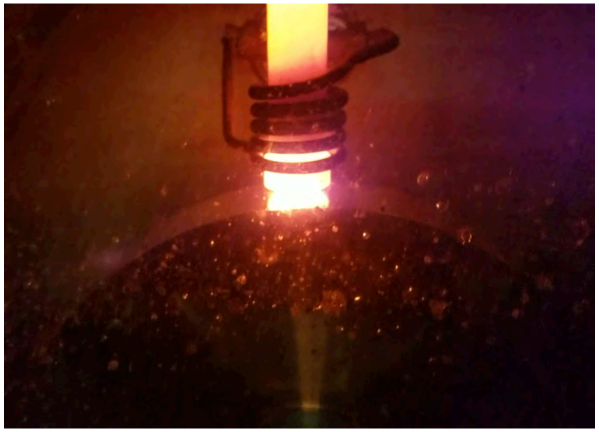
μ > 5000,
$W_{1.0/1kHz}$ < 10 W/kg

Technical Approach

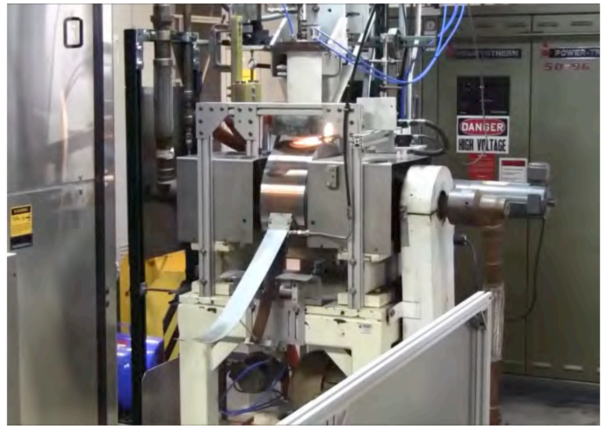
- Technical Approach:
  - *Identify prototype FEA motor design for MANCs (CMU/NETL);*
  - *Lab scale rapid solidification (RSP) & post-processing to tune magnetic permeability in cores (CMU);*
  - *Post processing into rotor/stator components (CMU, NETL);*
  - *Winding techniques for use in new topologies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

  Project Risks:
  - Cutting/shaping technologies, Mechanical Properties.

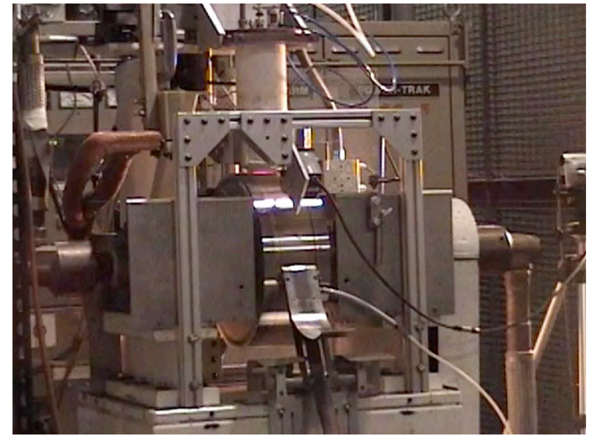
  Unique Advantages:
  - Commercial scale caster & US owned company, state of the art ribbon processing for permeability tuning, Patented alloys.



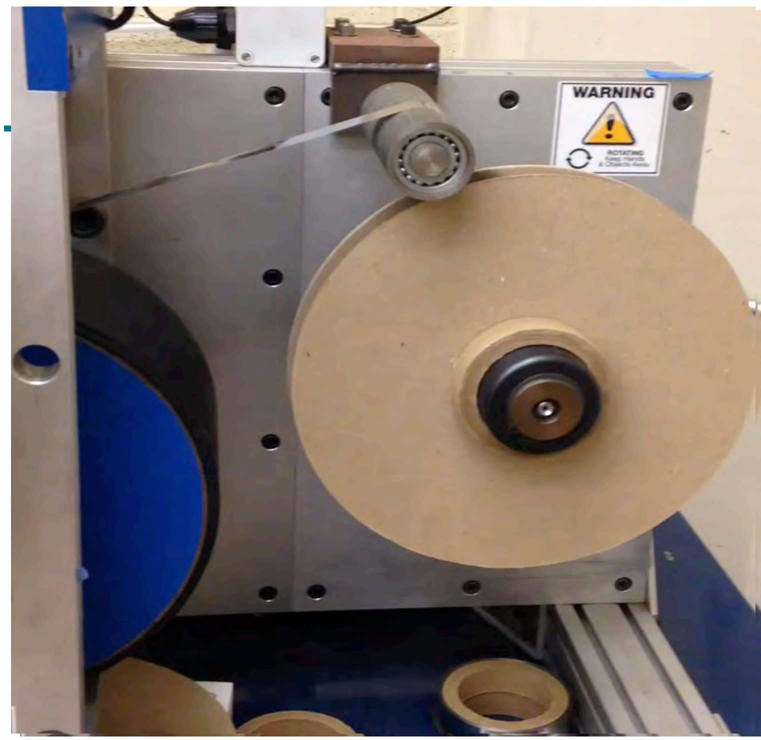
Lab Scale CMU (5-10 g)



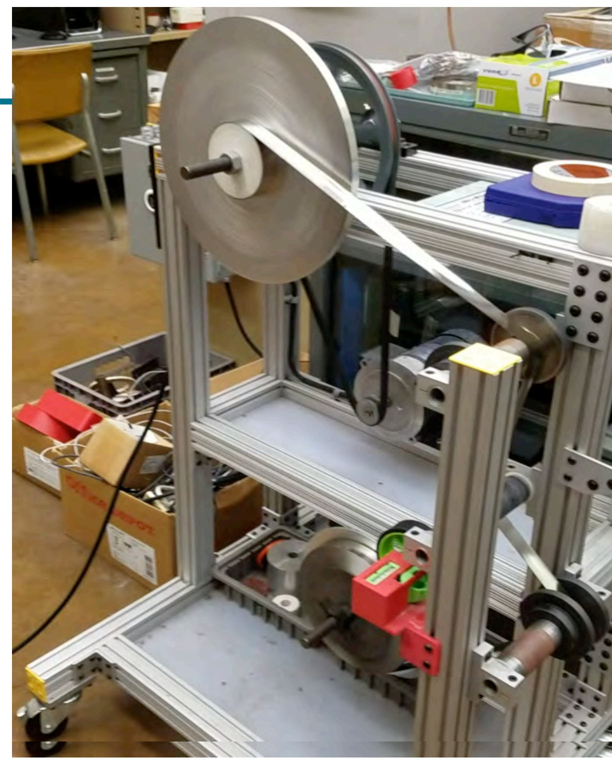
Lab Scale (3-5 kG,1-2”) NASA



Commercial Scale Casting -
Fort Wayne Metals (40 kG,2-4”)

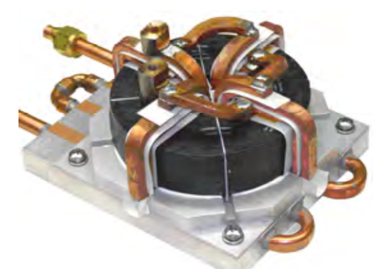


Strain Annealing Line at CMU



Core Winding Machine (CMU)

Wound Ribbon,
Converter- CMU,ARL



Results and Accomplishments

- Complete milestones:
- Milestone 1: Staff and Equip Project (App 1). Complete.
- Milestone 2: Reported FEA topology for gearless motors for > 1 kHz operation enabling 4% efficiency increase benchmarked with 0.35 mm non-oriented 3% Silicon steel, to reach 96% overall efficiency to DOE AMO. Complete.
- Milestone 3: Report Loss Analysis (DOE AMO) to show W10/1 k (Power loss at 1 T and 1 kHz) < 15 W/kG 50-60% that of non-oriented (0.35 mm laminated) Si steels, enabling 4% motor efficiency increase to a 96% overall. Complete.
- Milestone 4: Report Alloy Composition for Future Scaling to DOE AMO. Complete.
- Milestone 5: Q5 RSP Alloy at Pilot Lab Scale in Amounts >2 kg, sufficient for 2.5 kW motor build. Report core weight requirements to DOE, and combine with 3D modeling to confirm total core weight (stator + rotor) < 2 kg. Complete*.
- Accomplishments to-date:
- Project is staffed. (Natan Aronhime has defended his thesis, May 2018; Sam Greene will join the group in August)
- A FEA topology for an axial motor topology has been reported, FEA radial motor topology is being investigated.
- An FeNi-based MANC alloy n has been reported with magnetic properties and lossses that meet stated project goals.
- Results:
- Promising compositions met: Bs > 1.0 T, in H < 40 A/m, peak μ > 5000, ρ > 100 μΩ-cm, W10/1 k (Power loss at 1 T and 1000 Hz) < 10 W/kG. In press (App. 2): N. Aronhime, V. DeGeorge, V. Keylin, P. Ohodnicki, and M. E. McHenry, "The Effects of Strain-Annealing on Tuning Permeability and Lowering Losses in Fe-Ni based Metal Amorphous Nanocomposites. " J. Materials, (2017). 10.1007/s11837-017-2480-x.
- Report FEA topology for gearless motors suitable for 1 kHz operation enabling 4% efficiency increase benchmarked with 0.35 mm non-oriented 3% NGO Silicon steel, to reach 96% overall efficiency to DOE AMO: S. Simizu, P. R. Ohodnicki and M. E. McHenry, "Metal Amorphous Nanocomposite Soft Magnetic Material-Enabled High Power Density, Rare Earth Free Rotational Machines," *IEEE Trans. Mag*. 99, 1-5. doi: 10.1109/TMAG.2018.2794390.
- Work to be completed in BP2:
- Milestone 6: Assess Waterjet Processing on RSP Alloy (Milestone 4) Core.
- Milestone 6(a): Assess GFA RSP Alloy (Milestone 4) Core.
- Milestone 7: Report Winding Procedures to DOE/AMO.
- Milestone 8: Report Controller Design to DOE/AMO.

Appendix I: Staff List

- **Carnegie Mellon University Staff**

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  Mr. Yuval Krimer, M.S. Student: 412-535-3437, ykrimer@andrew.cmu.edu
  Lisa Vento, Project Accounting: 1210 Hamburg Hall, 412-268-7890, ventola@andrew.cmu.edu
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  Natan Aronhime, Graduate Student 335 REH, 410-491-4804, naronhim@andrew.cmu.edu

- **Technical Contacts at Sub-Contractors:**

  Dr. Paul Ohodnicki, NETL, 626 Cochrans Mill Road, Pittsburgh, PA 15236-0940, (412) 386-7389, paul.ohodnicki@netl.doe.gov
  Prof. Subhashish Bhattacharya, NCSU, 2701 Sullivan Dr., Admin Services III Box 7514, Raleigh, NC 27695, 919-513-7972, sbhattacharya@ncsu.edu

- **Industry Advisors:**

  Jeremy Pfister, Fort Wayne Metals, jeremy_pfister@fwmetals.com
  Dr. Frank Johnson, General Electric Global Research johnsonf@ge.com

Nota bene: Dr. Frank Johnson has recently left GE to take a position with Niron Metals. We will identify an additional Industry advisor in the coming months. We are collaborating with Carpenter on glass forming ability and mechanical processing issues. We plan on taking on an additional graduate student in Fall 2018 for the project (Sam Greene).

Appendix II: nc FeNi-based NC Baseline

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

Appendix 3: Accuracy and numerical consistency in FEA (in Q4 report)
Appendix 4: Anisotropy in FeNi-MANC (in Q4 report).

Metal Amorphous Nanocomposite Soft Magnetic Material-Enabled High Power Density, Rare Earth Free Rotational Machines

Satoru Simizu[1], Paul R. Ohodnicki[2], and Michael E. McHenry[1]

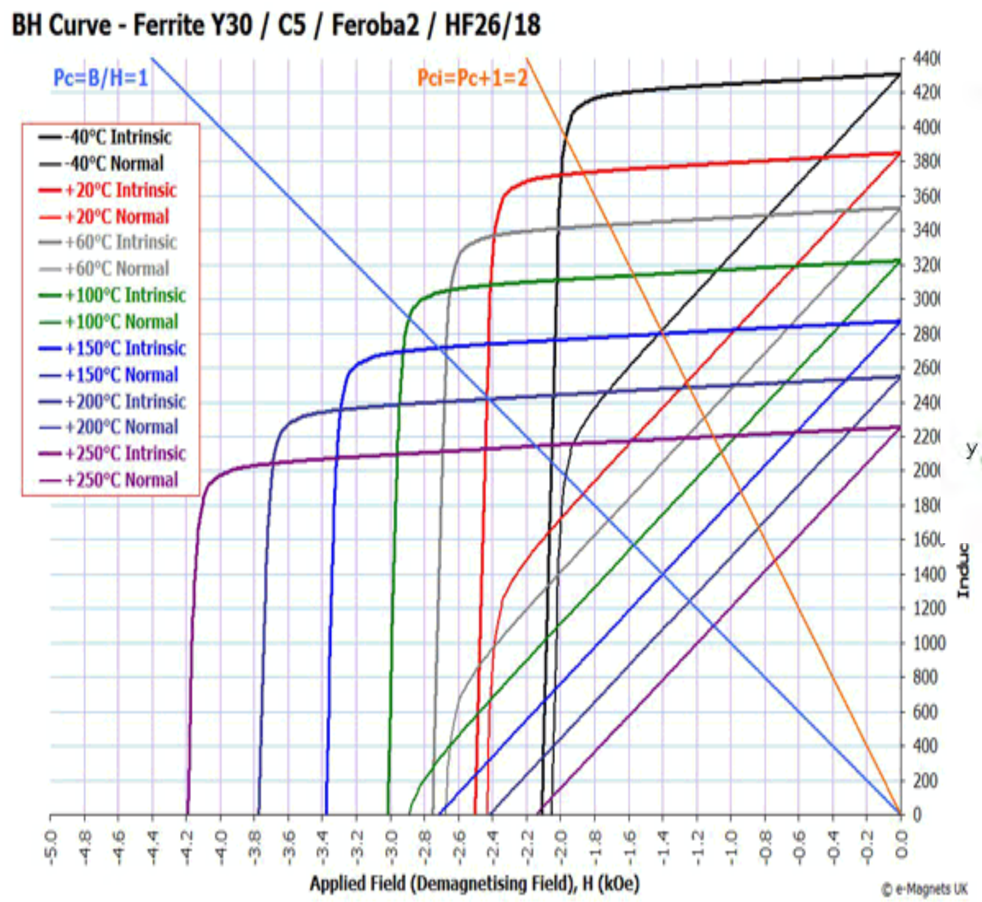
[1]Department of Materials Science and Engineering, Carnegie Mellon University, Pittsburgh, PA 15213 USA
[2]National Energy Technology Laboratory, Pittsburgh, PA 15236 USA

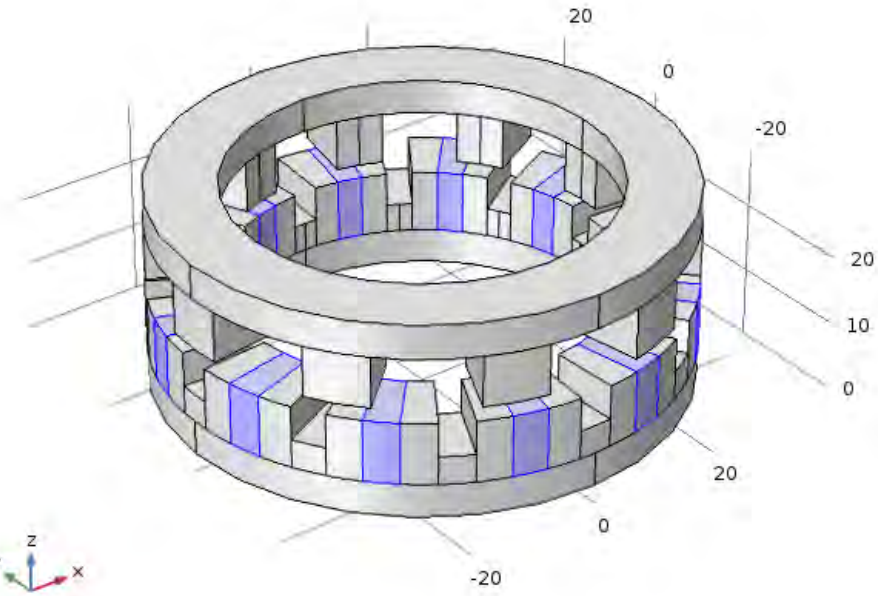
Metal amorphous nanocomposites (MANCs) are promising soft magnetic materials (SMMs) for power electronic applications offering low power loss at high frequency and maintaining a relatively high flux density. While applications in certain motor designs have been recently modeled, their widespread application awaits scaled manufacturing of MANC materials and proliferation of new higher speed motor designs. A hybrid motor design based on permanent magnets and doubly salient stator and rotor is reported here to develop a compact (a factor of 10 smaller than currently possible in Si steels), high-speed (>1 kHz, electrical), high-power (>2.5 kW) motor by incorporating low loss (<10 W/kg at 1 kHz) MANCs such as recently reported Fe-Ni-based alloys. A feature of this motor design is flux focusing from the permanent magnet allowing use of lower energy permanent magnet chosen from among non-rare earth containing compositions and attractive due to constraints posed by rare earth criticality. A 2-D finite element analysis model reported here indicates that a 2.5 kW hybrid motor may be built with a permanent magnet with a 0.4 T remanence at a rotor speed of 6000 rpm. At a magnetic switching frequency of 1.4 kHz, the core loss may be limited to <3 W by selecting an appropriate MANC SMM. The projected efficiency exceeds 96 % not including power loss in the controller. Under full load conditions, the flux density distributions for the SMM stay predominantly <1.3 T, the saturation magnetization of optimized FeNi-based MANC alloys. The maximum demagnetizing field in the permanent magnet is less than 2.2 x 10^5 A/m sustainable, for example, with a high-grade hard ferrite magnet.

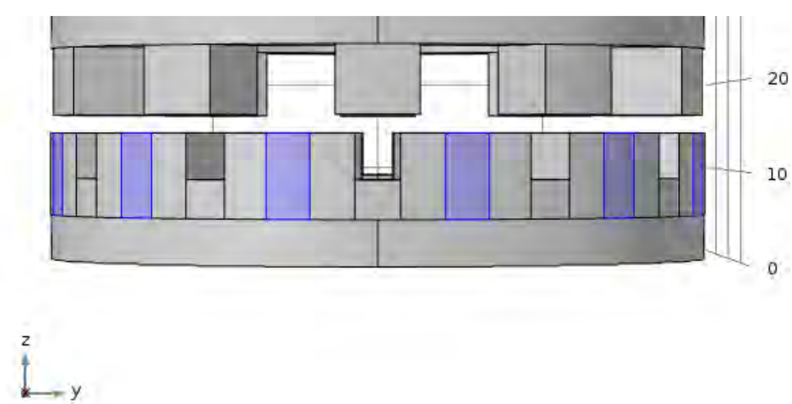
Commercial Ferrite PMs (Br ~ 0.4T) In FSWPM High Flux Density Results (1 T) from Flux Focusing of MANC

Power Density ~ #poles and angular speed

Axial Motor Designs with MANC Rotors







S. Simizu, P. R. Ohodnicki and M. E. McHenry, "Metal Amorphous Nanocomposite Soft Magnetic Material-Enabled High Power Density, Rare Earth Free Rotational Machines," *IEEE Trans. Mag*. 99, 1-5. doi: 10.1109/TMAG.2018.2794390. Also presented at MMM 2017, Pittsburgh, PA

Transition and Deployment

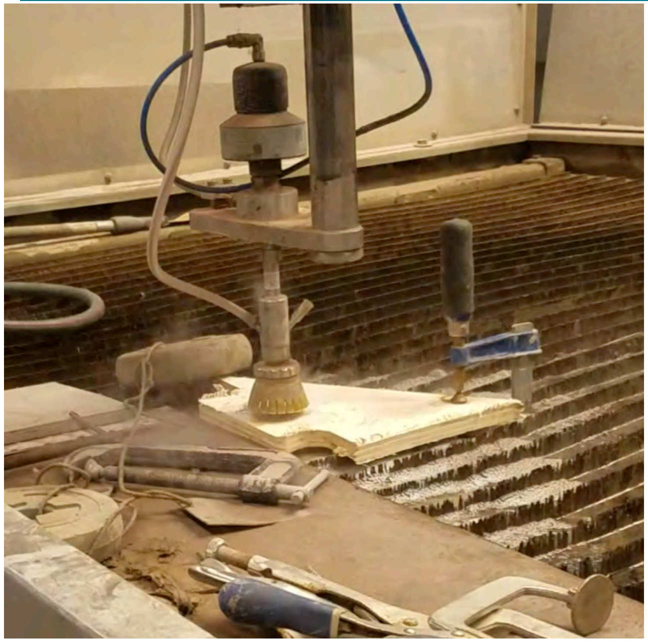
- Project seeks to demonstrate efficiencies in high speed motors that will open new markets for MANC ribbon.
- FWM will be the end user of casting technologies.

  A > 50 kg capacity VIM melting & planar flow cast facility is leased to FWM by CMU positioning them as a sole US MANC materials manufacturer.
- Commercialization approach:
  - Technology transfer of Casting technology to FWM
  - Scaling, control system development for strain anneal.
  - 2.5 kg Motor Demo
- This technology impacts materials criticality issues

  in magnet production in supply chain steps:

  Metals to Alloys; Magnet Production; Motors.

Transition and Deployment - II



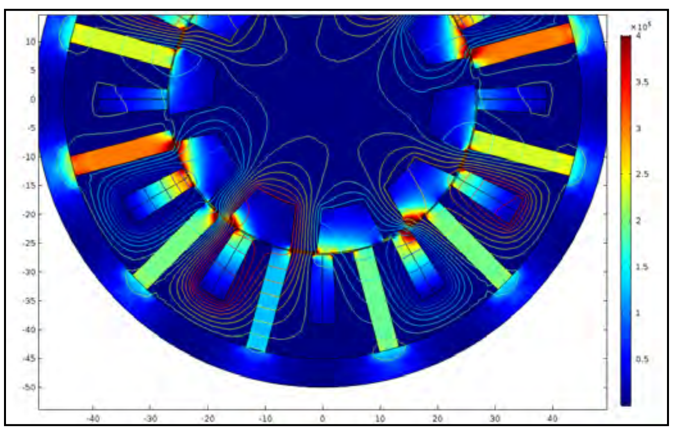
Training scale waterjet cutting was performed at TechShop, in Pittsburgh's Bakery Square. NETL has a 5-axis waterjet available in its WV facility for future work.

CMU offered a course on Power Magnetics in S'2017. P. Ohodnicki, NETL and M.E. McHenry, Instructors, M.S.& Ph.d student participants presented Comsol FEA power electronic simulations including motor topologies leveraging MANC materials. Course will be offered in 2019.

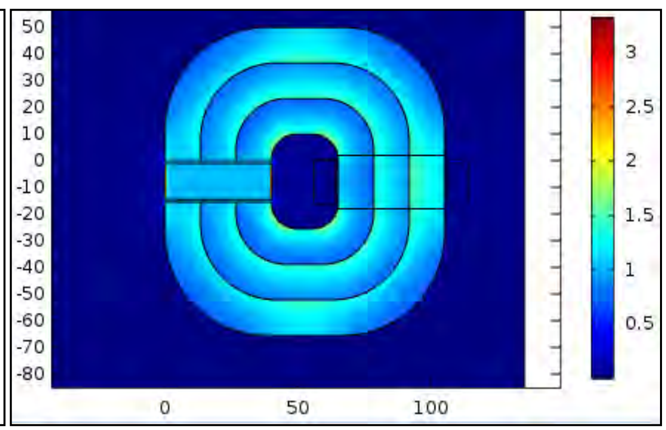
Collaboration with Carpenter on glass forming ability/stamping have Been initiated

NCSU will design motor controller for new motor topologies. NCSU sub-contract has been executed.

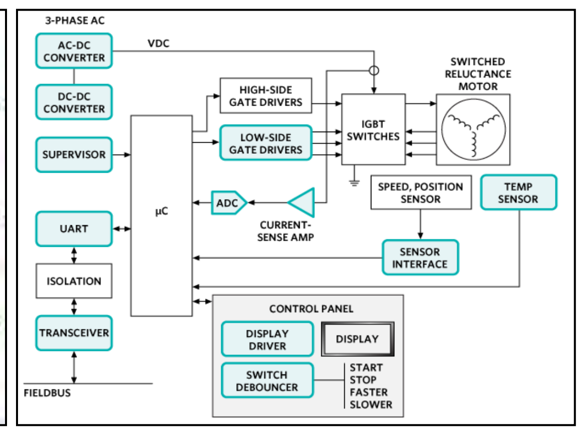
Waterjet Cutting Nanocomposites



Flux Switching Motor
IEEE 2005.



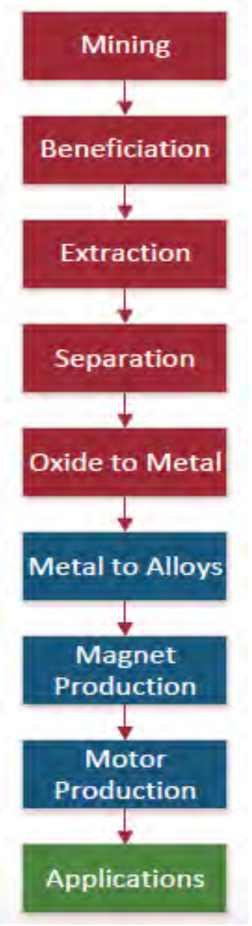
Cross-section of axial switched reluctance motor



Motor controller
(source: Maxim Integrated)

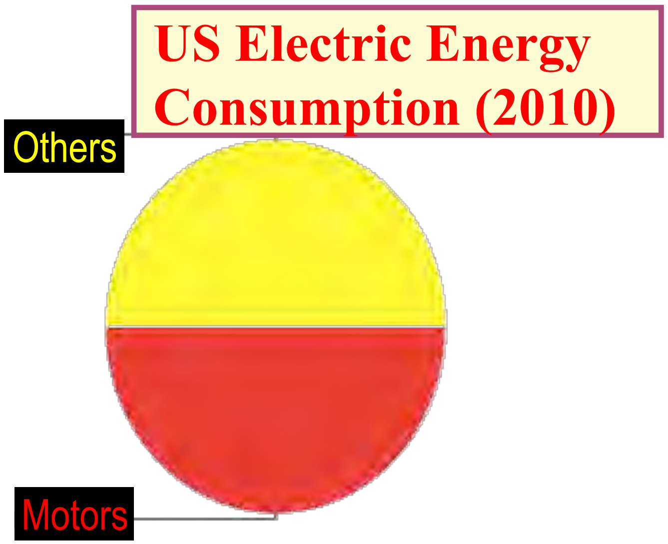
Transition and Deployment

- Project seeks to demonstrate high speed motor efficiencies opening new markets for MANC ribbons.
- FWM is an end user of casting technologies. > 50 kg VIM & planar flow casting facility is leased to FWM by CMU to position them as a sole US owned MANC manufacturer.
- Commercialization approach:
  - Technology transfer of casting technology to FWM
  - Scaling, control system development for strain anneal.
  - Investigate MANC stamping with Carpenter (BP2)
  - 2.5 kg Motor Demo
- Technology impacts materials criticality issues in magnet production in supply chain steps: Metals to Alloys; Magnet Production; Motors.



Measure of Success

- **GO/NO-GO DECISION 1:** Demonstrate metrics: Bs > 1.0 T, peak μ > 5000, ρ > 100 **μΩ-cm**, and W10/1 k (Power loss @ 1 T, 1 kHz) < 15 W/kg FEA motor model with energy losses 50-60% that of (0.35 mm laminated) non-oriented Si steels, enabling 4% motor efficiency increase, to an overall 96% metric.
- Potential for energy/economic impact:



Source: Moyer, Univ. Chicago, 2010

At the Project end we will be able to estimate size/weight reduction possible at higher frequencies to show where MANC motors will outperform other HSMs. This will provide a basis for future increases in power densities and extensions to other HSM and ultra-HSM motors

Questions?