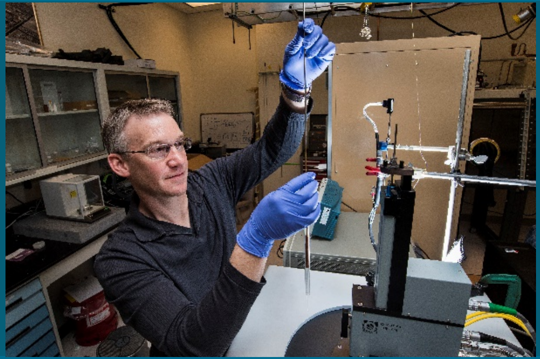
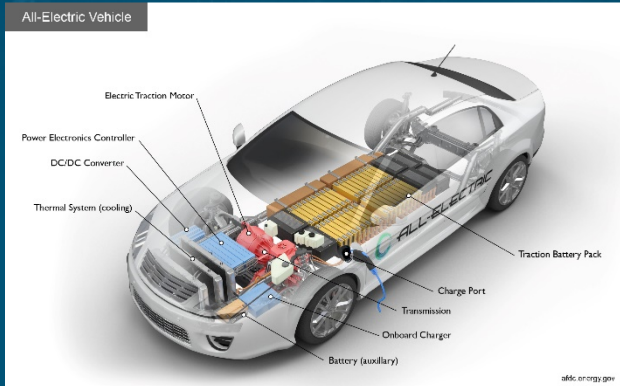
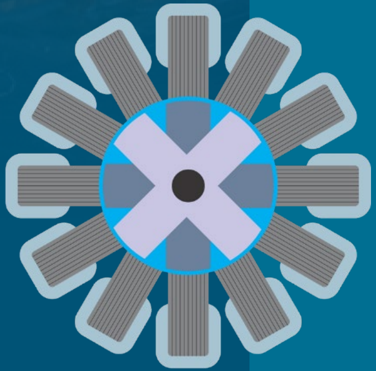
Isotropic, Bottom-Up Soft Magnetic Composites for Rotating Machines







2021 DOE Vehicle Technologies Office Annual Merit Review

Todd C. Monson, PI, Electric Motors

Sandia National Laboratories

June 22, 2021

Project ID: elt216

Overview

Timeline

- Start – FY19
- End – FY23
- 50% complete

Budget

- Total project funding
  - DOE share – 100%
- Funding for FY20: $150k
- Funding for FY21: $125k

Barriers

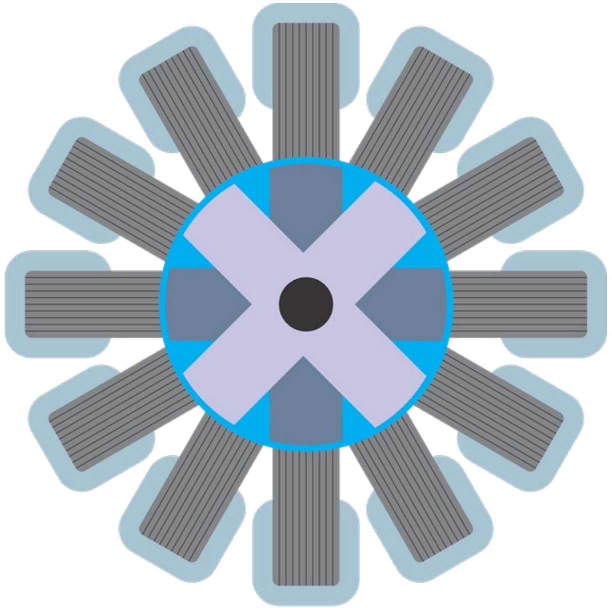
- Non-rare-earth electric motor performance
- Material property optimization (to lower cost and improve performance and reliability)
- Reliability: High temperature performance (150 °C) over a long lifetime (300,000 miles)

Partners

- ORNL, NREL, Ames Lab
- Purdue University, Illinois Institute of Technology (IIT)
- Project lead: Sandia Labs
  - Key Sandia staff: Lee Rashkin, Lee Gill, Bob Kaplar, CJ Pearce, Melinda Hoyt, Robert Delaney, and many others…

Relevance

- To meet 2025 goals for enhanced peak power (100 kW), specific power (50kW/L), and reduced cost ($3.3/kW) in a motor that operates at > 20,000 rpm, improved soft magnetic materials must be developed
- Improved soft magnetic materials will enable high performance non-rare-earth motors
- Replacement of permanent magnets with soft magnet materials highlighted in Electrical and Electronics Technical Team (EETT) Roadmap as a potential R&D pathway for meeting 2025 targets



Homopolar AC machine design that doesn't require permanent magnets

Courtesy of Scott Sudhoff at Purdue

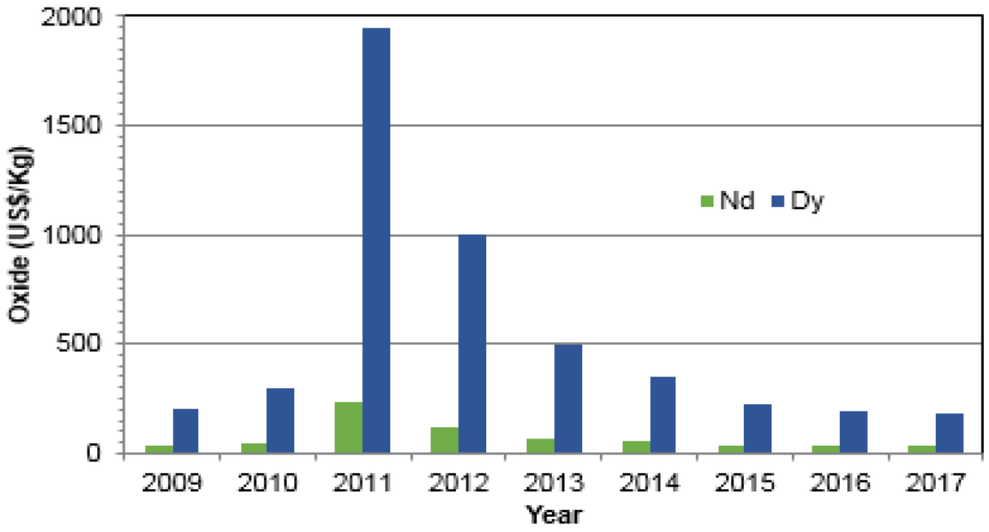


Figure 9. Rare Earth Metal Prices Track Oxides Very Closely

Source: Metal Pages courtesy of Critical Materials Institute

As seen in Oct. 2017 EETT Roadmap

Milestones

Milestone, Keystone 2 – Electric Motors	
FY21: 2.1 Demonstrate a net-shaped, iron nitride soft magnetic motor component with a vol.% loading of iron nitride > 70% and evaluate its saturation magnetic polarization and eddy-current losses. **(on schedule)**	9/30/2021
FY22: 2.1 Demonstrate a net-shaped, iron nitride soft magnetic motor component with a vol.% loading of iron nitride > 75% and evaluate its saturation magnetic polarization and eddy-current losses.	9/30/2022

Progress towards milestone to date:

- Demonstrated 71 vol.% loading iron nitride/epoxy composite
- Started hot pressing iron nitride/epoxy toroids for additional characterization
- Working with our collaborators at ORNL, Purdue, and IIT to target some representative soft magnetic part shapes

* Any proposed future work is subject to change based on funding levels

Approach

- Develop high magnetization, low loss iron nitride based soft magnetic composites for electrical machines
- Composite approach will lower losses even further and enable efficient operation at rotational speeds up to 20,000 rpm
- Epoxy based matrix (binder) capable of operating at elevated temperatures (up to 150 °C) over an extended lifetime (300,000 miles or 15 yrs.)
- γ'-Fe_4N has a higher saturation polarization (J_s = 1.89 T) and electrical resistivity than Si steel (J_s = 1.87 T)
- Use of abundant elements (Fe and N) will keep costs low

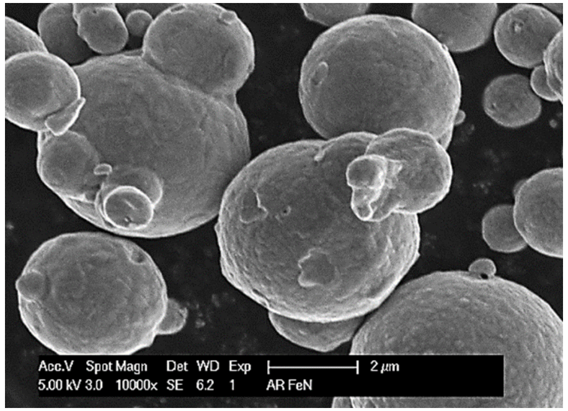
Element	Mass fraction (ppm)
Hydrogen	739,000
Helium	240,000
Oxygen	10,400
Carbon	4,600
Neon	1,340
Iron	1,090
Nitrogen	960
Silicon	650
Magnesium	580
Sulfur	440

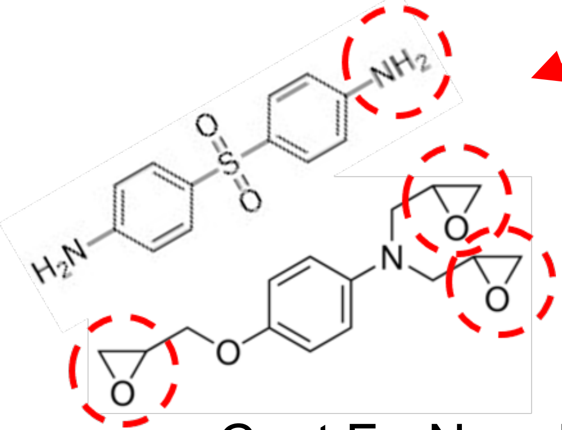
From Croswell, Ken (February 1996). Alchemy of the Heavens. Anchor. ISBN 0-385-47214-5.

Approach

Diamines will bond directly to Fe_4N surface and epoxy matrix for enhanced mechanical robustness and particle electrical isolation

Convert commercial Fe_xN powder to phase pure Fe_4N

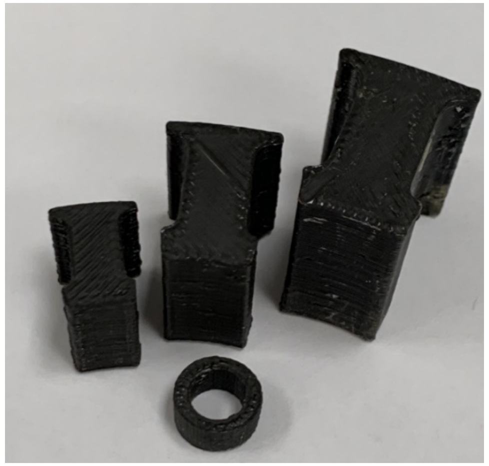


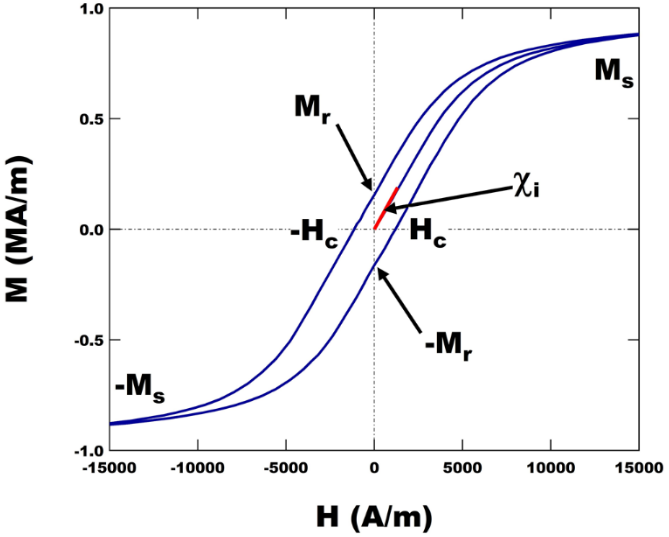


4-aminophenyl sulfone
&
N,N-diglycidyl-4-glycidyloxyaniline (NND)

Coat Fe_4N and mix with epoxy monomers

- Pour into custom graphite die
- Hot press to increase loading factor and cure epoxy
- Results in a net-shaped part (no machining required)





Evaluate and test

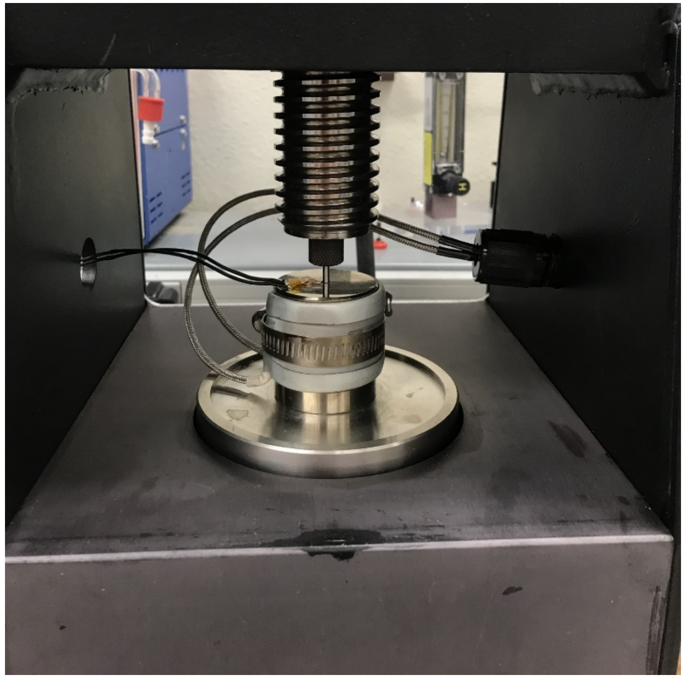
Approach – Epoxy Robustness in Motors

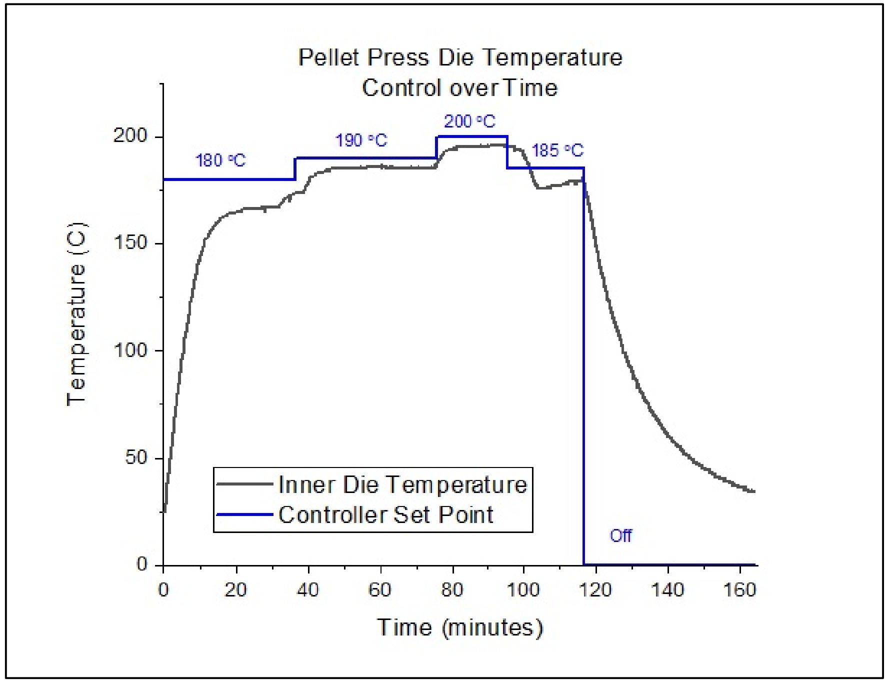
- Possible to design epoxy systems with glass transition temperatures (T_g) much greater than 150 °C [1,2]
- Epoxies are already ubiquitous in electrical machine construction [2,3]
- Composites have already been successfully demonstrated in high speed motors [4] and even flywheels rotating up to 60,000 rpm [5]
- Retention sleeves are being used already in some high speed designs to provide additional mechanical strength[6]
- Selecting our own epoxy monomers allows us to design our composite from the ground up and tailor its properties
- Diamines will bond directly to Fe_4N surface and epoxy matrix for enhanced mechanical robustness and particle electrical isolation

1. https://www.masterbond.com/techtips/how-optimizing-glass-transition-temperature-tg
2. https://magneticsmag.com/new-structural-adhesive-from-delo-for-magnet-bonding-has-high-temperature-stability/
3. http://www.crosslinktech.com/products-by-application/featured-electric-motor-products.html
4. A. Schoppa and P. Delarbre, "Soft Magnetic Powder Composites and Potential Applications in Modern Electric Machines and Devices," in IEEE Transactions on Magnetics, vol. 50, no. 4, pp. 1-4, April 2014, Art no. 2004304. DOI: 10.1109/TMAG.2013.2290135
5. Mason, Patrick & Atallah, K & Howe, D. (1999). Hard and soft magnetic composites in high speed flywheels. International Committee on Composite Materials, Paris
6. V. Cabral do Nascimento, S. Sudhoff, “Non-axisymmetric Structural Analysis of High Speed Rotor Orthotropic Retention Sleeve,” International Electric Machines & Drives Conference, San Diego, CA, May 12-15, 2019

Technical Accomplishments and Progress

Built and tested lab scale hot pressing setup

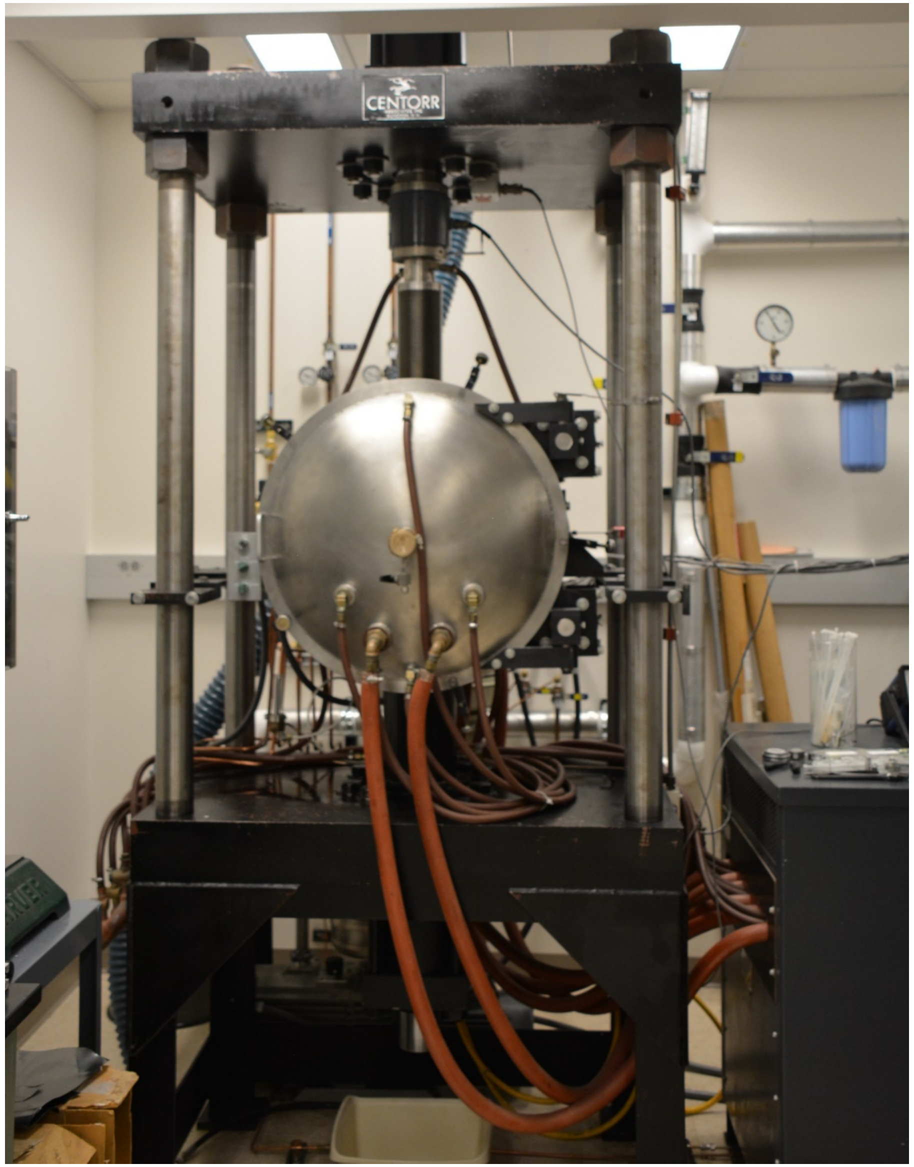




- Assembled lab scale hot pressing set up fabricating toroids and other custom soft magnet components
- Max. force of 4.5 ton, max. pressure of 81000 psi, max. temp of 350 °C
- Demonstrated good control over inner die temperature

Technical Accomplishments and Progress

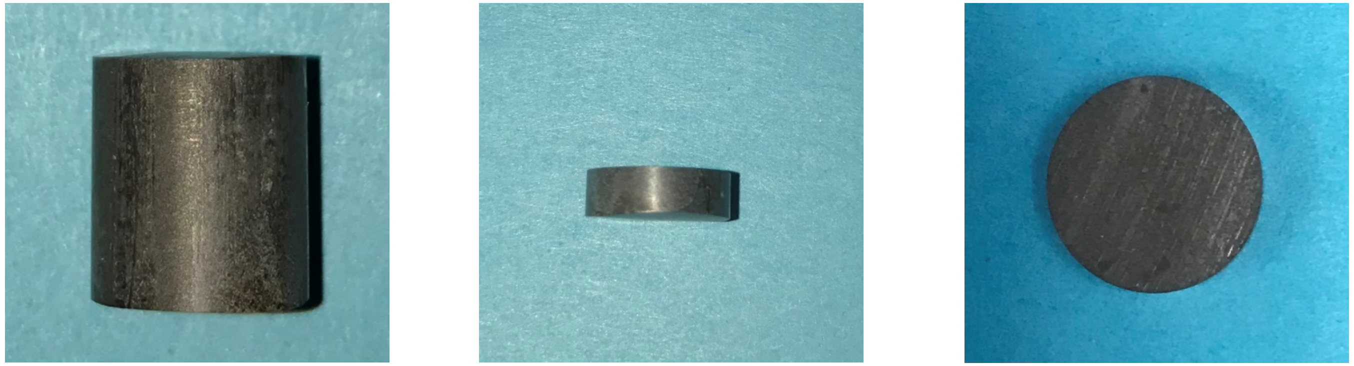
Evaluated hot pressing set up for fabrication of larger parts

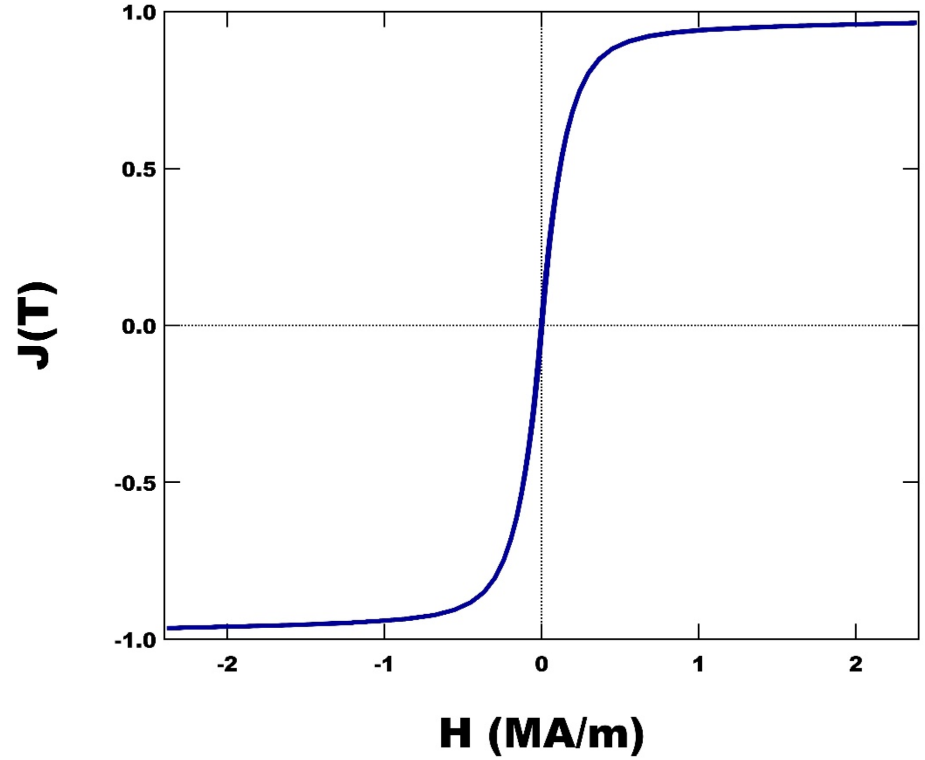


- Rated for 2300 °C and 50 tons of force
- Can operate under either N_2 or Ar atmosphere
- Custom die for the fabrication of larger parts on order

Technical Accomplishments and Progress

Hot pressed sample with > 70 vol.% Fe_4N

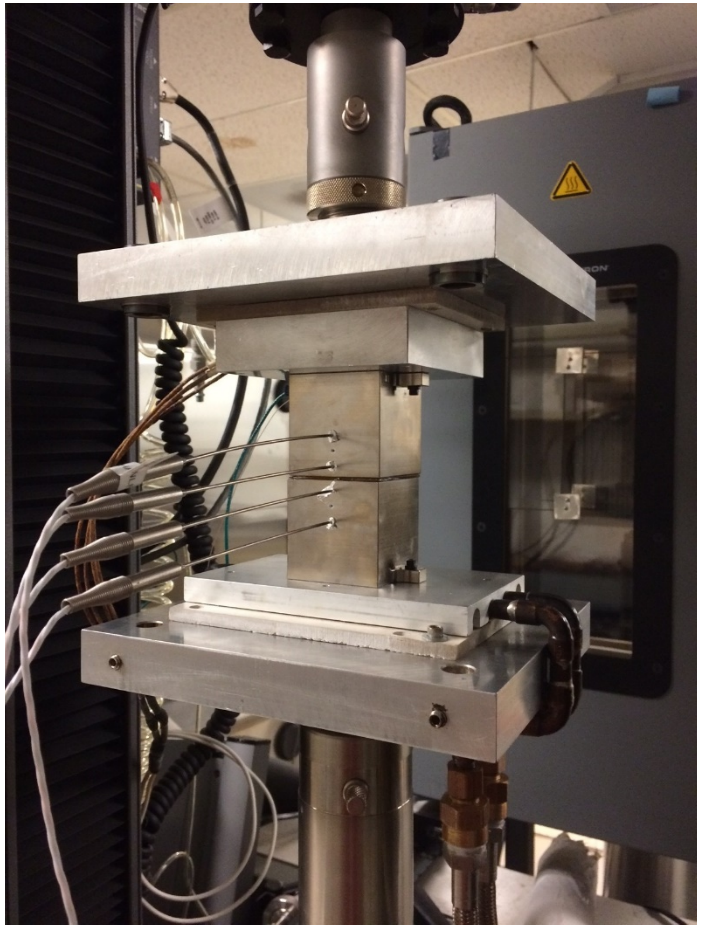




- 71.4 vol.% Fe_4N in epoxy
- BN spray (recommended by Ames Lab) working well as a release agent
- M_s = 144 Am^2/kg (bulk Fe Ms = 217 Am^2/kg)
- J_s = 0.96 T (Si steel J_s = 1.87 T and ferrite J_s ~ 0.5 T)
- Will see further increases in M_s and J_s as volume loading is increased

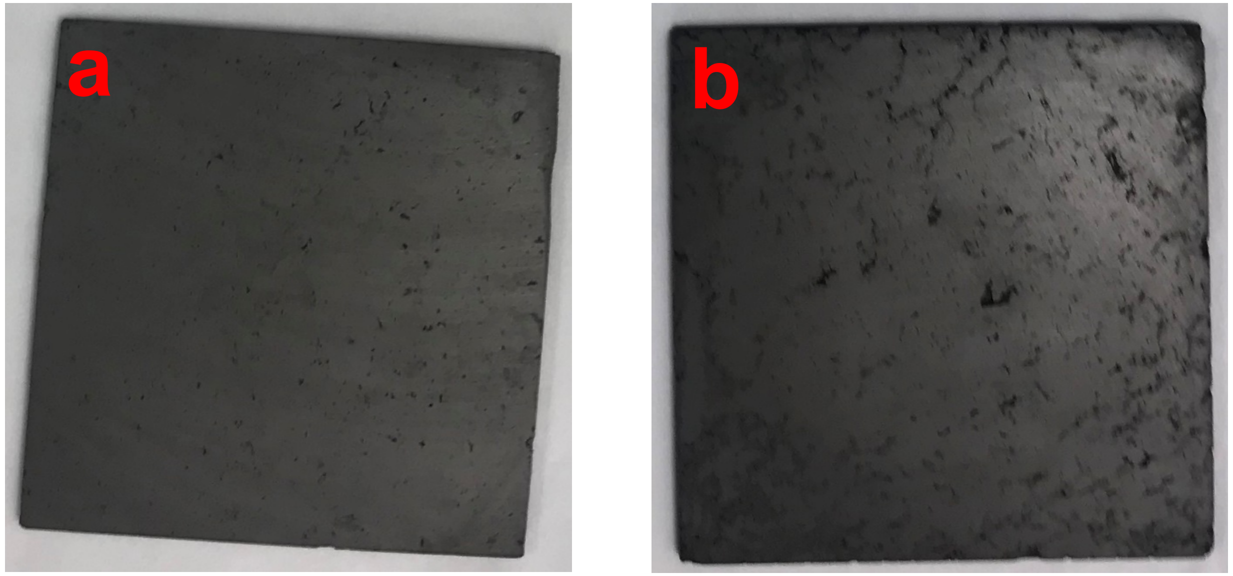
Technical Accomplishments and Progress

Fabrication of samples for thermal evaluation



NREL
NATIONAL RENEWABLE ENERGY LABORATORY

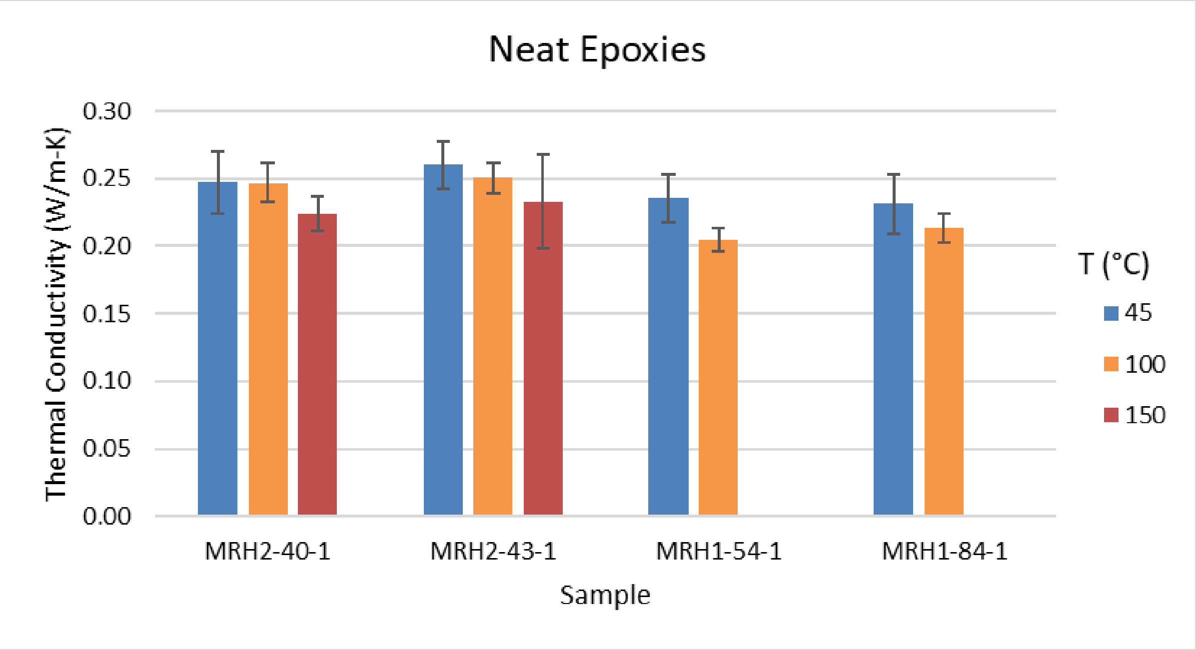
Bulk and interface thermal resistance of Fe_4N/epoxy sample under evaluation at NREL.

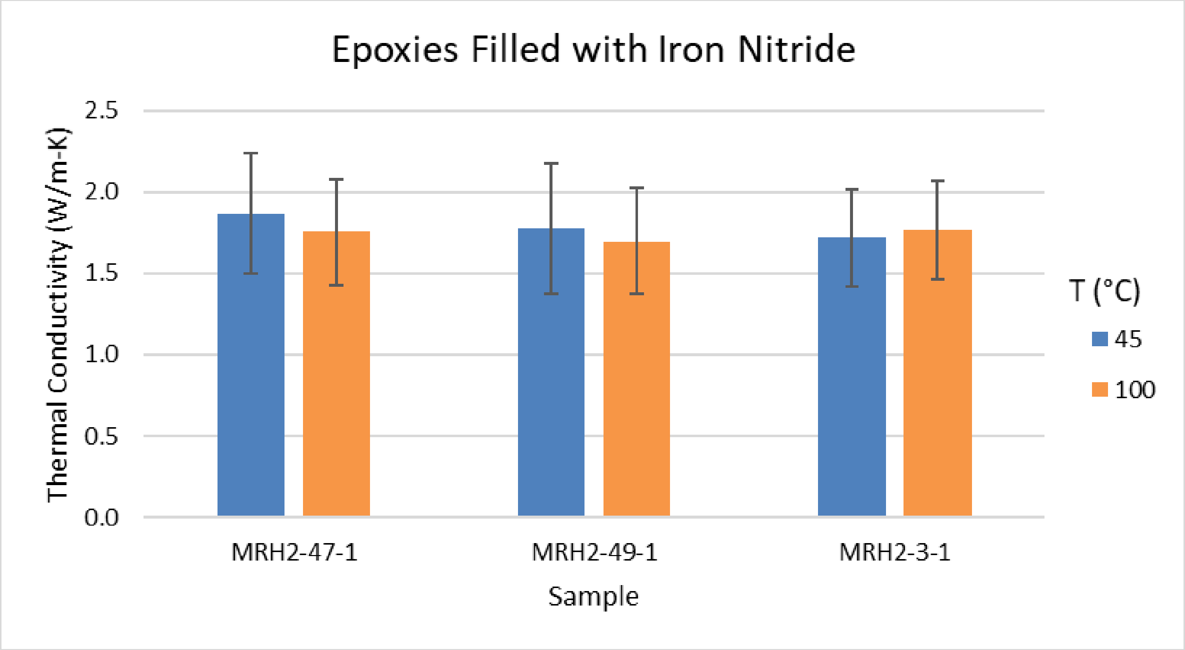


2” x 2” 60 vol.% Fe_4N/epoxy sample for thermal characterization

Technical Accomplishments and Progress

Thermal testing results





- Neat epoxy samples averaged 0.24 W/m·K
- 60 vol.% Fe_4N/epoxy samples averaged 1.8 W/m·K (Fe κ = 42 W/m·K)
- Possible temperature dependence in neat epoxy samples
- No apparent temperature dependence in Fe_4N based composite samples
- Cu, Fe metering blocks used to date; new data under collection with Al blocks

Responses to Previous Year Reviewers' Comments

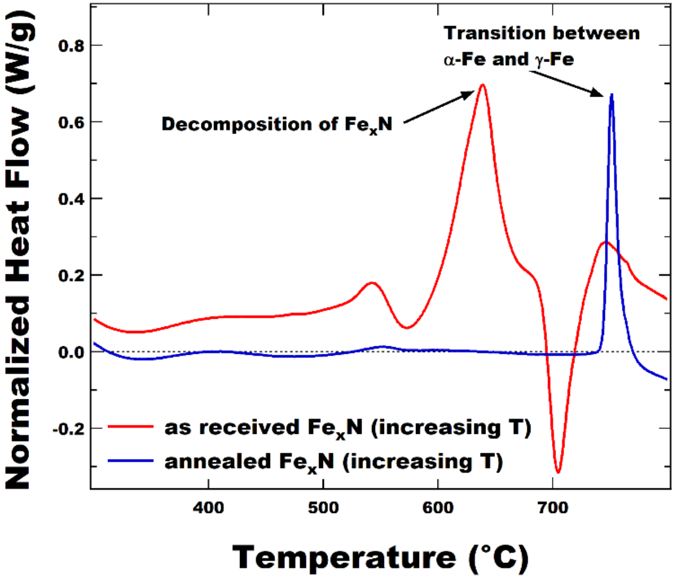
Q1: "The metallurgical characteristics of the γ'-Fe_4N compound should be addressed as well. In particular, this is not a thermodynamically stable compound at room temperature and pressure and will decompose and off-gas nitrogen at elevated temperature. This may influence the lifetime of the soft magnetics components. The rate of nitrogen evolution at the maximum operating temperature should be assessed. The stability of the compound under the hot-pressing conditions should also be evaluated."

- In regard to γ'-Fe_4N decomposition, please refer to the following differential scanning calorimetry (DSC) data presented as Fig. 6 in the publication below:

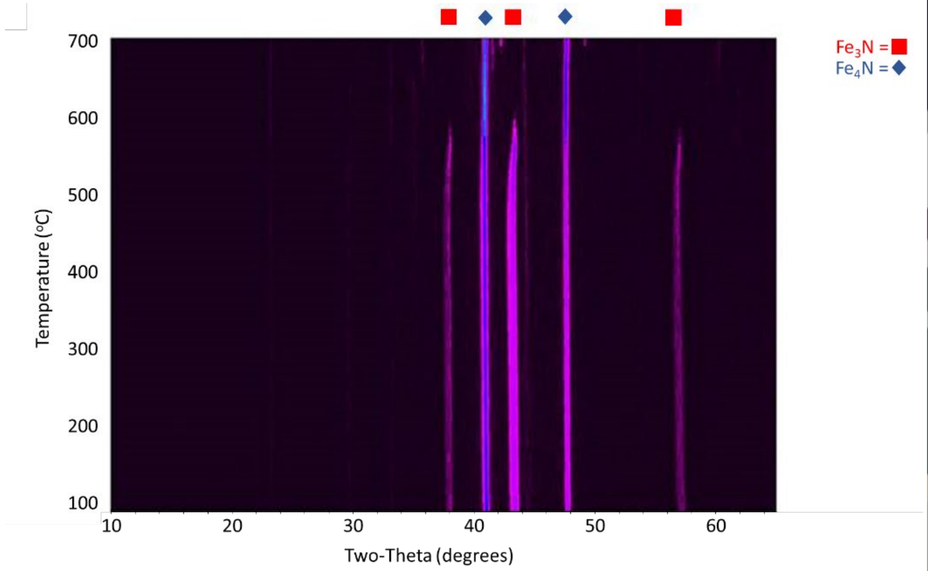
T. C. Monson, B. Zheng, R. E. Delany, C. J. Pearce, E. D. Langlois, S. M. Lepkowski, T. E. Stevens, Y. Zhou, S. Atcitty, E. J. Lavernia, "Soft magnetic multi-layered FeSiCrB–Fe_xN metallic glass composites fabricated via spark plasma sintering," IEEE Magnetics Letters 10, 1-5 (2019).

Additionally, please refer to the following temperature dependent X-ray diffraction (XRD) data presented during the 2019 Electrification AMR

DSC data for iron nitride



Temperature dependent XRD of iron nitride



Collaboration

PURDUE UNIVERSITY

ILLINOIS INSTITUTE OF TECHNOLOGY

OAK RIDGE National Laboratory

AMES LABORATORY Creating Materials & Energy Solutions U.S. DEPARTMENT OF ENERGY

NREL NATIONAL RENEWABLE ENERGY LABORATORY

- Purdue University (Scott Sudoff) – Motor design, prototyping, and testing
- IIT – Design, construction, and dynamometer testing of prototype electrical machines
- ORNL – High-fidelity multiphysics material models for electric motors, motor design
- Ames – Additional expertise in magnetic material fabrication, processing, and characterization
- NREL – Advanced packaging, reliability, prognostics, thermal management, thermal & mechanical testing

Remaining Challenges and Barriers

- Ensuring adequate mechanical strength for > 20,000 rpm motor operation
- Achieving sufficient magnetic particle volume loading for high performance in non-rare-earth electric motor designs
- Ensuring epoxy T_g > 150 °C ✓

Proposed Future Research

Remaining FY20 Tasks

- Evaluate eddy current losses > 70 vol.% Fe_4N/epoxy composites.
  - Will require hot pressed toroids of > 70 vol.% Fe_4N/epoxy composites

Research Beyond FY20

- Improve Fe_4N/epoxy composite based on evaluation of FY21 results
  - Via hot pressing, achieve Fe_4N vol.% > 80%
  - Via hot pressing, achieve $\mu_r > 100$
  - Make additional comparisons to state of the art materials (e.g. Si steel and soft magnetic composites)
- In collaboration with NREL, evaluate mechanical properties of Fe_4N composites
- Demonstrate Fe_4N/epoxy composite in prototype motor designs

* Any proposed future work is subject to change based on funding levels

Summary

Relevance: Improved soft magnetic materials will enable high performance non-rare-earth motors

Approach: Develop high magnetization, low loss iron nitride based soft magnetic composites for electrical machines

Technical Accomplishments

- Built and tested lab scale hot pressing setup
- Fabricated 71 vol.% Fe_4N in epoxy composite
  - J_s = 0.96 T (Si steel J_s = 1.87 T and ferrite J_s ~ 0.5 T)
- Thermal conductivity measurements near complete
  - 60 vol.% Fe_4N/epoxy samples averaged 1.8 W/m·K (Fe κ = 42 W/m·K)
  - Neat epoxy samples averaged 0.24 W/m·K
- Further improvements expected as we increase vol.% of Fe_4N!

Technical Back-Up Slides