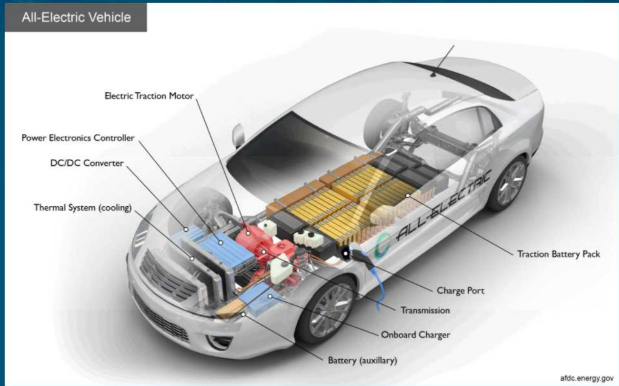
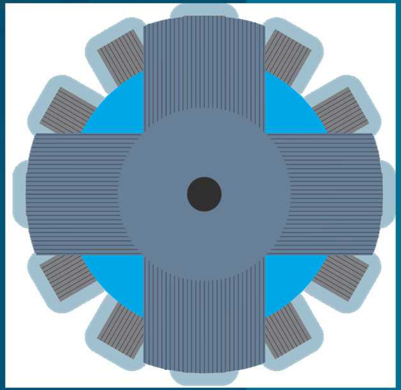
SAND2020-5026PE

Isotropic, Bottom-Up Soft Magnetic Composites for Rotating Machines





2020 DOE Vehicle Technologies Office Annual Merit Review

Todd C. Monson, PI, Electric Motors

Sandia National Laboratories

June 2, 2020

Project ID: elt216

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Overview

Timeline

- Start – FY19
- End – FY23
- 30% complete

Budget

- Total project funding
  - DOE share – 100%
- Funding for FY19: $125k
- Funding for FY20: $150k

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

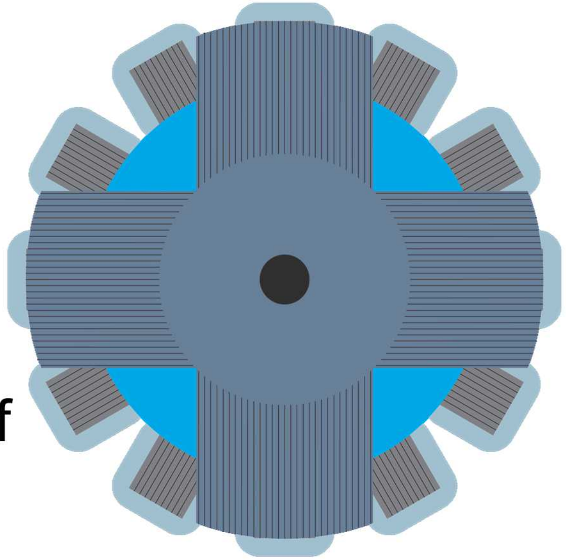
- ORNL, NREL, Ames Lab
- Purdue University, Illinois Institute of Technology (IIT)
- Project lead: Sandia Labs
  - Key Sandia staff: Jason Neely, Jack Flicker, Bob Kaplar, Tyler Stevens, CJ Pearce, Melinda Hoyt, Robert Delaney, and many others…

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 motor design that doesn't require permanent magnets

Courtesy of Scott Sudhoff at Purdue



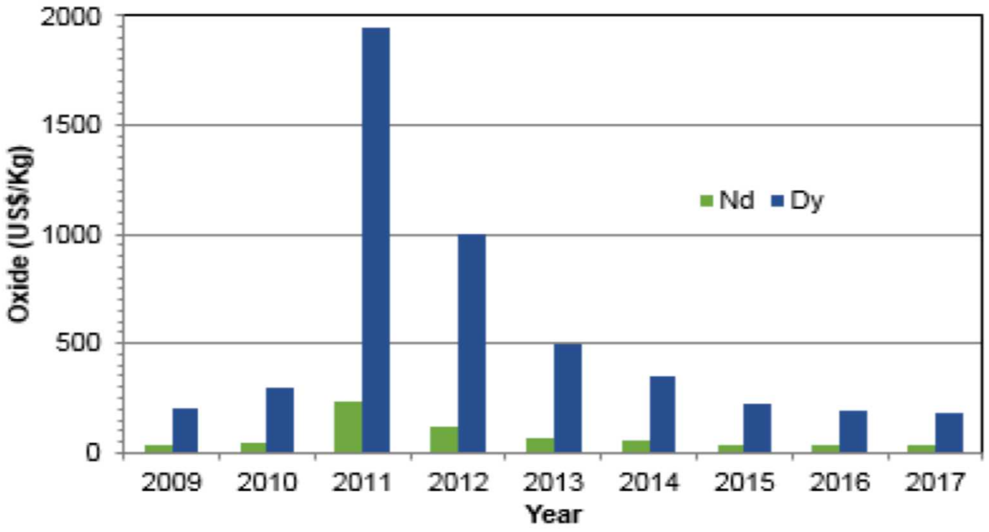


Figure 9. Rare Earth Metal Prices Track Oxides Very Closely
Source: Metal Pages courtesy of Critical Materials Institute

As seen in Oct. 2017 EETT Roadmap

Milestones

Milestone, Keystone 2 – Electric Motors	
FY20: 2.1 Demonstrate a net-shaped, high-volume loading, iron nitride soft magnetic motor component and evaluate its saturation magnetic polarization and eddy-current losses. **(On schedule)**	9/30/2020
FY21: 2.1 Demonstrate a net-shaped, iron nitride soft magnetic motor component with 80 vol.% loading of Fe_4N	9/30/2021

Progress towards milestone to date:

- Demonstrated 65 vol.% loading iron nitride/epoxy composite
- Started hot pressing iron nitride/epoxy composites to further increase volume loading
- 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
- Use of abundant elements (Fe and N) will keep costs low

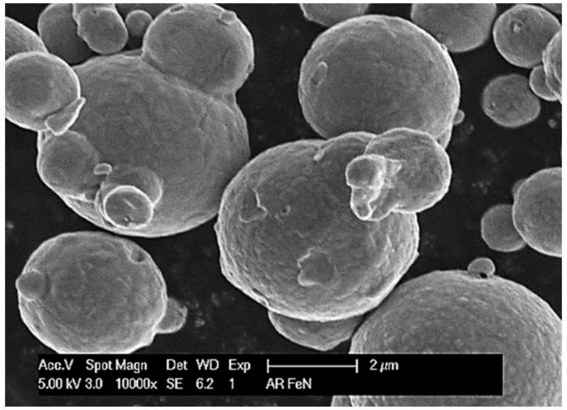
Element	Mass fraction (ppm)
Hydrogen	739,000
Helium	240,000
Oxygen	10,400
Carbon	4,600
Neon	1,340
Iron	1,090
Nitrogen	960
Silicon	650
Magnesium	580
Sulfur	440

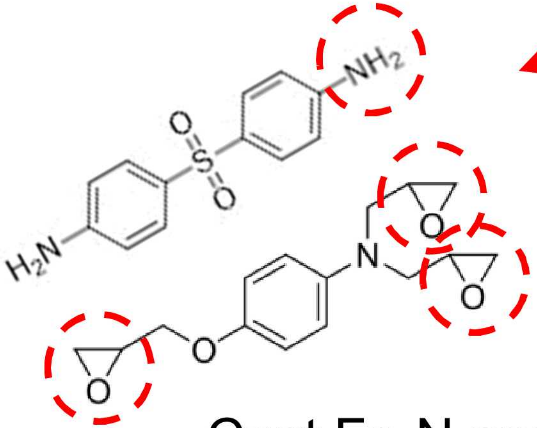
From Croswell, Ken (February 1996). Alchemy of the Heavens. Anchor. ISBN 0-385-47214-5.

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

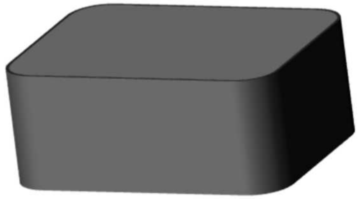


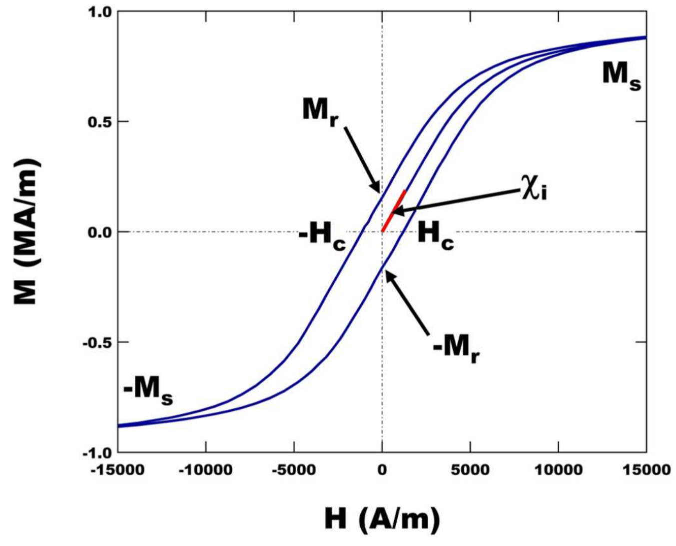


4-aminophenyl sulfone
&
N,N-diglycidyl-4-glycidyloxyaniline (NND)

Coat Fe_4N and mix with epoxy monomers

- Pour into 3D printed mold and cure into inductor/motor part
- Hot press to increase density and loading factor
- Results in a net-shaped part (no machining required)





Evaluate and test

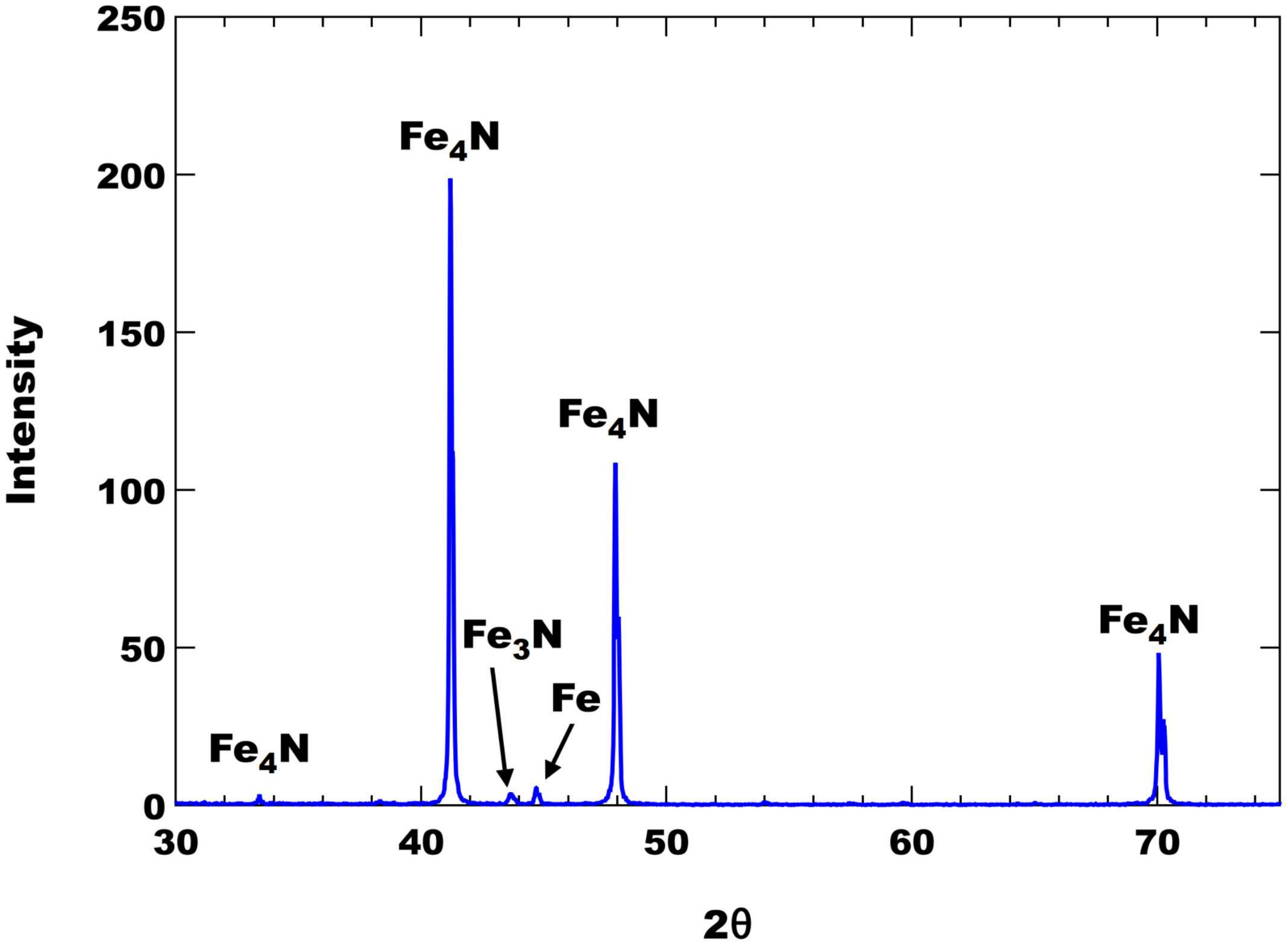
Approach – Epoxy Robustness in Motors

- 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

Production of phase pure γ’-Fe_4N powder



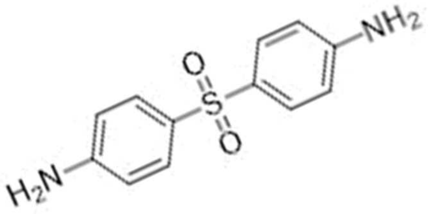
Fe_4N wt % = 96.2(6.7)
Fe_3N wt % = 2.3(0.2)
Fe wt % = 1.5(0.1)

- Easy heat treatment for commercially available mixed phase iron nitride powder
- Nearly phase pure result
- Trace amounts of Fe_3N and Fe not a significant issue
  - These compounds are also magnetic

Technical Accomplishments and Progress

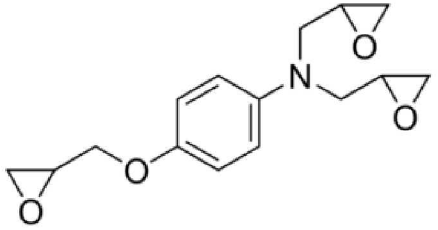
Net-shaped Fe_4N/epoxy composites fabricated

- Fabricated toroids for characterization (also representative of inductors) and varying scales of a rotor tooth from a ORNL motor design
- Epoxy based chemistry successfully demonstrated using 4-aminophenyl sulfone, trimethylolpropane triglycidyl ether (TTE), and Fe_4N
- Have also fabricated composites using N,N-diglycidyl-4-glycidyloxyaniline (NND) as the tri-epoxide



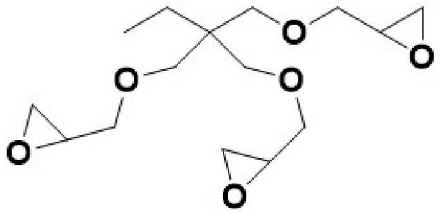
4-aminophenyl sulfone

+



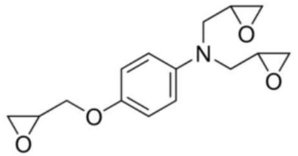
N,N-diglycidyl-4-glycidyloxyaniline (NND)

or



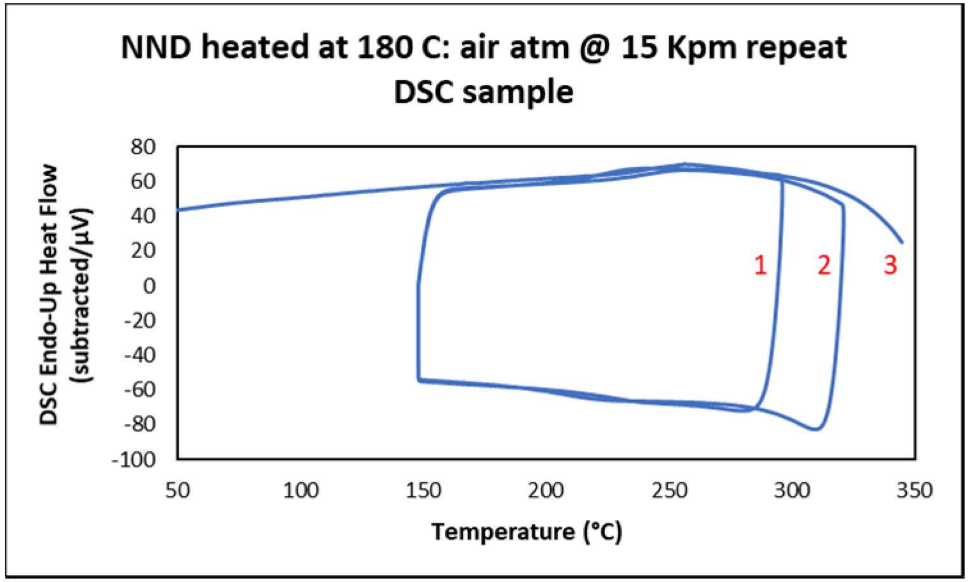
trimethylolpropane triglycidyl ether (TTE)

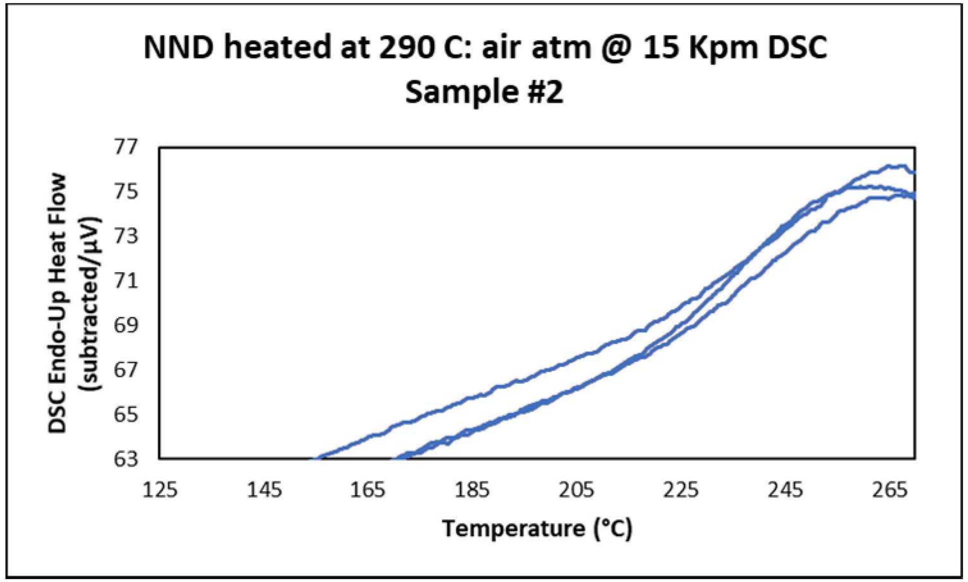
Technical Accomplishments and Progress



Epoxy thermal properties

- Differential scanning calorimetry (DSC) scans for the neat NND epoxy:
  - NND epoxy cure was incomplete after heating to 135 °C and still incomplete after heating to 180 °C
  - T_g for the fully cured epoxy is 245 °C
  - Cure limit reached when repeated DSC heating cycles leave T_g unchanged (as in TTE, not shown) or at onset of sample decomposition (as seen with NND).





Technical Accomplishments and Progress

NND based epoxy can operate well above 150 °C

Epoxy	T_g	Final Cure Temp.	Mass Loss in DSC
TTE	127 °C	180 °C (2 hrs.)	≤1%
NND	249 °C	255 °C (2 hrs.)	≤2%

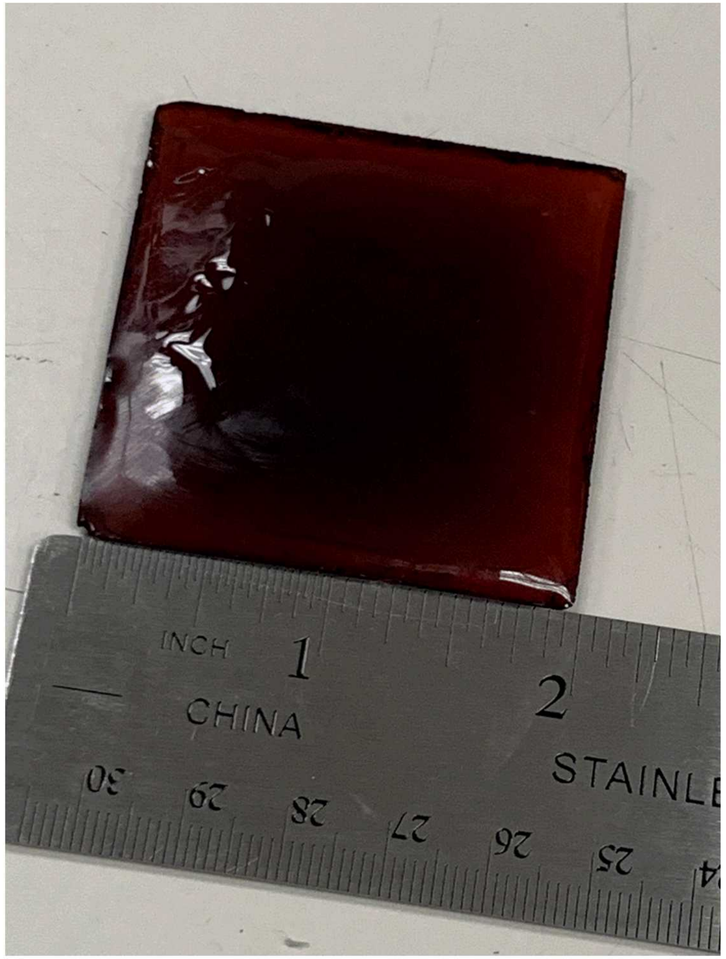
DSC Summary for TTE and NND Epoxies after heating overnight at 180 ° C

- The higher temperature T_g compared to the TTE epoxy due to the greater structural rigidity lent to the NND epoxy by its benzene ring.
  - Will lead to greater mechanical strength
- NND based epoxy's T_g of 249 °C significantly exceeds 150 °C target operating temperature

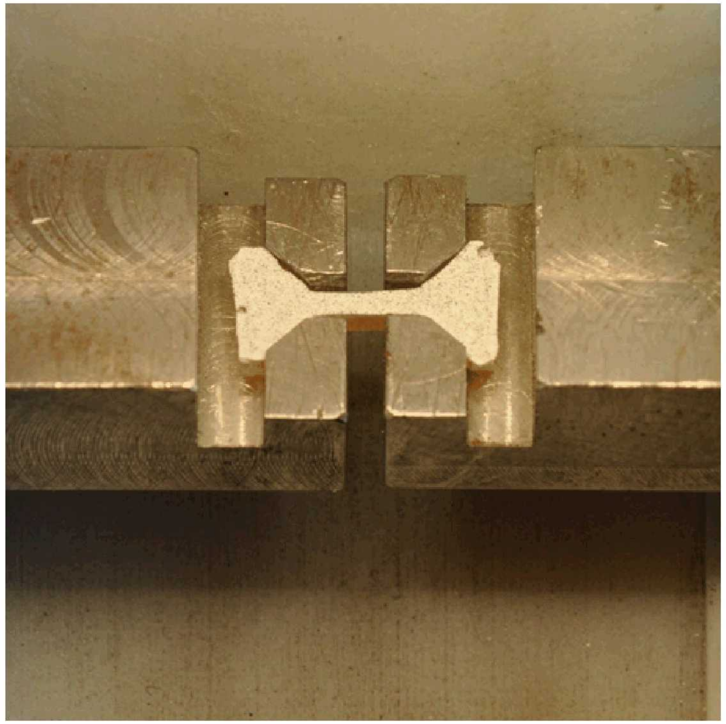
Technical Accomplishments and Progress

Fabrication of samples for thermal and mechanical testing

Experimental setup for evaluating motor material bulk and interface thermal resistance up to 200°C.



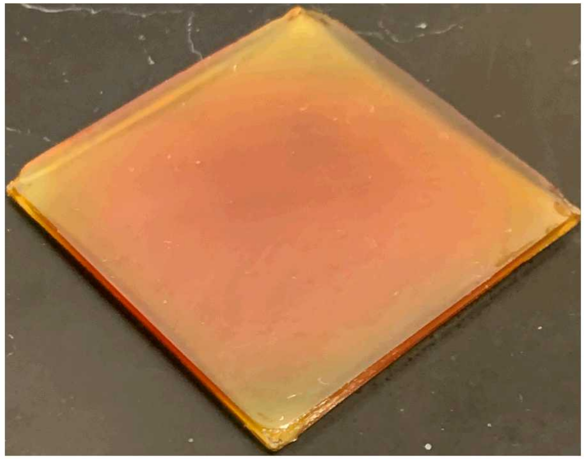
Neat 2" x 2" epoxy sample for thermal characterization

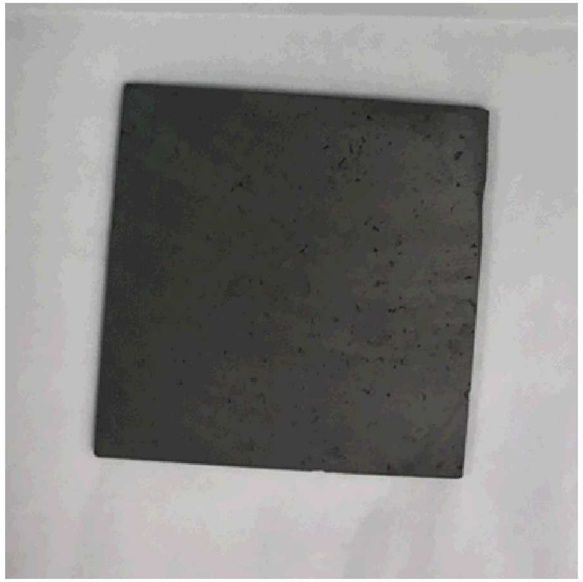


Example of composite sample undergoing mechanical testing

Technical Accomplishments and Progress

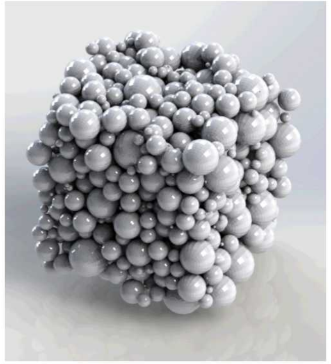
Thermal testing of epoxy based composites



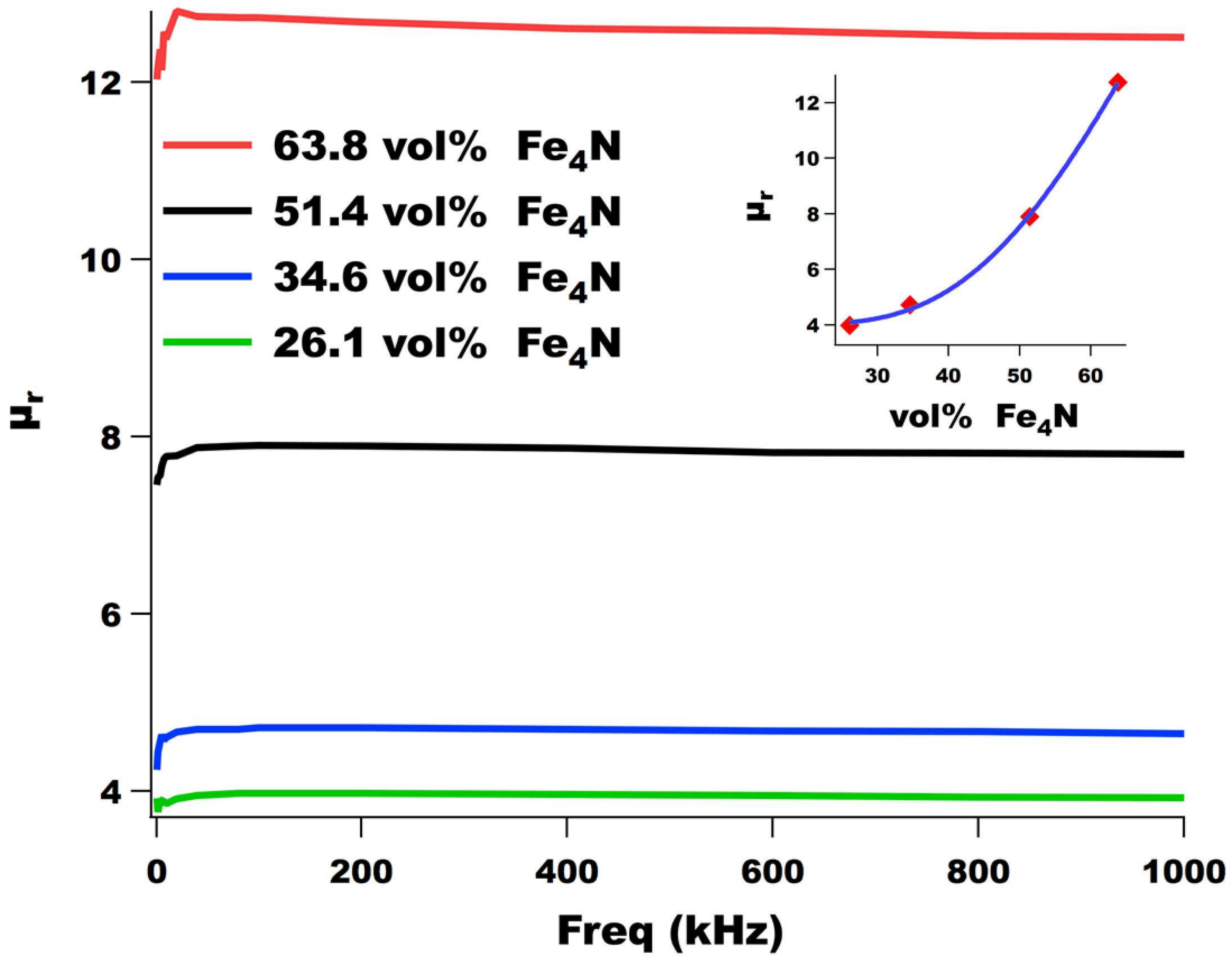


- Neat epoxy and 65 vol% Fe_4N in epoxy samples at NREL
- Testing delayed due to Coronavirus
- Additional Fe_4N/epoxy samples under production for better statistics
- “Dog bone” geometry sample for mechanical testing decided in collaboration with NREL
  - “Dog bone” samples under production

Technical Accomplishments and Progress



Sample permeability is increasing exponentially



- μ_r increases exponentially with Fe_4N vol.% loading
- Hot pressing will enable further significant increases in μ_r
- Additional increases possible through:
  - Particle morphology improvement
  - Annealing and/or curing in a magnetic field
- Magnetic composite inductor achieved 1% increase in efficiency over COTS inductor when tested in a 3.3 V synchronous buck converter circuit

Responses to Previous Year Reviewers' Comments

Q1: "It was not clear that the project has a good handle on the mechanical strength needed from the epoxy to hit 20,000 rpm. The reviewer asked if the new material will be evaluated based on a design that is optimized for this material; and if the 150°C temperature limit is the right limit for a motor design based on this material."

"The reviewer asked how advantageous SMC would be, because motors operate at much lower frequencies."

"It was not clear to this reviewer what the expected improvements with the developed materials are, compared to other soft magnetic composites that were previously developed."

- Slide 7 provides several references demonstrating epoxy robustness in high speed machines and flywheels
- Mechanical testing of "dog bone" structures is underway
- Bottom-up composite design (direct bonding of epoxy to iron nitride and strong cross-linking of matrix will lead to enhanced composite strength)
- Retention sleeves are being used already in some high speed designs to provide additional mechanical strength
- Using Fe_4N, we predict enhanced magnetic performance in comparison to silicon steel and soft magnetic composites not just at very high frequencies (such as 100 kHz) but also over ranges relevant to high-speed motors (1-10 kHz).
- Our Fe_4N/epoxy composites will also prove extremely beneficial as inductor cores for power electronics (Keystone 1) where operating frequencies as high as 1 MHz are anticipated

Collaboration

- 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

- Demonstrate a net-shaped, high-volume-loading, iron nitride soft magnetic motor component and evaluate its saturation magnetic polarization and eddy-current losses (end of FY20 milestone).

Research Beyond FY20

- Improve Fe_4N/epoxy composite based on evaluation of FY20 results (volume loading, eddy current loss, thermal & mechanical properties)
  - Via hot pressing, achieve Fe_4N vol.% > 80%
  - Via hot pressing, achieve $\mu_r > 100$
- 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

- Production of phase pure γ'-Fe_4N powder demonstrated
- Net-shaped Fe_4N/epoxy motor components and toroids fabricated
- Epoxy matrix has a T_g of 249 °C (well above 150 °C requirement)
- Thermal conductivity samples completed and mechanical samples started
  - NREL will begin testing after stay at home orders are relaxed
- Relative permeability is increasing exponentially with Fe_4N volume loading
  - Hot pressing will enable further significant gains in μ_r

Technical Back-Up Slides

Reviewer-Only Slides

Publications and Presentations

Publications

- Z. Fu, B.E. MacDonald, A.D. Dupuy, X. Wang, T.C. Monson, R.E. Delany, C.J. Pearce, K. Hu, Z. Jiang, Y. Zhou, J.M. Schoenung, W. Chen, E.J. Lavernia, “Exceptional combination of soft magnetic and mechanical properties in a heterostructured high-entropy composite,” Applied Materials Today, **15** (2019). DOI: 10.1016/j.apmt.2019.04.014
- E.D. Langlois, J. Watt, D.L. Huber, M. McDonough, T.C. Monson, J. Neely, “Design and evaluation of nano-composite core inductors for efficiency improvement in high-frequency power converter,” Proceedings of the 35th Annual IEEE Applied Power Electronics Conference & Exposition.

Presentations

- T.C. Monson, “Bottom-up soft magnetic composites for electric vehicles,” The Albuquerque IEEE Joint Chapter of AP/MTT/EMC/NPS, Albuquerque, New Mexico, January 2020.
- Invited talk: T.C. Monson, “Advancements in soft magnetic materials for future energy needs,” American Physical Society March Meeting, Denver, Colorado, March 2020. *Cancelled just prior to start due to Coronavirus

Critical Assumptions and Issues

- An epoxy composite can be designed with a T_g > 150 °C and the mechanical strength necessary for operation at > 20,000 rpm
- A Fe_4N/epoxy composite can achieve a sufficient magnetization for permanent magnet free motor operation