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Sandia National Laboratories

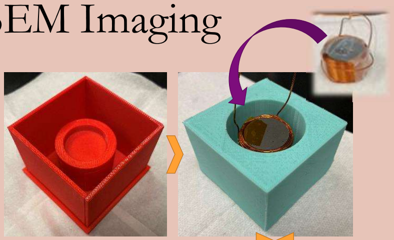
Exploring Iron Nitride-Based Soft Magnetic Composites for Electric Vehicle Technologies

Melinda Hoyt, Charles Pearce, Sophia Shaar, Sydney Fultz-Waters, Gillian Falcon, Robert Delaney, and Todd Monson
Sandia National Laboratories, Albuquerque, NM 87185

Abstract

Soft magnetic composites (SMCs) may improve the peak and specific power of electric motors while answering the need for cost reduction and replacement of rare earth materials. DOE 2025 goals target a peak power of 100 kW and a specific power of 50 kW/L in a motor operating at >20,000 rpm. This increased power needs to come at a cost of 3.3 \$/kW. SMCs offer a low-cost alternative to rare earth permanent magnets. Conventional soft magnetic materials face decreased motor efficiency at high rotational speeds due to eddy current losses. However, SMCs feature an insulating matrix. The insulating matrix in SMCs may decrease eddy current losses and increase electrical resistivity enough to permit motors to operate with high efficiency at high rotational speeds. The authors' project work has explored iron nitride-based SMCs because γ'-Fe_4N has a higher saturation magnetic polarization and electrical resistivity than silicon steel, a conventional soft magnetic material. The project entailed optimizing the chemistry, preparation, and cure of the iron nitride-based SMCs. Net-shaped iron nitride-based SMCs were prepared by curing in silicone molds. These materials were characterized by differential scanning calorimetry (DSC), scanning electron microscopy (SEM), magnetometry, thermal conductivity testing, and tensile testing.

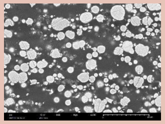
Synthesis & SEM Imaging



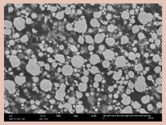
Prototype $Fe_{2\text{-}4}N$/epoxy bobbin inductors were made by preparing the core, winding the core, and adding the yoke. The core and yoke were cured in silicone rubber molds, which were prepared using 3D-printed antimolds. The net-shaped core and yoke were polished after curing to remove rough edges.

Polished samples with varying iron nitride content were imaged by SEM to assess $Fe_{2\text{-}4}N$ particle size vs. milling and dispersion in the epoxy matrix. Measurements revealed 1-10 μm particles with homogeneous dispersion in the epoxy for standard synthesis methods.

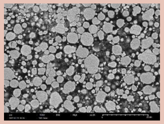
Polished 30 vol% (Left) & 65 vol% (Right) iron nitride in epoxy SEM samples.



40 vol% iron nitride in epoxy. Milled precursors 18 min. (BSE, x2.5k, 1 mm WD).



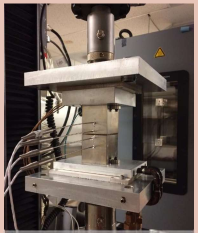
50 vol% iron nitride in epoxy. Milled precursors 18 min. (BSE, x2.5k, 1 mm WD).



65 vol% iron nitride in epoxy. Milled precursors 18 min. (BSE, x2.5k, 1 mm WD).

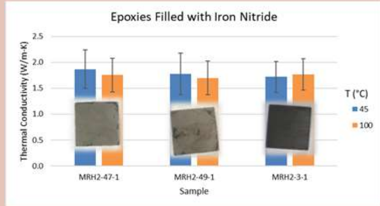
Thermal Testing

Two epoxies were studied for use in fabricating the iron nitride SMCs. DSC measurements showed that the first epoxy (TTE) had a T_g of 127 °C while the second (NND) had a T_g of 249 °C. The final SMC required a T_g above 150 °C for sustained operation in a motor. Thus, NND was chosen for the final SMC fabrication.



Bulk and interfacial thermal resistance testing at NREL.

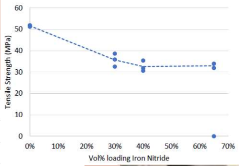
Samples were sent to NREL for thermal conductivity testing. The neat TTE and NND epoxies had thermal conductivities of 0.2 to 0.26 W/(m·K). Initial results for 61.5 and 65.0 vol% iron nitride in TTE SMCs showed thermal conductivities in the range of 1.5 to 2.0 W/(m·K). Further measurements are underway on neat NND and 65 vol% iron nitride/NND composites cured at high temperature (i.e. 255 °C).

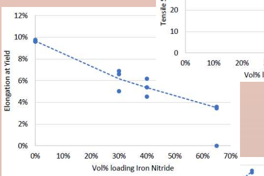


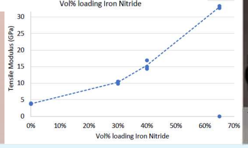
Samples MRH2-47-1 and MRH2-49-1 are 61.5 vol% $Fe_{2\text{-}4}N$/epoxy, while MRH2-3-1 is 65.0 vol% $Fe_{2\text{-}4}N$/epoxy. Data collected at NREL.

Mechanical Testing

NREL also performed tensile tests on neat NND, as well as 30, 40, and 65 vol% iron nitride in NND dog-bone samples. The data for the neat epoxies correlated with typical epoxies. Sample brittleness increased with iron nitride loading. The SMCs had an ~18 MPa weaker tensile strength than the neat epoxy.



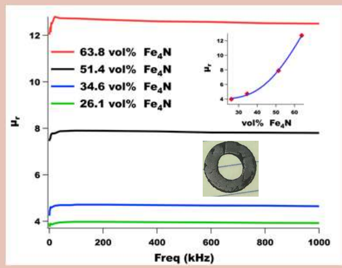




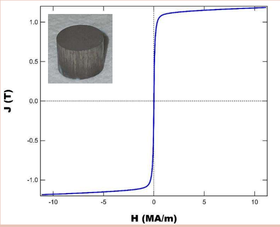
Tensile testing setup at NREL with a 65 vol% iron nitride in NND dog-bone.

Magnetometry

B-H analyzer measurements on toroids showed that relative magnetic permeability (μ_r) increased exponentially with vol% Fe_4N in NND epoxy. The Fe_4N loading was increased to > 75 vol% with hot-pressing. Saw a 1% increase in efficiency for a magnetic composite inductor compared to a commercial-off-the-shelf inductor upon testing in a 3.3 V synchronous buck converter circuit.



VSM measurements on 75.3 vol% Fe_4N/NND revealed a saturation magnetic polarization of J_s = 1.19 T, which lies between silicon steel (J_s = 1.87 T) and ferrite (J_s ~ 0.5 T). Polarization (J) is related to magnetization (M) by the equation $J = \mu_0 M$. Magnetization measures atomic magnetic moment density. Therefore, Fe_4N/NND SMCs surpass the magnetization of common permanent magnets and approach conventional soft magnetic materials.



Optimal magnetic properties will be sought with higher vol% loading of Fe_4N in the epoxy. Prototype motor parts will be made from the Fe_4N/NND composite.

Acknowledgements

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