Research in Soft Magnetic Materials at NASA Glenn

Randy Bowman

NASA Glenn Research Center

August 10th, 2017
Establishment of Magnetics Research Activities

Magnetic materials have not historically been an active research topic at NASA GRC

Motivation for Entering the Field:

Center-Level Motivation – Develop GRC expertise and capabilities in magnetic materials and initiate a presence in the application and research communities to support the future direction of NASA GRC, which emphasizes more vehicle electrification and “green” power generation and power conversion technologies.

Specific Tasks - Support the needs of the Advanced Air Transport Technology (AATT) Project by developing more capable soft and hard magnetic materials for use in motors, power conversion, and control circuitry for the Hybrid electric program.

Support and Main Activities:

• Thus far, the AATT project has provided the majority of the funding needed to establish the magnetics program at GRC.
• Program has been highly focused thus far on scale-up, manufacturability and component fabrication to support hybrid electric concepts.
• Also pursuing fundamental research on material behavior and alloy development.

• Funding has been augmented by other internal and external programs.
• Producing hardware and testing for external programs.
• Establishing a commercialization path with industry for these materials.
Establishment of Magnetics Research Activities

The timing of NASA’s interest in magnetics was fortuitous. NETL and CMU groups were looking for a location to host the large melt spin casters.

**Equipment**

3-kg caster – Returning this unit to operational status was key to producing large-scale components. This is necessary for determining the behavior of developmental alloys under relevant operating conditions.

**Partnerships**

Gave NASA access to the corporate knowledge that the NETL/CMU teams had accumulated and allowed us to contribute quickly.
Rationale for Material Investment

...Weight, Weight, Weight

Power system weights are very sensitive to
- Electrical Efficiency
- Component Specific Power
- Distribution Voltage

Key Material Technologies
- Wide band gap semiconductors—increasing frequency increases efficiency
- Magnetic Materials—increasing frequency and reducing component losses
- Insulation Materials—enabling higher distribution voltage
- Advanced Conductors—high risk / high payoff investment in new systems

Ref: Jansen et al., AIAA, 2016
Enabling Materials for Electrified Propulsion

Power System Weight Drivers

- Improved Power Density
  - OGA investment
  - CAS investment

- Magnetic Materials
  - Distribution Cables
    - AATT conductors
    - CAS transmission cables

- Insulation Materials
  - Elec. Machines
    - AATT Design
    - AATT Insulation
    - AATT Conductors
    - CAS Manufacturing

- High Efficiency Component Development
  - Inductor Filters – for 20 kHz ripple suppression in motor controllers
  - DOE sponsored PV-to-grid integration transformer

- High Conductivity Materials
  - Survey organic/inorganic composite solutions
  - Quantify thermal bottlenecks
  - Enable novel materials/engineering solutions
  - Theoretically CNT or graphene has high conductivity
  - Limited evidence of specific conductivity improvements
  - Looking at separated “metallic” CNT
Soft magnetic materials are considered to be a key technology for closing the hybrid electric design space.
**Objective:** Develop soft magnetic materials that possess low losses at high switching frequencies

Energy conversion/transformation requires the use of soft magnetic materials. Important for motors, filters, transformers, etc.

Faraday's Law of induction:

\[ \epsilon = -\frac{d\Phi}{dt} \]

where:
- \( \epsilon \) is the electromotive force
- \( \Phi \) is the flux density
- \( B \) is the magnetic field
- \( A \) is the area
- \( \mu_0 \) is the permeability of free space
- \( H + M \) is the magnetic flux density

**Approach:** Develop and produce nanocomposite materials fabricated via rapid solidification casting, followed by post-processing, to produce tailored magnetic properties

These amorphous and nanocrystalline materials bridge the large gap between low frequency steels and high frequency oxides

Most devices/components benefit from higher operating frequencies, which results in higher power densities (higher output and lower volume)

But electrical losses (resulting in internal heat generation) also increase with frequency.

- Cast ribbon
- Strain annealing
- Coated transformer core
Amorphous Ribbon Production

Production-scale and research-grade rapid solidification casters

Rapid solidification produces low-loss magnetic materials due to nano-size microstructural features

Small caster is useful for alloy development and for alloys that require protective environments

Casting produces 20-micron thick, 25 mm-wide ribbon

Large (5-kg) Rapid Solidification Caster

The ability to cast large quantities of wide ribbons gives GRC unique capability in the field.
Amorphous and Nanocomposite Ribbons
Produced at GRC

Very Pliable in As-Cast State

Wind these ribbons into the desired shapes for fabrication of components such as transformers, inductors, motor stators, etc.
Enabling Materials for Electrified Propulsion

Establish capability for complete cycle of alloy development-to-component development for nanocrystalline soft magnetic materials
Technologies Under Development for AATT Project

One milestone was to replace commercial inductor with a low-loss version capable of operating at 20 kHz for the AATT General Intelligent Motor Controller (GMIC).

GMIC specified commercial inductor is fairly bulky, is mounted on a dedicated circuit board, and requires a heat sink due to excess heat that is generated. Is the 2nd largest parasitic heat source in the system.

Proposed “bead” inductor made from GRC-developed and fabricated material is conformable and produces 20 times less waste heat, eliminating the need for a dedicated circuit board and significantly reducing the overall system cooling requirements.

Inductor has been delivered to the controller team for testing on a testbed system.
In-House Magnetic Modeling

• As magnetic component geometries become more complex, predicting the system response based on the measured material properties will become crucial.
• COMSOL finite element modeling is being used to predict losses under relevant conditions.

Actual core (without windings)
Modeled part with windings on one limb.
Representation of magnetic flux lines surrounding the part
Magnetic flux density in the core
Model of a 3-phase inductor.
Timeline of Magnetics Program

2014

- 0.5 FTE, $0K: Began establishing magnetic research capabilities and identifying how these materials can enable electrified aircraft propulsion

2015

- 1 FTE/$250K: arranged to transfer custom 3-kg caster to NASA to get nanocrystalline materials across manufacturing “valley of death”
- Received disassembled caster
- Completed initial characterization lab build-up
- Reassembled caster and performed first run.

2016

- Won $500K/3-yr DOE proposal (RSAA) for photovoltaic transformer development
- Established Space Act with DOE for inductor development

2017

- New CS hire in magnetics
- Delivered advanced inductor to AATT motor controller team

Finalized commercialization plan for 150-kg caster with industry and university partners
Other High Impact Applications And Future Growth Areas

Other than the specific AATT inductor application, these materials can have a large impact in other power applications by reducing size and increasing efficiency.

Funded by DOE for photovoltaic-to-grid power conversion via advanced transformers.

Motor stators for vehicle electrification and generators.

Power = Voltage • Current or Torque • Rotation speed

Power Transformer Market ~$10B

Electric Motor Market ~$90B
Facilities

Large (5-kg) Rapid Solidification Caster
Facilities

Small-Scale (50-g) Caster

- Produces 100 ft of 25-mm wide ribbon.
- Allows for fabrication of magnetic materials in inert environment.
- Rapid turn-around, several runs a day possible.
**Facilities**

**Vibrating Sample Magnetometer**

1) Variable temperature measurements from to 4.2K to 1000°C.
2) Can measure both hard and soft magnetic materials.
3) VSM directly measures the intrinsic moment (or magnetization) of a sample from which one can calculate the magnetic induction $B$, ($B = H + 4\pi M$).

**Permeameter**

Fully characterizes soft magnetic components over a wide range of frequencies using toroidal or ribbon samples.

**Core Testing System**

Characterization of soft magnetic components under relevant conditions.

**Custom Core Loss Measurement System**

**Hysteresigraph**

Facilities

• Kerr-Microscope & Magnetometer system is a facility for the visualization of magnetic domains.

• Direct observation of magnetic domain motion is key to understanding losses.

• High temperature measurements to 850 K (577 °C).

• Initial plans are to use this capability for alloy development and component-level measurements of transformer inductor cores (DOE SunLamp program).
• System has easily reconfigurable source, optics, and stages.
• Currently capable of Cu, Co, and Mo sources.
• Ideal for phase analysis of nano-sized microstructural features in either reflective or transmission modes of crystalline or amorphous structures.
• 45-sample unattended operation
• High temperatures measurements up to 2300°C.
• Capable of performing investigations that previously required synchrotron beam time.