Soft Magnetic Alloy Advanced Manufacturing Through In-Line Processing (Concept #1)

Metal / Oxide Nanocomposite Materials for High Frequency and High Power Magnetics (Concept #2)

TRAC Program Review
US Department of Energy, Office of Electricity

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Oak Ridge, TN

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• Anticipated challenges and risk mitigation strategies
• Broader impact
Project Overview

Project summary:

- **Concept #1**: Application of in-line processing in amorphous and metal/amorphous nanocrystalline alloy systems.
- **Concept #2**: Development of advanced oxide/metallic-based nanocomposite core materials for high frequency switching.
- **Goal**: Develop new materials and advanced manufacturing methods for soft magnetic applications spanning kHz – MHz and kW – MW range.

Total value of award: $1M ($500k per project) over 2 execution years

Period of performance: 10/1/2019 – 3/31/2021

The Problem Being Addressed: Research Motivation

What tools are needed to design high frequency magnetic components?

1. Advanced Manufacturing Processes and Materials

2. Application Relevant Core / Component Characterization
   – Publication of Data Sheets

3. Advanced Design Tools
   – Multi-Objective Optimization
   – Co-Simulation Methods

Optimal HF magnetic components
A Vision for Medium and High Voltage Power Electronics Has Been Put Forward by the OE TRAC Program through the Solid State Power Substation Road-mapping Effort.
Context concerning the problem: Drivers for Soft Magnetic Components

- **Wide Bandgap Devices** are a Reality and Creating New Challenges and Opportunities for Passives, Including Magnetics ...

- **Ultra-Wide Bandgap Devices** are Being Discussed for Next Generation Switching Devices to Push to Even Higher Voltage / Frequencies and Will Be Needed for MV-HV+ Power Electronics

- Breakthroughs in Passives Require Sustained and Focused R&D Efforts to Maintain Pace

- **Desired Attributes of New Magnetic Components:**
  - Improved Thermal Performance
  - Lower Loss at Higher Switching Frequencies
  - Higher Power Ratings
  - Linearity at High DC Bias Fields
  - Minimize Requirements for Insulation Materials
Current State of the Art: Inductive Components

- **Current Transformers / Sensors**
  - Gapped Electrical Steel Cores
  - Rogowski Coils (No Core Material)
  - Limitations: Bandwidth, Linearity, Saturation

- **Filter and Power Inductors**
  - Ferrite Cores
  - Powder Cores
  - Fe-Based Amorphous or Nanocrystalline Gapped Cores
  - Limitations: Temperature, DC bias, Linearity, High Frequency Losses (e.g. Proximity Losses Near Gaps), Mechanical Properties, Large Component Manufacturability
Transformers: Current State of the Art / New Technologies

- **Conventional Transformer (CT)**
  - Laminated core (E-I shape), Toroidal, or Electrical steel strip
  - **Advantages**: Cheap, Efficient, Reliable, Mature technology
  - **Disadvantages**: Bulky size / Heavy weight, No control mechanism from system disruptions / overloads.

- **Solid State Transformer (SST)**
  - Power electronic converter with semiconductor switch
  - High frequency (HF) transformer (e.g. amorphous / nanocomposite core material)
  - **Advantages**: Reduced size / weight, Fast fault detection / protection, Controllability
  - **Disadvantages**: Cost, Design requirements for HF transformer, Not a 1:1 replacement for CT
# Current State of the Art: Magnetic Core Materials

<table>
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<tr>
<th>Material Classes</th>
<th>Saturation Magnetization (T)</th>
<th>Resistivity (μΩ-cm)</th>
<th>Upper Temp. Limit (C)</th>
<th>Upper Freq. Limit (Hz)</th>
<th>Mechanical Properties</th>
<th>Manufacturing Scalability</th>
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<tr>
<td>Ferrites (NiZn, MnZn)</td>
<td>0.2-0.4</td>
<td>&gt;10³</td>
<td>100-300</td>
<td>10⁶-10⁹</td>
<td>Brittle But Machinable</td>
<td>Limited (Powder Process)</td>
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<tr>
<td>Bulk Crystalline Alloys</td>
<td>1-2.5</td>
<td>~10</td>
<td>400-1000</td>
<td>10^2</td>
<td>Excellent</td>
<td>Excellent</td>
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<tr>
<td>Amorphous Alloys</td>
<td>1-1.6</td>
<td>~100</td>
<td>150</td>
<td>10⁵</td>
<td>Good</td>
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<td>Commercial Metal / Amorphous Nanocomposites (MANCs)</td>
<td>1.3</td>
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<td>Emerging MANCs for WBG</td>
<td>1-1.9</td>
<td>~150</td>
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**New MANC Alloy Compositions and Manufacturing (Concept #1)**

**Completely New Materials Systems (Concept #2)**
Uniqueness of the Proposed Solution: Nanocomposite Magnetics

- Role of Intergranular Phase:
  - Refined Microstructure
  - Source of Induced Anisotropy
  - Intergranular Exchange Coupling
  - Increased Effective Resistivity
  - High Temperature Stable Microstructure

Nanoscale Microstructure Yields Soft Magnetic Properties

Metal Nanocrystal and Metallic Glass Intergranular Phase Nanocomposites (MANCs) are the Only Commercial Nanocomposites Available at Scale

AM Leary, PR Ohodnicki, ME McHenry, JOM 64 (7), 772-781 (2012).
Uniqueness of the Proposed Solution: Concept #1 Advanced MANCs

- Metal Amorphous Nanocomposite (MANC) Cores with “Tunable” Permeability

  Planar Flow Casting for Cobalt-Based Amorphous Alloy Synthesis

  Field and / or Strain Annealing to Optimize Properties and “Tune” Permeability in Full-Scale Cores

Recent Efforts Have Targeted Application of Advanced Manufacturing Processes to Newly Developed MANC Alloy Compositions For Optimized Properties at Component Scale
Uniqueness of the Proposed Solution: Concept #1 Advanced MANCs

- Cobalt-Based Nanocomposite Alloy Cores with “Tunable” Permeability

- Alloy Chemistry + Applied Tension Optimizes and “Tunes” Permeability

- Permeability Control From ~10-10,000 Spans the Entire Range of Inductive Applications

- Permeability Dictates Inductive Component Performance

**Composition Dependence at 200MPa**

B-H Loops, 8kA/m @ 400 Hz

Perm vs Tension

Applied Tension Dependence at Fixed Composition

Uniqueness of the Proposed Solution: Concept #1 Advanced MANCs

**Key to Manufacturability = Mechanical Properties of Alloys + Thermal Stage**

Successful Demonstrations of Strain Annealing Wide Width/Long Lengths Co-Based Ribbon for Large-Scale Core Fabrication Have Been Demonstrated with Conventional Strain Annealing

Mass = 10 kg, L = 400 μH
Uniqueness of the Proposed Solution: Concept #1 Advanced MANCs

Locally Engineered Permeabilities for Optimized Thermal and Efficiency Performance

Real-Time Process Controls Allow for Spatially Varying Permeability: Inductor Core Example

Uniqueness of the Proposed Solution: Concept #1 Advanced MANCs

New Design Spaces with Improved Thermal, Mass, and Loss Performance are Made Possible

Multi-Objective Optimization
Leveraging “Permeability Engineering” Methods

Flux Density Distribution

- Constant tension core (μ_r = 38.3)
- Graded tension core (μ_r = 27.8→44.5)

Improvements by "Permeability Engineering" Methods
Significance of the Results: Concept #1 Advanced MANCs

Application Perspective

1. **Inductors**: Flux smoothing = Core temperature smoothing
2. **Current Transformers**: Low permeability / Linear $B-H$ characteristic
3. **HF Transformers (Rectangular-shaped)**: Elimination of hot spots on inner radii / corners

Significance of the Results: Concept #1 Advanced MANCs

- **Technology Perspective**

1. Finer control of magnetic properties
2. More repeatable / reproducible properties (along the ribbon length)
3. Reel-to-reel process → Manufacturability of large parts is now independent of the furnace size
4. Reduction in number of processing steps → Possible to eliminate processing steps like impregnation / gapping
5. Compact heating zone → Cost and energy intensity savings
Project Schedule, Deliverables, and Current Status: Concept #1

- **Milestones:**
  - Commission a new small-scale annealing system (3/31/2020)
  - Perform literature review of various mechanisms of heating and annealing (9/30/2020)
  - Perform advanced annealing treatments for commercial Fe-based alloys (9/30/2020)
  - Perform advanced annealing treatments for newly developed alloys (3/31/2021)
  - Fabricate / characterize a toroidal core w/ one or more processed alloys (3/31/2021)

- **Deliverables:**
  - Literature review of advanced annealing mechanisms for nanocomposite alloy systems (9/30/2020)
  - Technical report outlining results of new annealing system / materials research (3/31/2021)

**Total Budget = $500k**

**Funding Received = $250k**

**Project to Initiate 10/1/2019**
Uniqueness of Proposed Solution: Concept #2 Metal / Oxide Based

- Insulating Oxide Phases Can Improve High Frequency Performance
- Metallic Phase Can Retain High Saturation Induction For High Power Applications

Examples of Processing Strategies:

- Thin Film Deposition
- Thick Film Deposition
- Powder Based Processing

Role of Intergranular Phase:

- Refined Microstructure
- Source of Induced Anisotropy
- Intergranular Exchange Coupling
- Increased Effective Resistivity
- High Temperature Stable Microstructure

New Nanocomposite Materials Comprised of Metal and Oxide Nanocomposite Based Systems Will Be Pursued in Terms of Scalable Manufacturing for Emerging Applications
Careful Control of Microstructure in Such Systems Has Historically Involved Carefully Controlled Synthesis Procedures Such as Thin Film Deposition Techniques, Not Scalable for High Power

Examples of Processing Strategies:

1) Thin Film Deposition
2) Thick Film Deposition
3) Powder Based Processing
### Significance of the Results: Concept #2 Metal / Oxide Systems

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- New Core Materials Would Be Relevant for Emerging Ultra-Wide Bandgap Semiconductors and Applications
- New Switches and Enabling Magnetics Will Be Critical for Realizing the Vision of MV-HV+ Power Electronics of SSPSs
Specific Research Questions Being Addressed: Concept #2

- Thermodynamic and Kinetic Factors Dictating Microstructure Evolution
- Inter-Relationships Between Magnetic Properties and Microstructure in Metal and Oxide Nanocomposites
- Phase Transformations and Microstructural Evolution for Various Compositions and Processing Conditions
- Underlying Physics of Intergranular Magnetic Coupling and Impacts on Core Material Performance

Example: Iron powder with resin coating layer
Project Schedule, Deliverables, and Current Status : Concept #2

- **Milestones:***
  - Perform literature review of existing oxide-based nanocomposite research (6/30/2020)
  - Establish laboratory facilities for synthesizing candidate materials (9/30/2019)
  - Synthesize new materials and perform structural / magnetic characterization (12/31/2020)
  - Fabricate / characterize at least one toroidal core based on the new material (3/31/2021)

- **Deliverables:***
  - Technical report outlining results of literature review (6/30/2020)

Total Budget = $500k
Funding Received = $250k
Project to Initiate 10/1/2019
## Anticipated Challenges and Risk Mitigation Strategies: Concept #1

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<th>Severity</th>
<th>Probability</th>
<th>Mitigation Strategy</th>
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<tr>
<td>Advanced Annealing Techniques Cannot Be Controlled Accurately</td>
<td>High</td>
<td>Medium</td>
<td>Optical thermometry can be used to monitor temperature in real-time. Initial studies will also be pursued on well-known commercial alloys to understand impacts of advanced annealing methods.</td>
</tr>
<tr>
<td>Difficulty Controlling Microstructure with Powder Based Processing Techniques</td>
<td>Medium</td>
<td>High</td>
<td>Literature reviews will be pursued to explore a number of parallel potential processing strategies to be pursued. Known processing methods for ferrites and powders will be leveraged where possible with minimal modifications.</td>
</tr>
<tr>
<td>Limited Scalability of Manufacturing Techniques Selected</td>
<td>High</td>
<td>Low</td>
<td>Scalability will be a key factor during early screening of synthesis techniques selected for further investigation.</td>
</tr>
<tr>
<td>Magnetic Properties of New Materials Can Be Difficult to Benchmark with Existing Materials</td>
<td>Medium</td>
<td>Low</td>
<td>Well established capabilities in magnetic property measurements will be leveraged to compare and benchmark performance of new materials.</td>
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Broader Impact

- **Patents**
  - “Advanced Annealing Techniques for Amorphous Metal Ribbons” (Converted to US Non-Provisional Patent Application, Filed by Carnegie Mellon University)
  - “In-Line Annealing of Amorphous and Nanocomposite Alloys for Inductive Applications” (Converted to US Non-Provisional Patent Application, Filed by Penn State University)

- **Presentations**

A Suite of Intellectual Property was Developed Around the Thermal Annealing Stage to be Leveraged in Upcoming Research Efforts Proposed Under The Project
3-Phase, 440μH Filter Inductor Fabricated with Strain Annealed Cobalt-Based Nanocrystalline Ribbon

12kg Metal Mass

Multi-Strand Wire

20kg Total Mass

Power Inductors for 1 MW-Scale Next Generation Electrical Machinery (NGEM)
Strain Annealed Core Technology VS. State of the Art:

**Strain Annealed**
- Gapless Design
- Oil Immersion
- **12 kg** Metal Mass
- **20 kg** Total Mass
- **2 – 2.5X** Smaller Volume

**Kool Mµ powder**
- Distributed Gap
- Glued Arc/Bar Segments
- Edge-Wound Coil
- Liquid Cooling with Pump
- **60 kg** Total Mass

**Iron-alloy powder**
- Distributed Gap
- Potted Assembly
- Liquid Cooling with Pump
- **100 kg** Total Mass
Successful Cast of Cobalt-Based Alloy and Reproduction of Strain Annealing Results
Contact Information

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