I. Introduction: Materials Paradigm for Power Magnetic Materials: Metal Amorphous Nanocomposites (MANCs)

II. New Metal Amorphous Nanocomposite (MANC) Soft Magnetic Materials: Synthesis → Structure → Properties Relationships
   II.1 Co-based MANC Materials for Permeability Engineering.
   II.2 FeNi-based MANC Materials.

III. Conclusions.

Support from DOE EERE AMO, DOE SUNLAMP, Eaton
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   A. Leary, R. Noebe, R. Bowman, NASA GRC;
   N. Aronhime and S. Kernion Cartech
Technology Pull

Barriers to market insertion

Established technologies

Industrial scale processing, cost & U.S. supply chain

Underdeveloped technologies

Power generation, conversion, conditioning

Next generation power grid components

5G mobile communication

Barriers to development & implementation

Topology dominated

Si-Steel-based

Nanocrystalline & Amorphous-based

Ferrite-based

Component Size

Interface/disorder dominated

Thin film – based

Material systems

10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^10

Frequency, Hz
History of Soft Magnetic Metals

Bulk (1880’s – 1940’s)
- Fe (Abundant, Cheap)
- Fe-Si (Resistivity)
- Fe-Co (High \( B_s \) High \( T_c \))
- Fe-Ni (High \( \mu \))

Amorphous Magnetic Ribbon (AMR) (1960’s – 1980’s)
- Fe based
- Co based
- Ni based

Metal Amorphous Nanocomposite (MANCs) (1980’s – Present)
- Fe-Si based (FINEMET)
- Fe-based (NANOPERM)
- Fe-Co based (HITPERM)
- Co-based Fe(Ni)-based

References:
Similar trends in SS power transformers.
Ferromagnetic Nanocrystals Embedded in an Amorphous Matrix:
Nanocrystals $\rightarrow$ High Induction
Amorphous Phase $\rightarrow$ Small Grain Size and Large Resistivity
Composite $\rightarrow$ Low Losses

Intro: What are Nanocomposites?
Energy loss upon cycling a magnetic material = Area of the hysteresis loop

Nanocrystalline Grains
→ Strong Intergranular Exchange Interactions
→ Dramatic Reduction in Energy Losses

High Resistivity of Nanocomposites Also Reduces Losses at High Frequency

Why are Nanocomposite Magnets so “Soft”? 

$$\langle K \rangle = \frac{K_1}{\sqrt{N}}$$

$$L_{ex} = \sqrt{\frac{A}{\langle K \rangle}}$$

$$N = \left( \frac{L_{ex}}{D} \right)^3$$

$$H_C \propto < K > D^6$$


Hysteresis Losses

\[ P_h = a f B^2 \]

Random crystal anisotropy
(MANC \( H_c < 40 \) A/m)

Eddy Current Losses

\[ P_e = b f^2 B^2 \]

Resistivity, Thickness
\( \rho > 100 \) \( \mu \Omega \)-cm
\( t < 25 \) \( \mu \)m

Anomalous Losses

\[ P_a = e (f \cdot B)^{1.5} \]

Tunable (graded)
Induced Anisotropy

\( \mu > 5000 \)
W1.0/1kHz < 10 W/kg
II. New Metal Amorphous Nanocomposite (MANC) Soft Magnetic Materials: Synthesis → Structure → Properties Relationships

II.1 Co-based MANC Materials and Permeability Engineering.

II.2 FeNi-based MANC Materials.
Strain Annealing Line at CMU
A.1 Co-rich Alloys with Multiple Nanocrystalline Phases: Resistivity Tuning and Permeability Engineering by Strain Annealing (SA)

Filter Inductor Applications

Tuning Permeability Eliminates Gapping, Reduced Stray Fields:
1) Reduced Electromagnetic Interference
2) Reduced Proximity Losses in Windings

TMF

SA

Reduced Electromagnetic Interference
Reduced Proximity Losses in Windings

EATON
NC STATE UNIVERSITY
NATIONAL ENERGY TECHNOLOGY LABORATORY
NASA
Carnegie Mellon University
Induced Anisotropy – Tunable Permeability

Strain Annealing in Co-rich Alloys
Induced Anisotropy per Increment of Stress

Co-rich Alloys with Virtual Bound States

2015

2014

2012

2010

Co-rich Alloys

Fe-rich Alloys

μ $\sim$ 3 – 10,000
Virtual Bound States - Friedel

Virtual Bound States:
1. Magnetization reduction (price we must pay)
2. Resonant scattering $\rightarrow$ Resistivity.
3. Change stacking faults (hcp vs. fcc) $\rightarrow$ Induced anisotropy

Converter
Motor (Si-steel, MANC)

$$g(e) = \frac{5}{d}^{2} + \frac{2}{d}$$

$$= \frac{2}{\hbar|V_{sd}|^{2}} g_{Al}(d)$$

Impurity Virtual Bound States in Co Host

Resistivity ($\mu\Omega$--cm)

Converter
Motor (Si-steel, MANC)
Resistivities

Figure 1: Resistivity of V, Cr, Nb, and Mo series.

- **V**: 25-35% Increase in resistivity as large as 200 $\mu\Omega$-cm. Plateau at ~1 at%.
- **Cr**: V, Cr, Nb → Plateau at ~2.5-3%.
- **Nb**: Mo at ~2.5-3%.

Figure 1: Resistivity of V, Cr, Nb, and Mo series.
**Induced Anisotropy: SA vs. TMF**

\[ K = K_{\text{magnetocrystalline}} + K_{\text{induced}}(\theta, H) + K_{\text{shape}}(H, \frac{c}{a}) \]

\[ \frac{1}{\chi_{\text{hard}}} - \frac{1}{\chi_{\text{easy}}} = \frac{1}{M_s} (H_{\text{hard}} - H_{\text{easy}}) \quad \text{with uniaxial anisotropy Ku} = MH/2. \]

\[ \Delta K_u = \frac{\mu_0 M_s^2}{2} \left( \frac{1}{\chi_{\text{hard}}} - \frac{1}{\chi_{\text{easy}}} \right) \]

**Graph**

- **SA**
- **TMF**

**Samples annealed at 560 C**

- \( K_u = 11.5 \text{ kJ/m}^3 \)
- \( \mu_r = 34.6 \)

- \( K_u = 2 \text{ kJ/m}^3 \)
- \( \mu_r = 199 \)
Three modes of controlling stress during strain annealing:
- "Tunable" or constant stress
- "Graded" or ramped stress
- "Cyclic" or oscillating stress

Real-time control and monitoring of applied stress is necessary.

Comsol FEA Modeling and Thermal Characterization

**Flux Density Distribution**

**Constant (µ_r=38.3)**

**Graded (µ_r=27.8→44.5)**

**30 Min Thermal Rise**

**Flux Density Distribution**

**Constant tension core**

**Graded tension core**

**Flux Density Distribution**

**Temperature (°C)**

**Time (min)**

A.2: FeNi-based MANC Materials

Low Core Loss at High Frequency (B = 1 T)

• Clear B partitioning after annealing
• Residual amorphous is close to 23:6 composition
• Fe:Ni maintain parent alloy ratio
• $B_S$ decreases with increasing Ni ($\mu_{Fe}=2.2$ $\mu_B$, $\mu_{Ni}=0.6$ $\mu_B$)

• $a-T_C$ peaks at $\sim30\%$ Ni

In patented compositions we can induce longitudinal anisotropy enabling increasing as-cast permeability of $\sim1000$ To $>16,000$. High permeability is desirable for motor applications.

Figure 5.4: Saturation induction and Curie temperature for as-cast ribbon. Curie temperature for $\gamma$-FeNi is in blue.
Benchmarking: nc FeNi-based NC Baseline

Table I: Coercivity, saturation induction, thickness, losses at 1 T and 400 Hz, and losses at 1 T and 1 kHz for nanocrystalline \((\text{Fe}_{70}\text{Ni}_{30})_{80}\text{Nb}_{4}\text{Si}_{2}\text{B}_{15}\), nanocrystalline \(\text{Fe}_{85}\text{B}_{13}\text{Ni}_{2}\), Fe-based Metglas 2605SA1, and non-oriented 3\% Si-steel and 6.5\% Si-steel. *\(H_c\) measured at 60 Hz and 1 T induction.

<table>
<thead>
<tr>
<th>Material</th>
<th>(H_c) (A/m)</th>
<th>(B_s) (T)</th>
<th>(t) (μm)</th>
<th>(W_{1.0/400}) (W/kg)</th>
<th>(W_{1.0/1k}) (W/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{nc-Fe}<em>{70}\text{Ni}</em>{30})<em>{80}\text{Nb}</em>{4}\text{Si}<em>{2}\text{B}</em>{15})</td>
<td>7.0*</td>
<td>1.3</td>
<td>20</td>
<td>0.9</td>
<td>2.3</td>
</tr>
<tr>
<td>(\text{nc-Fe}<em>{85}\text{B}</em>{13}\text{Ni}_{2})</td>
<td>4.6</td>
<td>1.9</td>
<td>13.4</td>
<td>2.3</td>
<td>6.3</td>
</tr>
<tr>
<td>(\text{nc-Fe}<em>{89}\text{Hf}</em>{7}\text{B}_{4})</td>
<td>5.6</td>
<td>1.59</td>
<td>17</td>
<td>0.61</td>
<td>1.7</td>
</tr>
<tr>
<td>Fe-based amorphous (^{38})</td>
<td>2.4</td>
<td>1.56</td>
<td>23.9</td>
<td>1.6</td>
<td>4.7</td>
</tr>
<tr>
<td>3% Si-Steel (^{39,40})</td>
<td>55</td>
<td>2.05</td>
<td>100</td>
<td>8.5</td>
<td>27.1</td>
</tr>
<tr>
<td>6.5% Si-Steel (^{40})</td>
<td>18.5</td>
<td>1.85</td>
<td>100</td>
<td>5.7</td>
<td>17.2</td>
</tr>
</tbody>
</table>

Summary: Promising compositions met: Bs > 1.0 T, in H < 40 A/m, peak μ > 5000, ρ > 100 mΩ·cm, W10/1 k (Power loss at 1 T and 1000 Hz) < 10 W/kG.

MANC Mechanical Properties

Videos showing brittleness of FINEMET-type alloy:

Ductility of Strain annealed FeNi- MANC

VS.
Commercial Ferrite PMs (Br ~ 0.4T) In FSWPM High Flux Density Results (1 T) from Flux Focusing of MANC Power Density ~ #poles & angular speed

Axial Motor Design with MANC Rotors

Stators with coils and rotor
(3-d printed mock-up, > 50% wire fill factor)
Conclusions.

- A Variety of Emerging Trends Drive the Need for Innovations in Soft Magnetics for Power Electronics and Power Conversion Applications:
  - Electricity Grid Infrastructure
  - Large-Scale Electrical Machinery
  - “Electrification” of the Transportation Fleet
- Metl Amorphous Nanocomposites (MANCs) in Novel Topologies Show Promise for a Range of Applications Spanning Various Application Areas
- Inductor Applications:
  - Engineered Permeability Through Field and Strain Annealing
  - Temperature Stability and Performance Under DC-Bias Conditions
- Transformer Applications:
  - Temperature Stability Even Under “Ambient” Conditions
  - Losses Under Application Relevant Excitation
  - High Frequency Transformer Technology Can Be Cost Effective
- Motor Applications are being demonstrated in DOE Advanced Manufacturing Program.
  - Higher rotational speeds yield higher power densities.
  - Potential for operating at speeds unreachable by steels.
  - New MANC compositions of matter.
- We Are Always Looking for Partners to Collaborate
Michael E. McHenry is Professor of Materials Science and Eng. (MSE), with an appointment in Physics and Biomedical Engineering at Carnegie Mellon. He graduated with a B.S. in Metallurgical Eng. and Materials Science from Case Western Reserve in 1980. From 1980 to 1983 he was employed as Process Engineer at the U.S. Steel Lorain Works. In 1988 he earned a Ph.D in Materials Science and Eng. from MIT. He was a Director's Funded Post-doctoral Fellow at Los Alamos Lab from 1988 to 1989. He has expertise in the area of nanocrystalline magnetic materials including soft magnetic nanocomposites, faceted ferrite nanoparticles and materials for power conversion, biomedical, energy and data storage applications. His research involves rapid solidification processing, plasma and solution synthesis of nanoparticles, magnetic field of processing materials, structural characterization by x-rays and electron microscopy and magnetic properties characterization as a function of field, temperature and frequency. He directed a Multidisciplinary University Research Initiative (MURI) on high temperature magnetic materials for aircraft power applications and led an ARPA-E program in magnetic materials for power electronics. He served as Technical Evaluator for the NATO AVT-231 Specialists Meeting on "Scarcity of Rare Earth Materials for Electrical Power Systems". Brussels, Belgium, (Oc. 13-15, 2014) and continues with a NATO team considering implications Rare Earth Element scarcity for NATO countries. He has served as proceeding Editor, Publication Chair and a member of the Program Committee for the Magnetism and Magnetic Materials (MMM) and Intermag Conferences. He has published over 350 papers and owns two patents in the field. He has co-authored, with Marc DeGraef, the textbook “Structure of Materials”, Cambridge University Press, 2007 with a second edition in 2012.