Magnetic Nanocomposites for Inductive Components in Power Electronics.

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Target Opportunities.

Recent Cost Models (Al Hefner, SECA) for power electronics indicate substantial cost savings for medium and high voltage inverter circuits.

Power electronic devices require power conditioning using HF transformers, inductive filters and other inductive components.

Nanocomposite magnetic materials offer significant advantage over Si steels at higher frequencies because of their high resistivities and thin cross-section.

HITPERM nanocomposite magnetic materials offer significant advantage over ferrites because of their large inductions and field tuneable permeabilities.

HITPERM nanocomposite magnetic materials have robust high T properties and high frequency performance superior to FINEMET.

CMU – Alloy Development
Magnetics – Core Development
LANL – Transformer Design, Construction
NETL – Energy Applications

\[ P_L \sim B^2 f n t / \rho \]

\[ n \sim 1-2 \]
High Frequency Nanocrystalline Transformers Are Over 150 Times Lighter And Significantly Smaller (At Same Power)

HVCM Transformer

- 150 kV, 20 KHz
- 20 Amp RMS
- 1 MW Average (3) Present Use
- 450 LBS for 3
- 3 KW Loss At 2 MW
- “C” Core Design (Parallel Windings)

Typical H.V. Transformers

- 100 kV, 60 Hz
- 20 Amp RMS
- 2 MW Average
- 35 Tons
- ~30 KW Loss

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What are Nanocomposites?

Ferromagnetic Nanocrystals Embedded in an Amorphous Matrix:

Nanocrystals → Desired Magnetic Properties
Amorphous Phase → Small Grain Size and Large Resistivity
### Materials Choices: Permeability, Induction and Curie Temperature

<table>
<thead>
<tr>
<th>Alloy Name</th>
<th>Typical Composition</th>
<th>Nanocrystalline Phase</th>
<th>$B_s$ (Tesla)</th>
<th>$T_c$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FINEMET</td>
<td>Fe$<em>{73.5}$Si$</em>{13.5}$B$_9$Nb$_3$Cu$_1$</td>
<td>α-FeSi, FeSi (DO$_3$)</td>
<td>1.0 – 1.2 T</td>
<td>&lt; 770 °C</td>
</tr>
<tr>
<td>NANOPERM</td>
<td>Fe$_{88}$Zr$_7$B$_4$Cu</td>
<td>α-Fe (BCC)</td>
<td>1.5 – 1.8 T</td>
<td>770 °C</td>
</tr>
<tr>
<td>HITPERM</td>
<td>Fe$<em>{44}$Co$</em>{44}$Zr$_7$B$_4$Cu</td>
<td>α, α'-FeCo, (BCC,B2)</td>
<td>1.6 – 2.1 T</td>
<td>&gt; 965 °C</td>
</tr>
</tbody>
</table>

**Frequency Response:**

- Resistivity
- Lamination
- Thickness
Lab Scale Planar Flow Casting.
**Results:** New high-Bs, high-T_c nanocomposite, with nanocrystals with a FeCo A2 or B2 structure embedded in an amorphous matrix for high-power inductors.

**FOM:**
1. Linear $B-H$ response $\mu_r \sim 1400$, constant to $H = 1.2$ T.
2. Material was used in a 25 $\mu$H inductor for a 25 kW DC-DC converter rated for use in discontinuous conduction mode at 300 A peak current and 20 kHz switching frequency.
3. Compared to commercially available materials this new alloy can operate at higher flux densities and higher T’s thus reducing the overall size of the inductor.
Melt Spinning Processing

- Amorphous Ribbon
- Melt in Progress
- Melt Spinner at CMU for Early Stage Alloy Design and “Proof of Concept”
- Planar Flow Caster at Magnetics for “Scaled up” “Miles” of Amorphous Ribbon Obtained From Magnetics Planar Flow Cast

HITPERM Materials
- BCC
- BCC nanox’tals
- Large $B_s$
- High $T_C$
- Large $K_u$
Production Caster
HTX002: \((\text{Fe}_{65}\text{Co}_{35})_{80+x}\text{B}_{13}\text{Nb}_{4-x}\text{Si}_{2}\text{Cu}_1\)

- Ideal Fe:Co ratio of 65:35 found
- Nb-content reduced to increase induction
- 1 at% Nb alloy demonstrated low losses and high saturation induction

4 at% Nb

1 at% Nb
Why is High $K_U$ Technologically Relevant?

Power Electronics: Energy Storage and Conversion... Inductor Applications

![Cut Core Power Transformer](image)

1) Inductance

$$L = \mu \left( \frac{N^2 A}{L} \right)$$

Nonlinear B(H)

DC Bias Problems

$$\mu = \frac{dB}{dH}$$

2) Higher $K_U$, Lower $\mu$

Higher Stored Energy

$$E_{\text{Stored}} = V_{\text{Core}} \left( \frac{B^2}{2\mu} \right)$$

No Field Crystallized

Field Crystallized

Courtesy of J. Long

Why is High $K_U$ Technologically Relevant?
C-core Design, Graded Permeability – Higher Efficiency

Advanced Winding Topology Minimizes Field Stresses And Leakage Inductance
Boost Transformer Windings

- Wire
- Busbar
- Corona Rings

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## Alloy Comparison

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Remarks</th>
<th>Applied field</th>
<th>Bm, T</th>
<th>μ</th>
<th>Kr</th>
<th>P0.2/20, W/kg</th>
<th>P0.1/100, mW/cc</th>
<th>Tmax, °C</th>
<th>λs, ppm</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTX 002</td>
<td>Nanocrystalline</td>
<td>TMF</td>
<td>1.47</td>
<td>1500</td>
<td>0.02-0.03</td>
<td>4-6</td>
<td>150</td>
<td>250</td>
<td>20</td>
</tr>
<tr>
<td>C</td>
<td>Amorphous</td>
<td>TMF</td>
<td>0.94</td>
<td>670</td>
<td>0.01</td>
<td>5</td>
<td>150</td>
<td>~0</td>
<td></td>
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<tr>
<td></td>
<td>Nanocrystalline</td>
<td>TMF</td>
<td>0.88</td>
<td>480</td>
<td>0.01</td>
<td>8</td>
<td>230</td>
<td>400</td>
<td>1.4</td>
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<tr>
<td>F</td>
<td>Nanocrystalline</td>
<td>TMF</td>
<td>0.82</td>
<td>220</td>
<td>0.01</td>
<td>6-8</td>
<td>150-200</td>
<td></td>
<td>0.3</td>
</tr>
<tr>
<td>A</td>
<td>Amorphous</td>
<td>No field</td>
<td>1.50</td>
<td>1k to 3k*</td>
<td>0.05-0.15*</td>
<td>3-5</td>
<td>70-90</td>
<td></td>
<td>22</td>
</tr>
<tr>
<td>D</td>
<td>Nanocrystalline</td>
<td>TMF</td>
<td>1.20</td>
<td>9k to 18k*</td>
<td>0.02-0.04*</td>
<td>1.5</td>
<td>35-45</td>
<td>~0</td>
<td></td>
</tr>
<tr>
<td>2605SA1</td>
<td>Amorphous</td>
<td>No field</td>
<td>1.56</td>
<td>1k to 5k*</td>
<td>0.10-0.20*</td>
<td>10</td>
<td>120</td>
<td>155</td>
<td>25</td>
</tr>
<tr>
<td>FT-3</td>
<td>Nanocrystalline</td>
<td>TMF</td>
<td>1.25</td>
<td>15k to 20k*</td>
<td>0.04-0.08*</td>
<td>2</td>
<td>60-70</td>
<td>125</td>
<td>~0</td>
</tr>
</tbody>
</table>

* - depend on annealing conditions

Annealing conditions were optimized to get flat B-H loop and minimal watt loss.
300 MW PCS

- Semiconductors
- Packaging and Interconnects
- HF transformers
- Filter Inductors and Capacitors
- Cooling System
- 60 Hz Transformer up to 18 kV
- Breakers and Switchgear

$40-100 / kW

- Ripple < 2%
- Stack Voltage Range
- ~700 to 1000 V

IEEE – 519
IEEE – 1547
Harmonic Distortion
HF Transformer versus 60 Hz Transformer
Introduction: Soft Magnetic Nanocomposites