Amorphous and Nanocomposite Magnets for Energy-efficient Electric Motors

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Outline
- Motivation: Electric motors, energy, hard magnets
- Soft magnets: steel vs amorphous and nanocomposites
- Parallel Path Magnetic Technology
- Brushless permanent magnet motors
- Conclusions & Future work

Magnetic Materials for Energy and Power Applications:
- Soft Magnetic Materials
- Hard Magnets
- Electric Vehicles
- Motors
- Interconnects
- Packaging
- Sensing
- Active Cooling

Scaling
Material properties necessary for high-f operation?

Converter applications: Controlling losses allow 100-fold or more reduction in size/mass. Materials must have robust properties in extreme environments; P, T, stress, corrosion.
Materials Paradigm for Magnetic Materials

Power Converters
Electric Vehicles
Motors
Sensors

Collaborations (funding):
- NETL, ANL, PNNL
- WPAFB, ARL
- NASA Glenn
- NSF
- Industry

Scale-Up

2 in – 14 in. wide

Nanostucture

Growth Faults

Deformation Faults

Atom Probe Field Ion Microscopy

Co-rich Alloys with Virtual Bound States

2010 - 2015

Energy (eV)

Density of States (1/eV)

Impurity Virtual Bound States in Co Host

Co-Co

Mn

Cr-Co

V-Co

Strain Ameliorating Co-rich Alloys: Induced Anomalies per Increment of Strain

Annealed Field Ion Micrographs
Electric Motors & Energy
- Motors usually comprise ferromagnets, either to produce or to direct magnetic flux, which varies temporally/spatially.
- Even small efficiency improvements from the ferromagnet’s field would lead to large energy savings.

Electric motors & Hard magnets
- The advent of modern electronics and high-energy hard magnets (SmCo, NdFeB) have promoted the use of permanent magnet (PM) motors in the past years.
- PM motors have high performance, high power density, high robustness, and high reliability.

Advantages of amorphous & nanocomposite soft magnets
- The reduction in core losses allows to excite the motor at higher frequencies without incurring unacceptable heating.
- The motor can therefore operate at higher rotational speeds.
- An increase in speed proportionally increases the output power for an equivalent torque level, or smaller and lighter machines for the same output power.
- Motor size reduction leads to less amount of rare-earth hard magnets.

Electric Energy Consumption


Heat / Light / Electronics / Electrolysis / Standby / Motors

Applications of Nd-magnets

China controls about 80% of the world’s rare earths.
PM are sensitive to high temperature.

<table>
<thead>
<tr>
<th>NdFeB Type</th>
<th>Maximum Operating Temp</th>
<th>Curie Temp</th>
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<tbody>
<tr>
<td>N</td>
<td>176 °F (80 °C)</td>
<td>590 °F (310 °C)</td>
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<tr>
<td>NM</td>
<td>212 °F (100 °C)</td>
<td>644 °F (340 °C)</td>
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<tr>
<td>NM</td>
<td>248 °F (120 °C)</td>
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<td>NSH</td>
<td>302 °F (150 °C)</td>
<td>662 °F (350 °C)</td>
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<tr>
<td>NUH</td>
<td>356 °F (180 °C)</td>
<td>662 °F (350 °C)</td>
</tr>
<tr>
<td>NEH</td>
<td>392 °F (200 °C)</td>
<td>662 °F (350 °C)</td>
</tr>
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</table>
Fe-based and Co-rich alloys

- Recent efforts in replacing Si-Steel by Fe-based amorphous components to develop highly-efficient low-rare-earth-PM motors:

Fe-based and Co-rich alloys

- But Fe-based alloys are very brittle, especially nanocomposites.

Co-rich alloys (HiTperms) have robust mechanical properties, better tunable anisotropies, can have \( \sim \)zero magnetostriction, and can operate at higher temperatures (\( >300°C \))

Coils

Soft magnets

Permanent magnets

Power = Torque x Speed
Parallel Path Magnetic Technology

Silicon Steel

HTX-005C

Common Permanent Magnet Brushless Motors

Radial flux machine

Axial flux machine

Stacking

Winding

Radial Permanent Magnet Brushless Motor

We built a small outrunner (i.e. outer rotor) with custom-made ferrite hard magnets and soft magnetic stations: from Si-steel or nanocomposite

Laser cutting

• Made out of Metglas amorphous Fe-based stacked cut sheets
• Failed attempt to use Finemet nanocomposite material due to its brittleness
• Holy Grail ➔ Thermoplastic deforation processing.

#1 Fe-based (Fe-Si-B-Nb-Cu)
#2 Fe-rich (Fe-Co-Si-B-Nb-Cu)
#3 Co-rich (Co-Fe-Mn-Si-B-Nb)
Modeling Radial PM Brushless Motors

### Inner Stator
- Silicon steel or Co-rich alloy laminated core
- Coils

### Outer Rotor
- Silicon steel ring
- Custom-made Ferrite (C-8) magnets

### Stress Distribution on the Motor
Rotational speed at 32,000 rpm

Simulations prove rotor to be mechanically stable at 32,000 rpm (validated with experiments)

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Core losses

- Si steel
- Co-rich alloy

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### Magnetic Flux Density (T)
- Co-rich stator
- Si Steel stator

We computed the iron loss in the stator from the previous iron loss models and the flux density distribution obtained through finite element analysis.

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Loss density distribution (W/kg) on the stator

- Si Steel stator
- Co-rich stator

Co-rich stator loss = 20% Si Steel stator loss
Conclusions

- Electric motors still seem to be a good niche for amorphous and nanocomposite materials, especially for Co-based alloys.
- Energy efficiency improvement, size reduction and rare-earths reduction may be achieved with these materials in electric motors.

POSCO Steel

POSCO TMC: Transformer, Motor Core Company

“Under the motto of becoming a global leader in green energy parts, POSCO TMC is preparing for new changes to achieve Vision 2020. First, with the development of Fe Amorphous, an eco-friendly high efficiency new material, which can significantly reduce the no-load loss to transformers, we will build up the full line-up for transformers to provide a solution for increased energy demand.”