Nano-Magnets and Additive Manufacturing for Electric Motors

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Enabling Technologies for High Power Density, High Performance Electric Motor

- Advanced electrical and magnetic materials
  - Magnets
  - Conductors
  - Insulation
- Thermal management
  - Thermal materials
  - Cooling technologies
- Power electronics
- Advanced topology
- Lightweight materials and structural concepts
- Advanced manufacturing processes
Advances in Permanent Magnets

Theoretical $\text{(BH)}_{\text{max}}$ for $\text{Nd}_2\text{Fe}_{14}\text{B}$ is 64 MGOe

$\text{(BH)}_{\text{max}} = \text{maximum energy product}$
Concept of Nanocomposite Magnet

Requirements:
- Both phases in intimate contact with each other
- Size of individual phases < 10 nm
- Alignment of magnetic easy axis

Soft phase (Fe) – high magnetic saturation

Hard phase (Nd-Fe-B) – high coercivity
Promise of Nanocomposite Magnets

Theoretical $(BH)_{\text{max}}^3$, MGOe

- Sm-Co
- Nd$_2$Fe$_{14}$B
- SmCo$_5$/Fe$_{65}$Co$_{35}$
- Sm$_2$Co$_{17}$/Fe
- FeP$_{1}$/Fe
- Nd$_2$Fe$_{14}$B/Fe
- Sm$_2$Fe$_{17}$N$_3$/Fe
- Sm$_2$Fe$_{17}$N$_3$/Fe$_{65}$Co$_{35}$

Only 2 wt. % Samarium (rare earth element)

10nm alternate hard and soft magnet layer
Challenges With Fabrication of Nanocomposite Magnets

Challenges:
• Achieving a uniform mixture of hard and soft phases with a length scale on the order of 10 nm
• Arranging the nanostructure so that the coercivity of hard phase remains high as the percentage of soft phase is increased
• Aligning the easy anisotropy axes of the hard-phase
• Fabricating dense-packed bulk magnets for practical use
Nanocomposite Thin Film Magnets

FePt/Fe$_3$Pt Nanocomposite Film

Best results so far for Fe-Pt nanocomposite film - 54 MGOe
Advanced Processing Techniques Critical for Achieving Desired Properties in Bulk Nanocomposite Magnets

Bottoms-Up Chemical Approach

Surfactant-assisted high energy ball milling to produce nanoparticles

Functionalization to align particles

Sm$_2$Co$_7$/FeCO Nanocomposite Fabricated by High Energy Ball Milling Followed by Warm Compaction

Univ. of Delaware

Univ. of Texas

Isotropic Sm$_2$Co$_7$

Graph showing BH$_{max}$ (MGO) vs. FeCo content (wt.%)
Nanocomposite High Temperature Magnets

SmCo/NdFeB Nanocomposite Magnet
Nanocomposite Magnets are Promising, But Significant Challenges Remain

From University of Delaware presentation
“3D printing that has the potential to revolutionize the way we make almost everything” President Obama
Principles of Additive Manufacturing

Sliced file

CAD-file

Deposition of new layer

Lowering of building platform

Finished part

Fused deposition modeling (FDM) process
Additive Manufacturing Through Powder Bed Processes

Laser sintering
Electron beam melting
Direct Writing Processes

- **Ink-jet process**
- **Extrusion-based process**
- **Aerosol-based process**
- **Laser writing process**
Examples of Direct Writing Processes

60 micron Ag lines written over a 500 micron trench

Printing of Cu interconnect

3D silver interconnects, 150 micron line width written over an alumina cube

Concave antennas
Application of Direct Write Process for Fabricating Printed Circuit Stators in Small Permanent Magnet Motors

Top layer

Bottom layer

Substrate

Application of Direct Printing Technology for Large Stators

Printed circuit board stator by Boulder Wind Power using CORE (conductor optimized rotary energy) technology
Example of Direct Printed Stator
3D Printing of Electromechanical System

From the work of Aguilera et. al., University of Texas at El Paso
Additive Manufacturing of Electric Motors

Fig. 3

Fig. 4

Concluding Remarks

- Nanocomposite magnets offer significant potential to increase maximum energy product in magnets (and reduce size of magnets) for permanent magnet motors
  - Significant advances in fabrication technology required to produce bulk magnets

- Additive manufacturing is emerging as a promising technique for fabrication of electric motors and offers several potential advantages:
  - High power density and reduced volume
  - New electromagnetic design
  - Reduction of cost
  - Integration of electronics