Permanent Magnet Development for Automotive Traction Motors

Includes: *Beyond Rare Earth Magnets (BREM)*

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May 11, 2011

Project ID #APE015

U.S. DEPARTMENT OF ENERGY
Energy Efficiency & Renewable Energy

FreedomCAR & Fuel Partnership

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THE Ames Laboratory
Creating Materials & Energy Solutions
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Overview

Timeline

- Start - August 2001
- Finish - September 2014
- 73% Complete

Budget

- Total project funding
  - DOE share $8,150K (since FY01)
- FY10 Funding - $2000K
- FY11 Funding - $2400K
- FY12 Funding - $2400K (planned)

Barriers

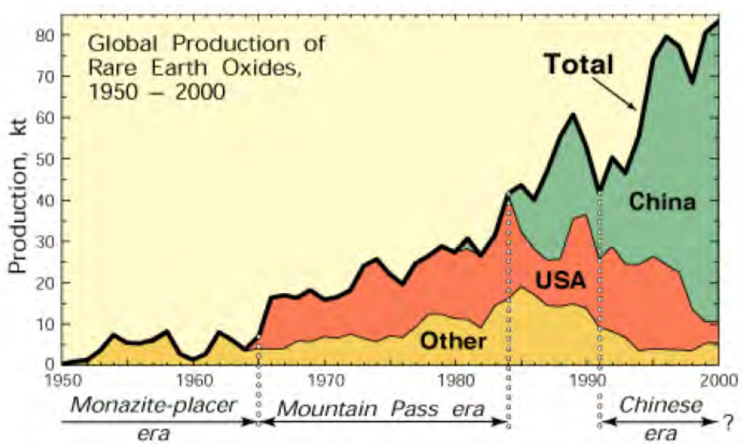
- Higher operating temperature (150-200˚C) and long life (15 yrs.) needed for magnets in PM motors.
- Permanent magnet (PM) energy density increase needed in PM motor (Specific power >1.4kW/kg) to reduce cost (<$8/kW).
- Highly efficient interior PM motors (>94%) require sintered or bonded magnets with complex shape and simplified mass production capability.
- Looming shortage and rising prices of Rare Earth (RE) elements, especially Dy.

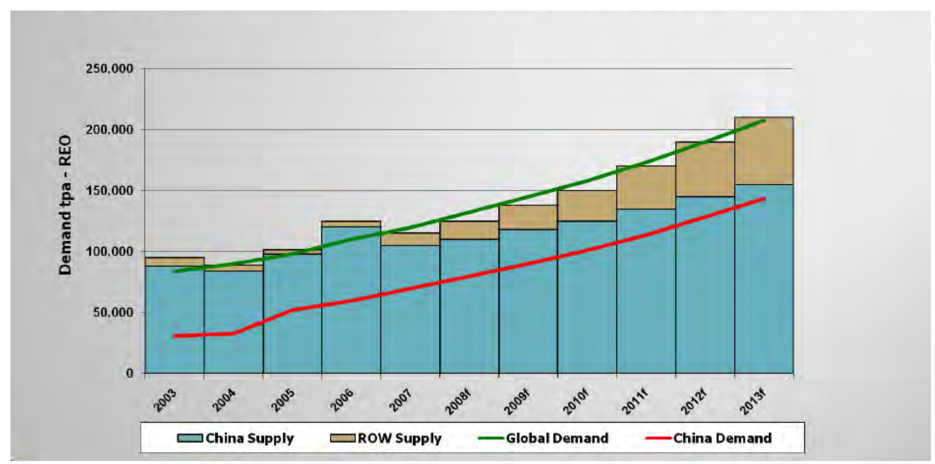
Partners

- Baldor, U. Wisc., U. Texas, GM, GE, UQM, Motor Excellence, Synthesis Partners (collaborators)
- ORNL, U. Maryland, U. Nebraska, Brown U., Arnold Magnetics (BREM subcontractors)
- Project lead: Ames Lab

Objective

- To meet 2015 goals for enhanced specific power and reduced cost for high volume manufacturing of advanced electric drive motors, it is essential to improve the alloy design and processing of permanent magnets (PM), particularly by coupling theory, novel synthesis and bulk processing, and advanced characterization.
- The fully developed PM material must:
  - ✓ achieve superiority for elevated temperature (150-200˚C) operation to minimize motor cooling needs.
  - ✓ remain competitive at room temperature with current high magnetic energy density (MGOe) materials to conserve valuable materials.
  - ✓ minimize or eliminate use of scarce RE, e.g., Dy, due to an impending world wide RE shortage or be developed as RE-free magnet alloys





Project Relevance

Goals

- Develop non-RE permanent magnets with sufficient coercivity and energy product for advanced IPM traction motors.
- Further develop anisotropic sintered RE magnets to achieve highest energy product (4-6X isotropic bonded) with high temperature stability from single crystal/single domain micron-sized particles from alloy with little or no Dy.

Targets Addressed

The research targets are to maintain high temperature tolerance while improving the energy density of permanent magnets to permit advanced traction motors to reach 2015 goals of enhanced specific power (>1.2kW/kg), reduced size (>5kW/l), and reduced cost (<$12/kW).

Uniqueness and Impacts

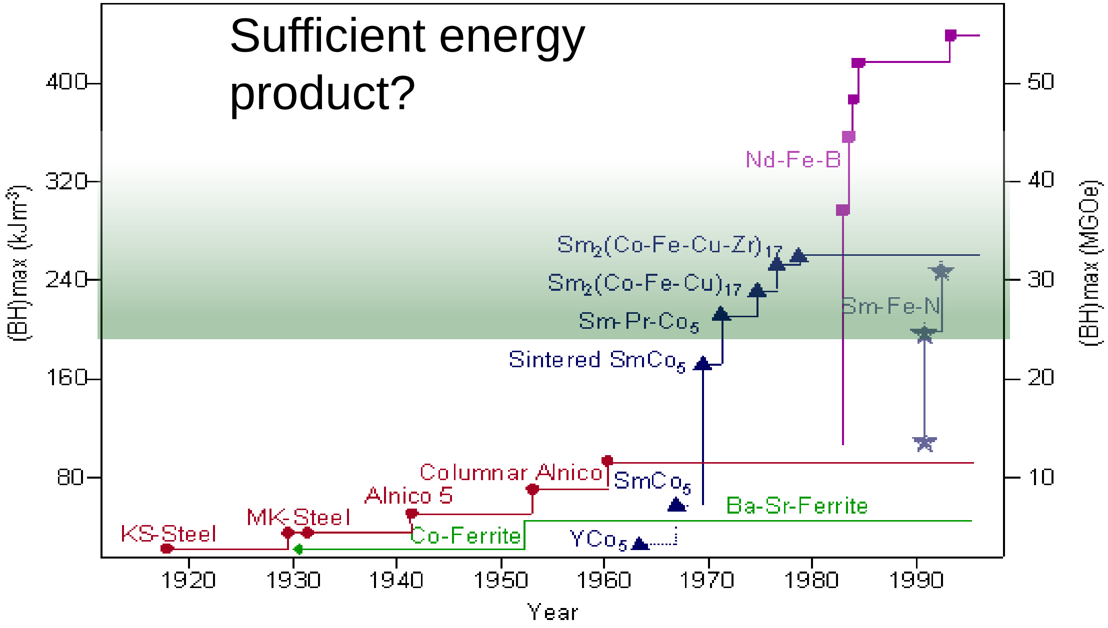
Current RE magnet cost pressure (2X in one year) and recent threats to RE supply motivated a large augmentation (3X) of the permanent magnet project in FY2010 to include a major research effort to elevate transition metal-based permanent magnet designs (modify or discover new) to the realm of high magnetic strength (especially coercivity) necessary for high torque drive motors..

Milestones for FY10 and FY11

Month/Year	Milestone or Go/No-Go Decision
Sep-10	Milestone: Select viable processing approach for anisotropic sintered RE permanent magnets from either intrinsic or extrinsic sintering approaches and demonstrate potential for high-energy product and reduced temperature coefficients for operation up to 200˚C.
Sep-11 May-11 Sep-11	Milestone: Conduct initial search for new monolithic high performance non-RE permanent magnets, reporting results in papers and generating intellectual property, if needed. Milestone: Conduct fourth regular BREM workshop to exchange results and refine directions for continued research in high performance non-rare earth permanent magnets with team. Milestone: Start development of enhanced coercivity in existing Alnico type magnets with BREM research team by enhancing crystallization and precipitation alignment and interface straining.
Sep-11 Jul-11	Milestone: Pursue anisotropic sintered MRE-Fe-B permanent magnets with pressurized intrinsic sintering at reduced temperature and explore extrinsic additives to eliminate Dy use. Complete study of aligned solidification patterning in MRE magnet alloy ribbon with low Dy to accentuate anisotropy in crystallized particulate for bonded magnets.

Approach/Strategy

- Cost Effective RE permanent magnets
  - Lower or eliminate Dy and maintain high temperature performance
    - innovative chemistries
    - new methods of grain alignment



•Develop non-rare earth magnets

State of the art in non-RE magnets

Data Mining of the Literature

Source of coercivity (H_c): Shape anisotropy – Alnico

Magneocrystalline anisotropy in non RE magnets

Synthesize Pt-Co with cheaper materials

Bring to bear new materials knowledge

Materials by Design – advanced computational tools

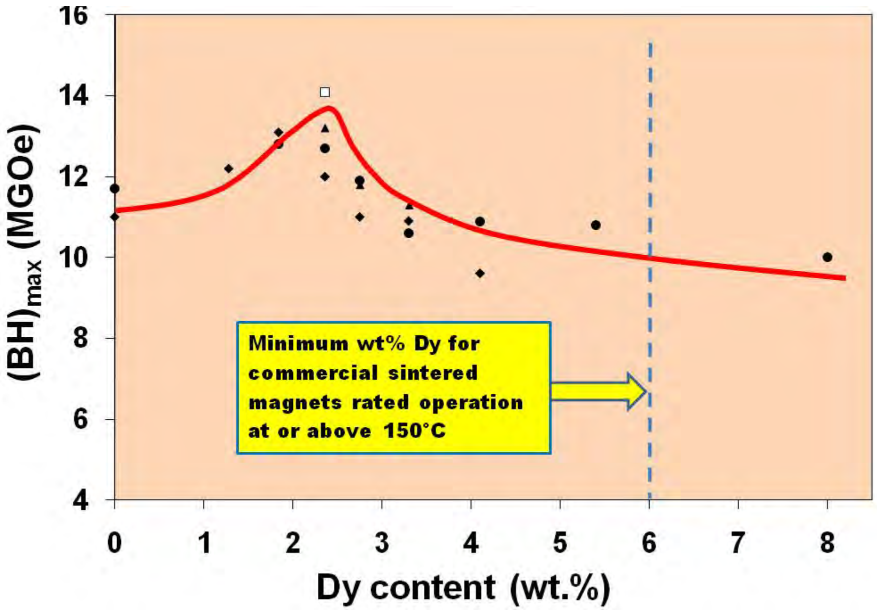
Bottom Up architectures (self assembly of nanoclusters)

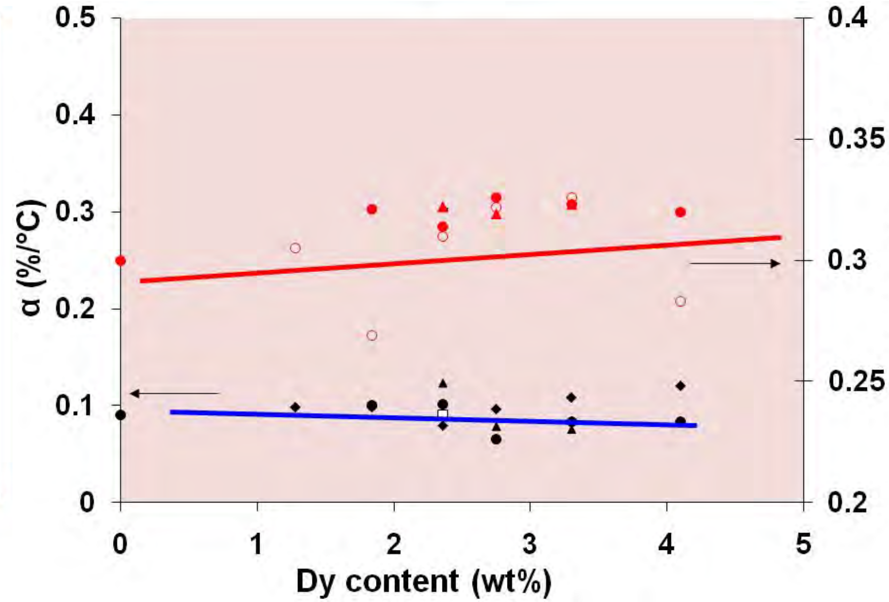
Combinatorial Materials Search and Improved characterization

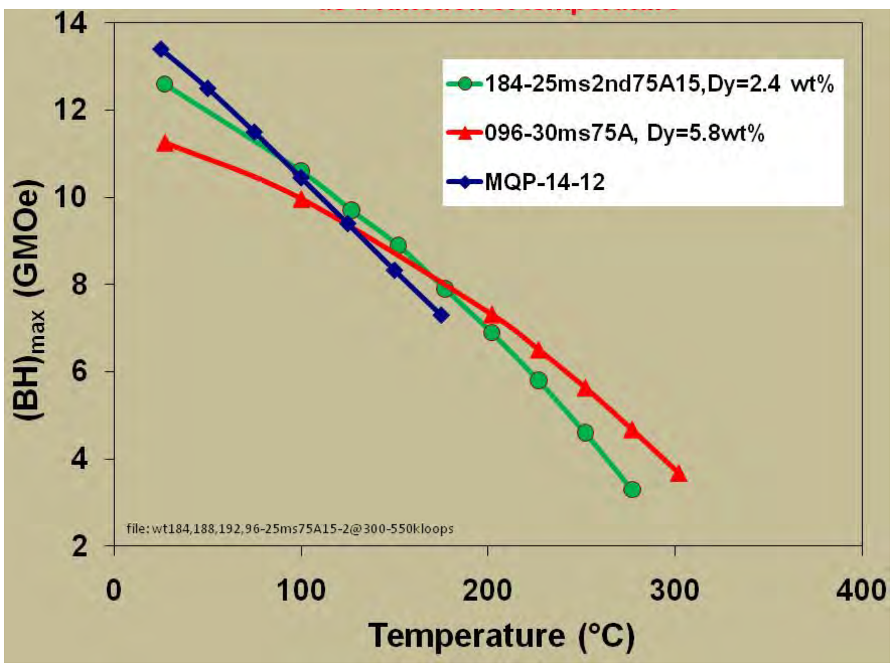
High T Performance for RE PM

- Increase H_c at $T > 150°C$ without Dy
  - Heavy REs less abundant, cost ~6x Nd
  - Increasing K, decrease M_s
    - Other chemistries can do the same, Y
- Anisotropic Alloys
  - Strategies for direct texturing
- Exchange Coupling
  - Increases BH_{max} with less RE

Previous Isotropic (Nd,Y,Dy)-(Fe,Co)-B magnets with low Dy



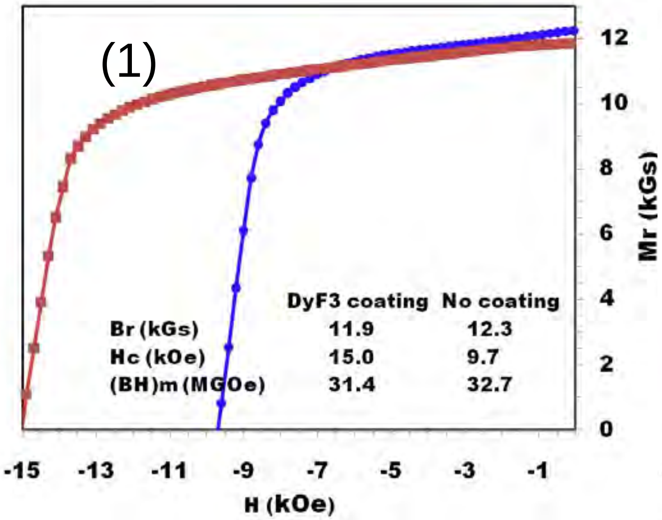


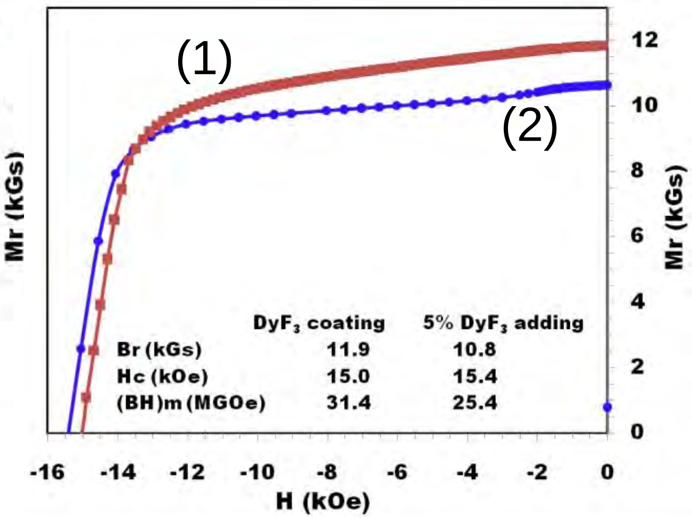


- With decreasing Dy content, $(BH)_{max}$ of melt spun ribbons (Zr substitution and ZrC) exhibits a peak; α and β have minor change.
- Isotropic MRE-Fe-B magnets can be developed with thermal stability but less Dy.

- When Dy content is reduced from 5.8 to 2.4 wt% {peak $(BH)_{max}$ value from Y substitution}, the sample still obtains a better temperature dependence of (BH)max compared to the commercial magnet that is recommended for operation at or above 150°C.

New Sintered Anisotropic MRE-(Fe,Co)-B Magnets with Low Dy



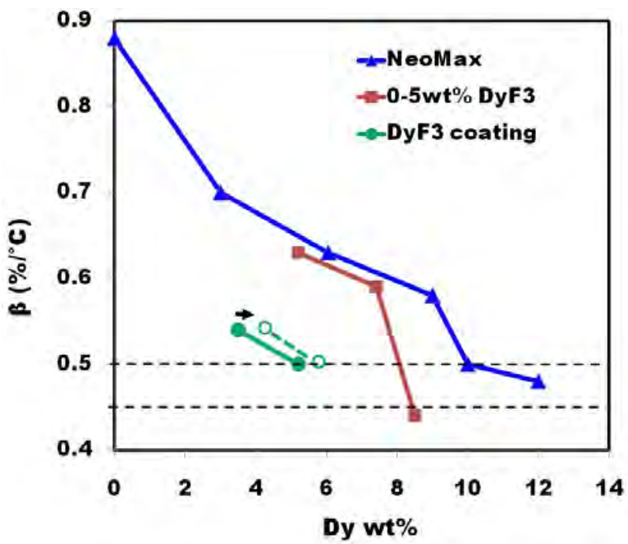


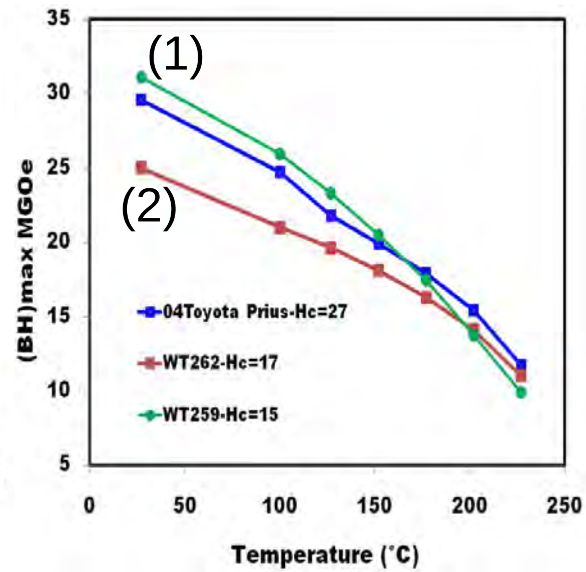
- •High strength magnets more effectively use scarce Dy.
- •High temperature sintering with MRE (low Dy) segregates RE and degrades magnetic properties.
- •Addition of DyF_3 is less costly than Dy and coating of 2-14-1 grains can increase HT coercivity with minimum Dy.

- ❑ Temperature coefficient less than -0.5%/°C required for magnets operating above 150°.
- ❑ NeoMax (10 wt% Dy)
- ❑ MRE blended DyF_3 (7 wt% Dy)
- ❑ MRE DyF_3 painted (6 wt% Dy)

- ❑ Both MRE magnets have competitive $(BH)_{max}$ with commercial magnets for above 180°C.
- ❑ Promising results for sintered MRE-Fe-B magnets with higher temperature stability and lower Dy content.
- ❑ Need lower or no Dy content.

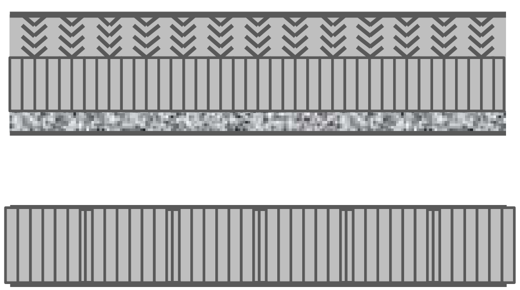
1) Coating of finished MRE (low Dy) magnet with DyF_3 paint to diffuse in along grain boundaries at 900˚C.
2) Blending and 1050˚C sinter of same MRE magnet powder with DyF_3 to add Dy surface layer to all 2-14-1 grains.

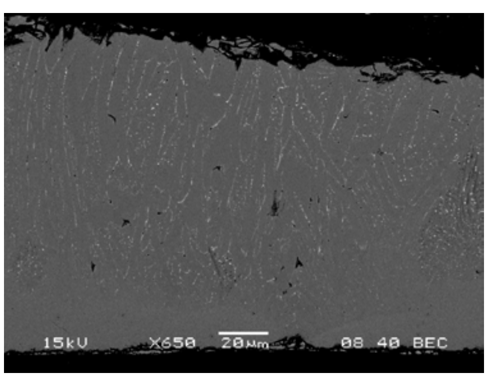


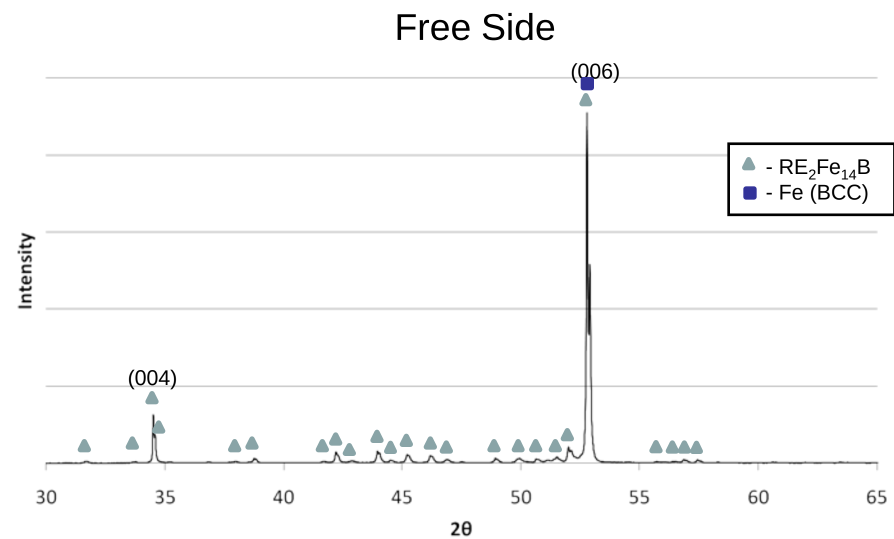


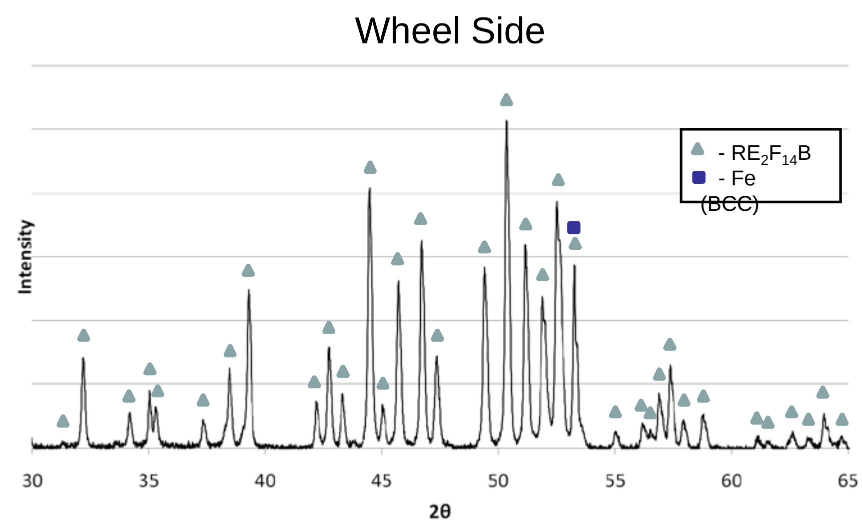
New Results for Direct Texturing Strategy

- Typical low wheel speed melt spinning produces three distinct regions
  - Caused by variance in solidification front velocity through the thickness of the ribbon
  - Fine equiaxed zone
    - Minimal texturing
  - Columnar cellular region
    - C-axis texturing
  - Dendritic region
    - Secondary arms can break off, reducing texture
- Can we stabilize/extend cellular region?
- Fine, through-thickness cells desired
- Mild crushing of ribbon
- Embedding and alignment of particulate within polymer matrix
  - Results in anisotropic polymer bonded magnet







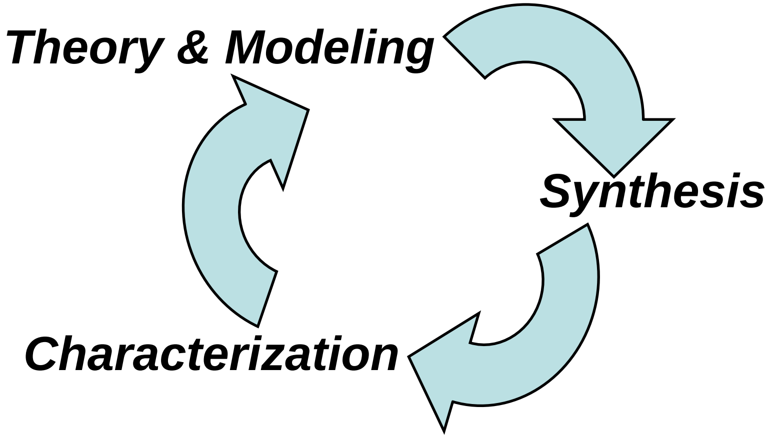


Results for Cu addition in MRE magnet (low Dy) at 5m/s wheel speed.

Approach/Strategy
Description of Technology:
Routes to Improved Non-Rare Earth Permanent Magnets

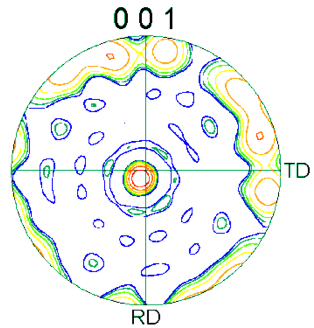
New high strength *non-RE anisotropic* permanent magnets will be developed that meet the requirements for advanced interior PM electric traction motors. The investigation will involve theoretical and modeling efforts, as well as experimental synthesis of magnet compounds and prototype magnet fabrication and characterization.

- Improve on known systems
  - Enhanced knowledge of coercivity mechanisms
  - Enhanced control of composition and microstructure
- Discover new primary phases (helped by theory)
  - High Curie temperature
  - High Magnetization
  - Magnetic anisotropy

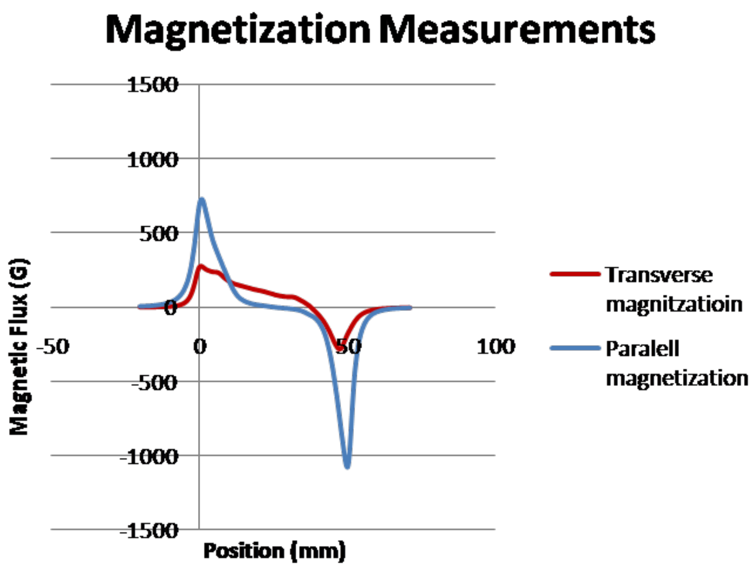


New Understanding of Current Materials

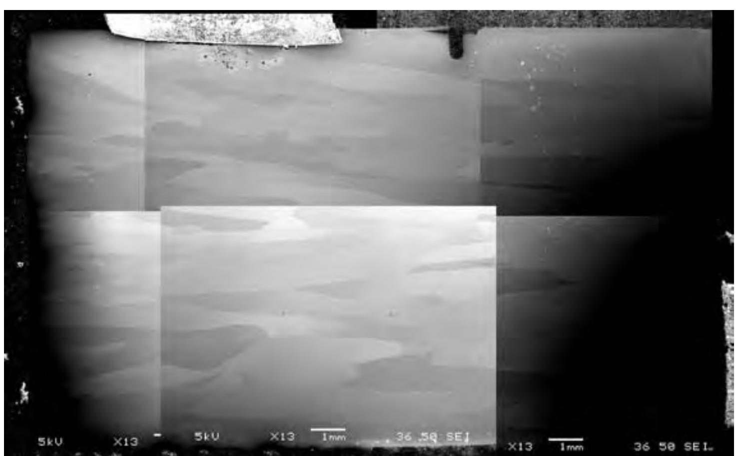
- Characterization of commercial Alnico 5-7 magnet castings (Arnold)
  - Additives to promote columnar microstructure
  - Highest energy product of non-rare earth PM alloys but low coercivity reduces energy product.
- Investigation of coercivity mechanism(s)
- SEM and OIM shows alignment of the grains along the longitudinal axis of the casting but random orientation transversely.



Pole figure from transverse section Alnico 5-7 showing excellent grain alignment along magnetization direction but random orthogonal



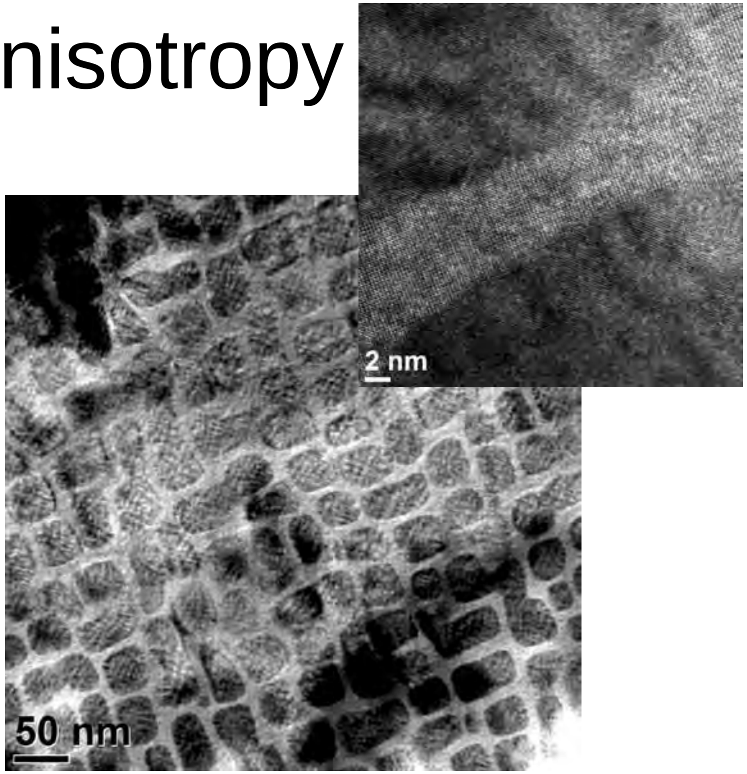
Hall probe scans of longitudinal section



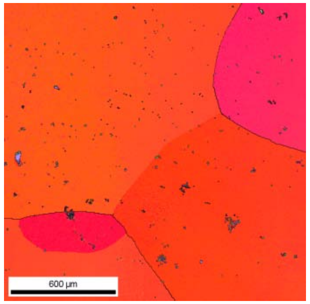
SEM composite of longitudinal cross-section

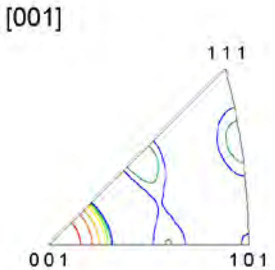
New Investigation of Shape Anisotropy

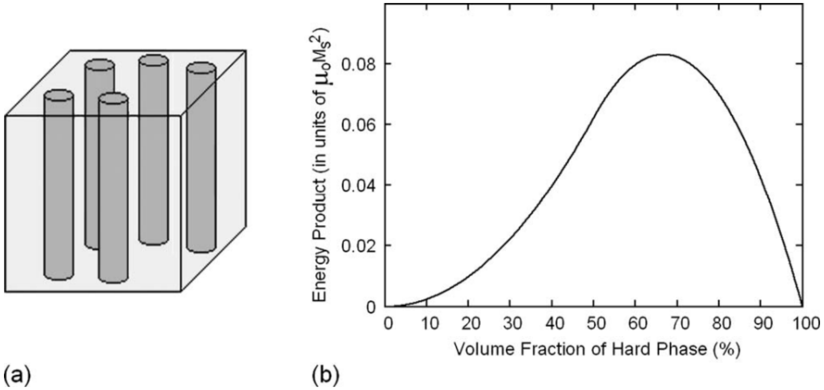
- Improving on state-of-the-art (Arnold)
  - Highest energy product of non-RE PM
  - Curie T ~860°C
- Boost H_c
  - Plan to enhance anisotropy though Interface engineering
- Reduce costs
  - Improve solidification control
    - Role of minor elements
  - Better methods and understanding of phase selection
  - Optimization in spinodal formation
    - Fe/Co fraction is near optimal
    - Interface chemistry?



TEM composite of transverse section







Skomski, R. et al.(2010). Permanent magnetism of dense-packed nanostructures. *Journal of Applied Physics*, *107*(9)

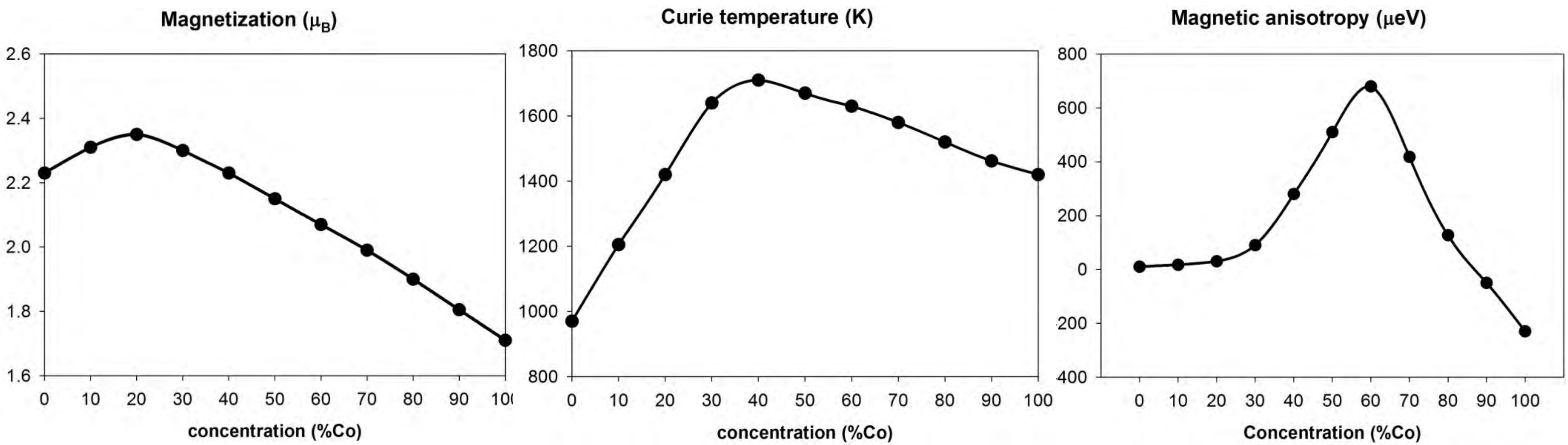
New Theoretical Optimization of Fe-Co Properties

L. Ke and V. Antropov (Ames)

Figures of merit: Magnetization, Curie temperature, Magnetic anisotropy

Method: Ab-initio electronic structure calculations

LMTO, linear response and the total energy calculations as a function of concentration and c/a ratio

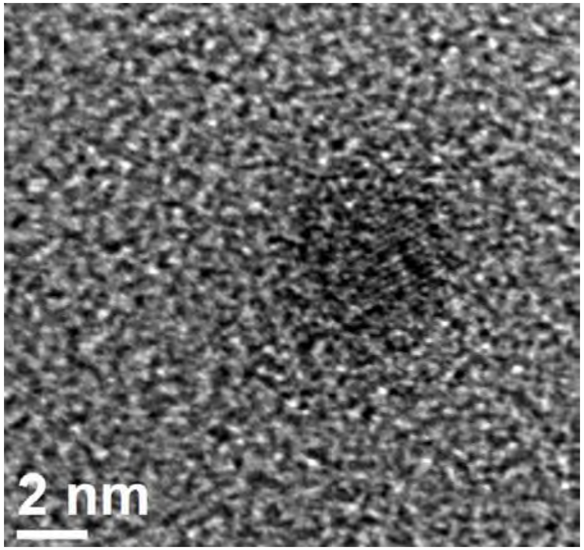


Conclusions:

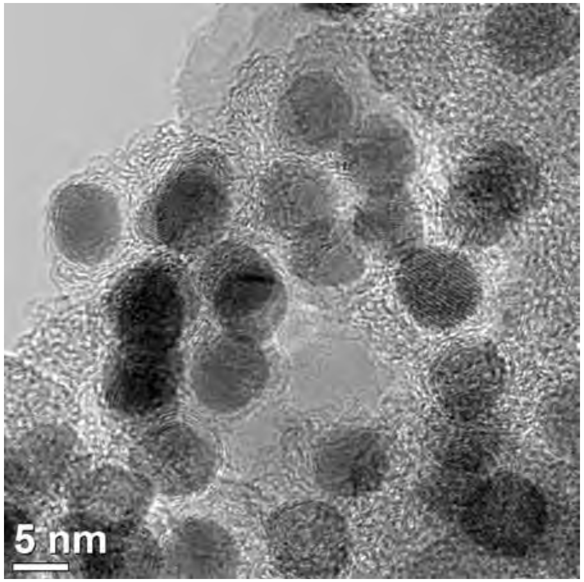
- **Crucial factors are c/a ratio for magnetic anisotropy (1.1-1.2).**
- **Maximum values of these three quantities are obtained at very different concentrations: (20% for M, 35% for Tc, 60% for K).**

New Magnetic Clusters Synthesized

- Novel Chemistries and Structures
  - Non-equilibrium structures
  - Tailored interfaces
  - Self-assembly
- Scale comparable to atomistic modeling
  - Better understanding of the intrinsic effects of chemistry and crystalline structure and extrinsic effect of boundaries



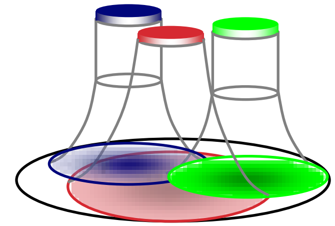
HRTEM Co-W alloy clusters



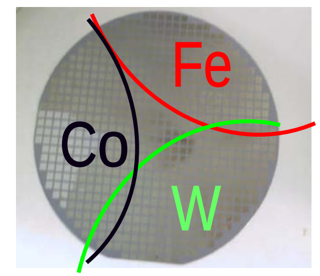
FePt + MgO

Combinatorial Magnet Alloy Search

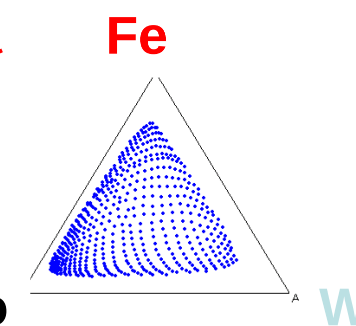
- Rapid investigation of phase space for Fe-Co-W magnet alloys.
- Utilize educated ‘guesses’ from modeling and data mining
- Used advanced characterization tools to rapidly analyze alloys

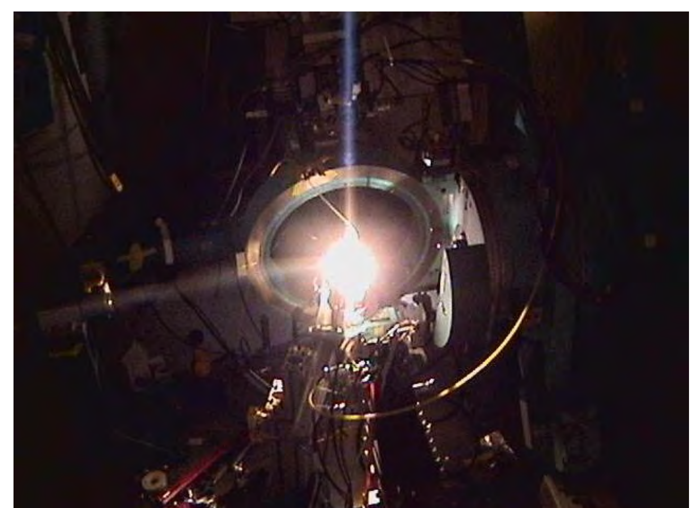


Co-sputtering scheme



3” wafer

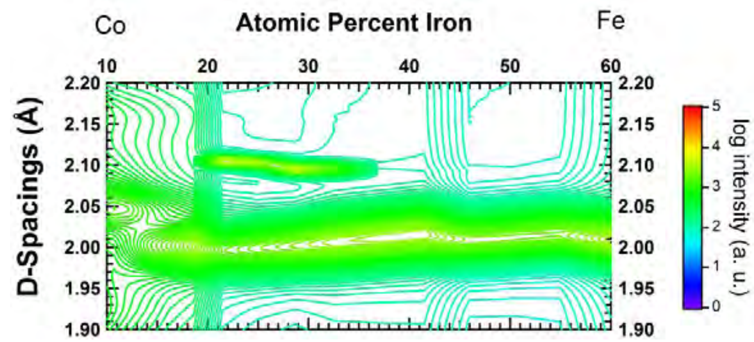


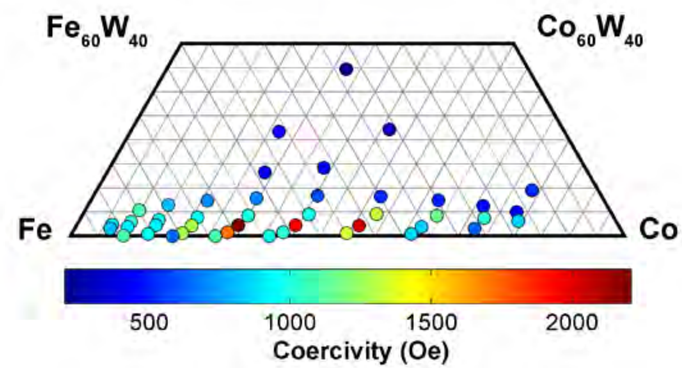


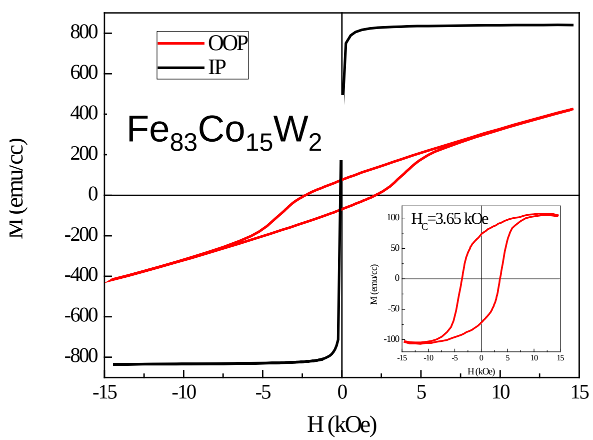
Newly designed sample holder and IR furnace to perform in situ diffraction analysis of combi samples at Stanford Synchrotron Research Laboratory (Feb 2011)

Putting the New Pieces Together

- Fe-Co-W
  - Theory
    - 5d elements in 3d matrix induces magnetocrystalline anisotropy
  - Multipronged Approach
    - Clusters (UNL and Brown)
    - Combi (UM)
    - Bulk synthesis (Ames)
    - Modeling (Ames, ORNL, UNL)







Results of the diffraction and magnetization analysis of the combinatorial experiments on Fe-Co-W

H_c as large as 3.7 kOe is observed

Roles of BREM Team Members

Leadership: Ames Lab (USDOE) <u>I.E. Anderson</u>, R.W. McCallum, M.J. Kramer

Theory:

Search for new structures: <u>K.M. Ho</u>, C.Z. Wang (Ames)

Intrinsic magnetic properties: V. Antropov, B. Harmon,(Ames); M. Stocks (ORNL)

Extrinsic magnetic properties: V. Antropov (Ames); R. Skomski, (UNL)

Solidification: R. Napolitano (Ames)

Synthesis:

Combinatorial synthesis: I. Takeuchi (UM), M.J. Kramer (Ames)

Chemical synthesis: S. Sun (Brown)

Clusters: D. Sellmyer, J. Shield (UNL)

Bulk synthesis: I.E. Anderson, <u>R.W. McCallum</u> (Ames); S. Constantinides (AMT),

Characterization:

Structural: <u>M. J. Kramer</u> (Ames); J. Shield (UNL); I. Takeuchi (UM)

Magnetic: R. W. McCallum (Ames); S. Constantinides (AMT); D. Sellmyer, J. Shield (UNL), S. Sun (Brown), I. Takeuchi (UM)

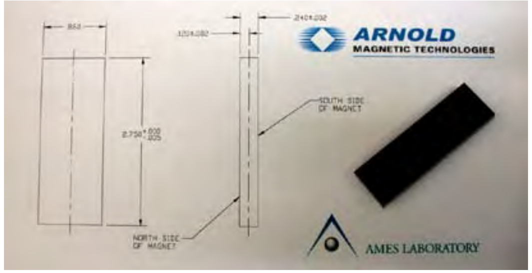
Collaborations and Partnerships

Collaborators:

- Magnequench International (Jim Herschenroeder): Magnet material manufacturing technology, CRADA partner.
- Arnold Magnetic Technologies (Steve Constantinides): Permanent magnet manufacturing technology, CRADA partner.
- Baldor (Mike Melfi): Electric motor manufacturing technology.
- Univ. Wisconsin-Madison (Tom Jahns): Electric machine design.
- General Motors (Greg Smith, Mike Milani): Traction drive design and manufacturing technology, CRADA partner.
- General Electric (Frank Johnson): Rare earth magnet technology and motor design.
- Unique Mobility (Jon Lutz): Advanced motor design.
- Univ. Texas-Arlington (Ping Liu): Nano-composite magnet design, DARPA partner.
- Motor Excellence (Tom Rainey): Advanced motor design.
- Molycorp (John Burba): RE resources/magnet technology, CRADA Partner.
- Univ. Delaware (George Hadjipanayis): Development of high-energy permanent magnets, ARPA-E partner (project lead).
- Universidad Nacional de Córdoba-Argentina (Paula Berkoff): Novel ferrite alloys having enhanced coercivity, Fulbright Scholar.

BREM Project:

- ORNL, Univ. Maryland, Univ. Nebraska, Brown Univ., Arnold Magnetic Technologies.
- Synthesis Partners (Chris Whaling): Automated search of permanent magnet literature---parallel project.



Remaining FY11 Highlights

- High Temperature RE Permanent Magnets
  - Complete development of anisotropic sintered magnets using pressure assisted sintering at reduced temperature.
  - Begin exploration of extrinsic additives to eliminate Dy use.
  - Complete study of aligned solidification patterning in MRE magnet alloy ribbon with low Dy, promoting anisotropic particulate for bonded magnets.

- Non-RE Permanent Magnets

– Develop theoretical tools for the investigation of potential new phases

– Complete analysis of commercial Alnico
  - Understand texture development during directional solidification
  - Explore parameter space for spinodal decomposition

– Complete combinatorial investigation of the Fe-Co-W system

– Complete analysis of cluster deposition in the Co-W system

– Chemically synthesize Co and Fe magnet particles for nanocomposites

- Regular WebEx Sharing of Results and Spring Workshop (May 2011)

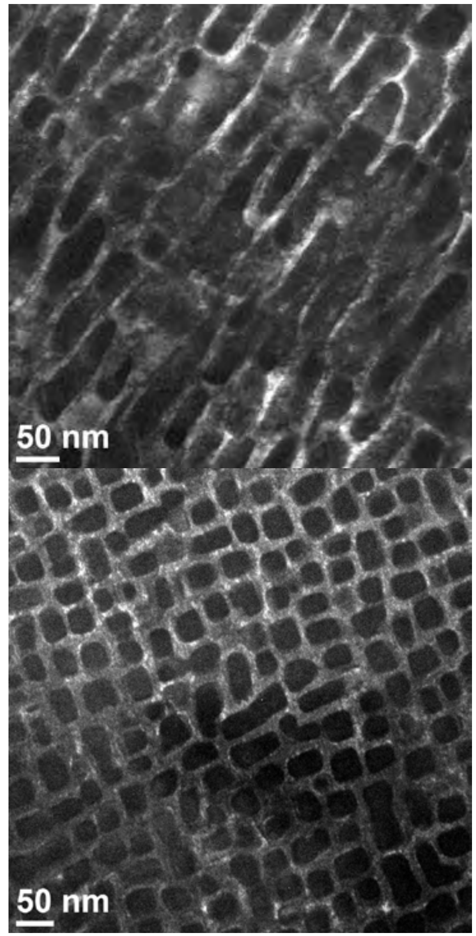
Beyond FY11

FY12

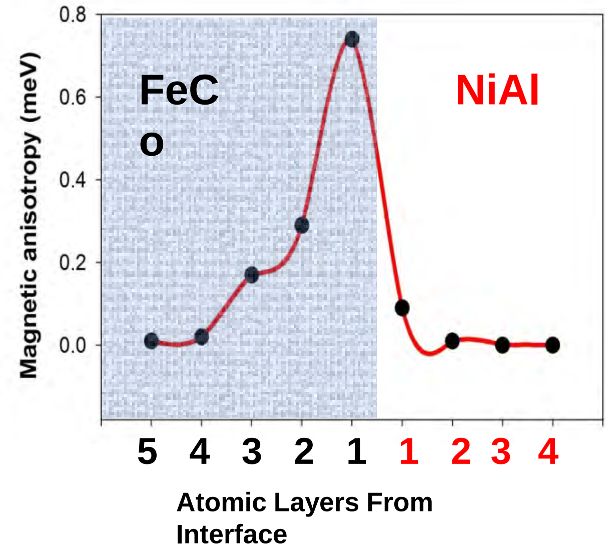
- High Temperature RE Permanent Magnets
  - Extend study of extrinsic additives to eliminate Dy use using pressure assisted sintering at reduced temperature..
  - Produce sufficient anisotropic particulate from MRE magnet alloy ribbon with low Dy to produce prototype bonded magnets.
- Non-RE Permanent Magnets
  - Based on theoretical guidance, identify ternary systems for further investigation
  - Use cluster synthesis to evaluate new systems
  - Use both thin film and bulk approaches to generate test samples of new magnet alloys
  - Investigate exchange coupled composites made by chemical synthesis
- Regular WebEx Calls and Fall/Spring Workshops

Alnico Microstructure

- Fe-Co rich precipitates in Ni-Al rich matrix
  - Decomposes along {001} planes
  - Proceeds in the <001> directions
- Preferential growth of precipitates parallel to a magnetic field
  - Spinodal decomposition range lies below $T_{(c)}$, allowing alignment
- Aligned precipitates enhance coercivity through shape anisotropy



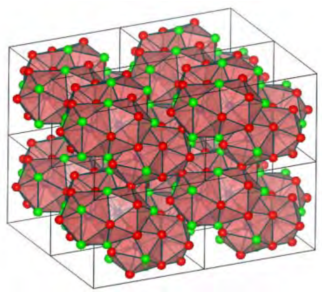
TEM DF images of Arnold Alnico 5-7
Fe-Co precipitates (dark) in a NiAl matrix (light)



- self consistent full potential density functional calculations predict anisotropy of FeCo layers at FeCo-NiAl interface is increased by two orders of magnitude

Structural Modeling

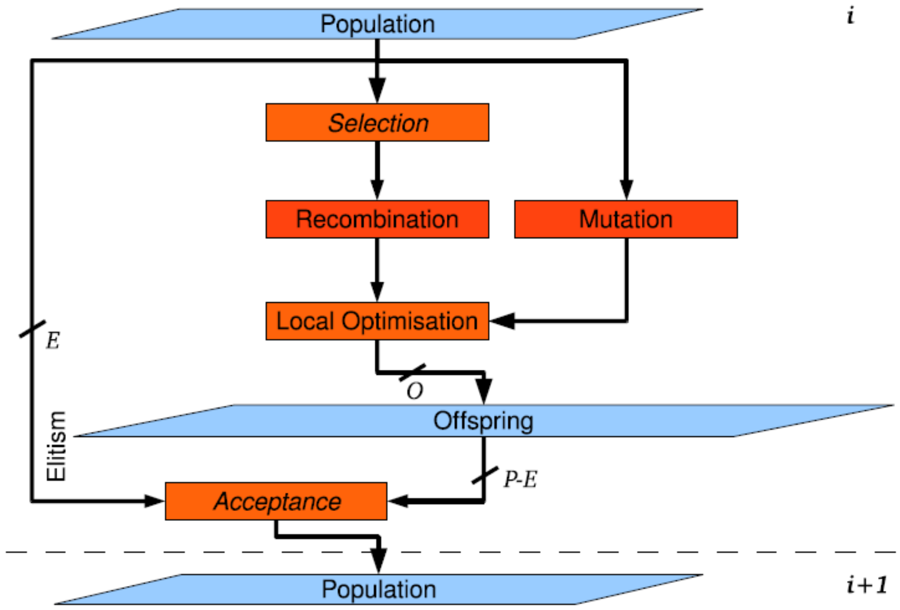
Genetic algorithm (GA) for global structure optimizations



•Our GA approach based on a physical representation (i.e., atomic coordinates) is simple but performs better than simulated annealing

Such GA approach has been successfully applied to

- Atomic clusters
- Surface reconstruction and step geometries
- Nanowires (Silicon)
- Interfaces (grain boundaries, metal/semiconductor)
- Crystal structures and compound semiconductors



- Searches using empirical potentials are fast but suffer from inaccuracies which can lead the search to wrong structures.
- GA searches using ab-initio calculations are restricted because the computational effort needed to effectively sample the structure configuration space is extremely demanding for any but the smallest unit cells.
- A breakthrough has been achieved that can address both the speed and effectiveness of the search with an accurate description of interatomic interactions in the Fe-Co system.

Summary

- ***High Temperature RE Permanent Magnets***

  Strong and dense anisotropic magnets of MRE (low Dy) magnet alloy were vacuum hot pressed at 800˚C and pressure-less sintered at 1050˚C, but more HT tests and a cost comparison are needed to select the best approach.

  Promising aligned solidification patterns resulted from RE magnet alloy ribbon with low Dy that was melt spun at low speed on a new heated wheel to promote anisotropic particulate for bonded magnets.

  A creative idea for an extrinsic additive to eliminate Dy use is just starting to be explored.

- ***Non-RE Permanent Magnets***

Analysis of commercial Alnico is underway to determine the action of additives for texture development during directional solidification and to map the parameter space for spinodal decomposition to improve coercivity, but a new alloying idea could add significantly to coercivity, if proven.

Theoretical tools are being exercised for the investigation of potential new phases that will be built around Fe-Co.

Combinatorial investigation of the Fe-Co-W system showed recently that W alloying in Fe-Co can increase coercivity, but the mechanism is unclear.

Cluster deposition in the Co-W system looks promising, but needs better control.

Chemical synthesis of Co and Fe based magnet alloy nano-particles has begun.