Creating Materials and Energy Solutions

Permanent Magnet Development for Automotive Traction Motors

2010 DOE Vehicle Technologies Annual Merit Review

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Project ID # APE015

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Project Overview:

Timeline

- Start - August 2001
- Finish - September 2014
- 65% Complete

Budget

- Total project funding
  - DOE share $5,750K (since FY01)
- FY09 Funding - $660K
- FY10 Funding - $2000K
- FY11 Funding - $2000K (planned)

Barriers/2020 Targets

- 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.

Partners

- Arnold Magnetic Technologies, Baldor, U. Wisc., GM, GE, Synthesis Partners (collaborators)
- ORNL, U. Maryland, U. Nebraska, Brown U. (subcontractors)
- Project lead: Ames Lab

Overall Objectives:

- To meet enhanced performance and reduced cost goals for simplified mass production of advanced electric traction motors, it is essential to improve the alloy design and processing of permanent magnets (PM), either with or without rare earth (RE) content.

- The fully developed PM material must be suitable for elevated temperature (150-200˚C) operation with superior magnetic performance to minimize motor cooling needs and must have competitive room temperature magnetic properties with high magnetic energy density to conserve strategic materials, especially for RE magnets.

Objectives for FY10

Increase energy density & retain high temp. tolerance

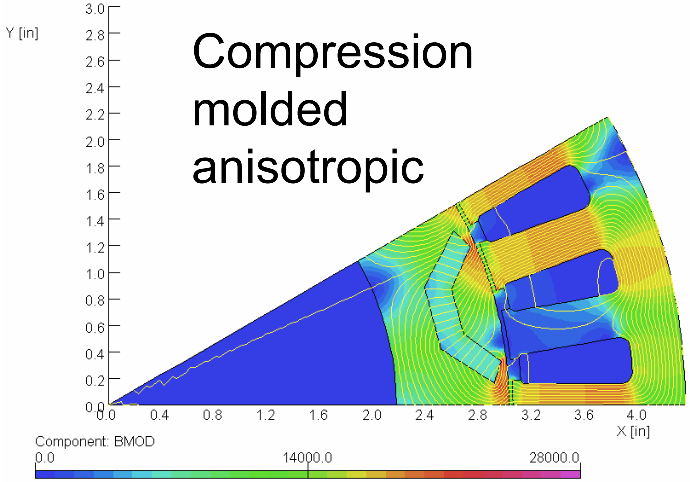
- Select intrinsic or extrinsic sintering approach for anisotropic full density magnets with highest energy product (4-6X isotropic bonded) with high temperature (HT) stability from single crystal micron-sized particles.
- Test methods for anisotropic nano-crystalline particulate production to enable molding of aligned net-shape polymer bonded magnets for 2-3X greater magnetic strength than isotropic bonded magnets.
- Initiate high risk major thrust “Beyond Rare Earth Magnets” (BREM) to develop permanent magnets without RE content to meet performance metrics aligned with advanced motor requirements.

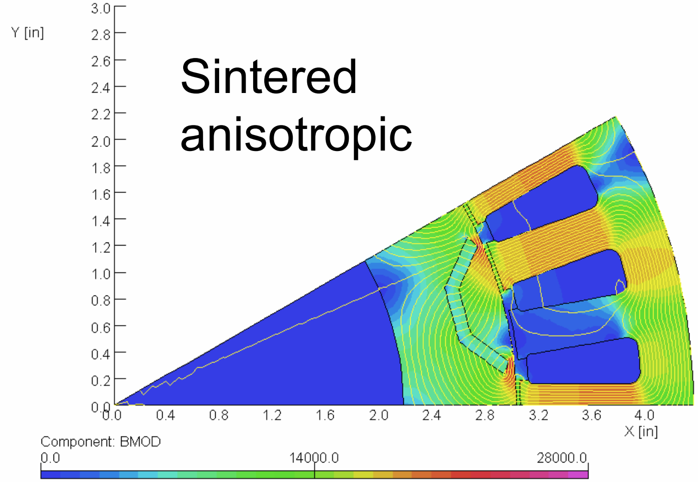
DOE 2020 targets: Enhanced energy density (Specific power >1.4kW/kg) and reduced cost (<$8/kW)

Milestones for FY09 and FY10

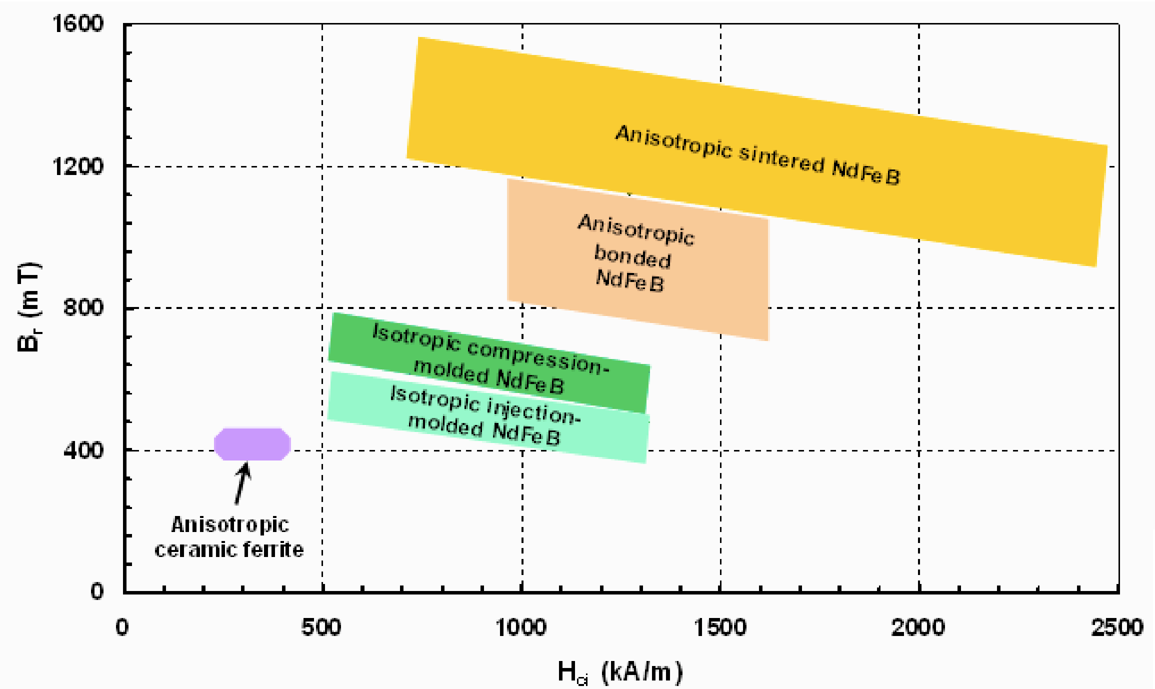
Month/Year	Milestone or Go/No-Go Decision
Jan-09 Mar-09 Sep-09	Milestone: Report results of industry expert (Peter Campbell) magnet cost/motor technology study and analyze project impact. Milestone: Determine initial alloys for anisotropic nano-crystalline magnetic particulate processing trials. Milestone: Assess process options for anisotropic bonded magnet particulate development.
Dec-09	Milestone: Conduct a special invited workshop to identify productive directions for research in high performance non-rare earth permanent magnets with the planned research team that will lead to development of a detailed action plan for the project.
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.

Anisotropic Magnet Types for IPM Motor Designs





•FEM magnetic field analysis comparison from Peter Campbell (industry expert) report.*



*Ames Laboratory Report No. IS-5191 (2008)

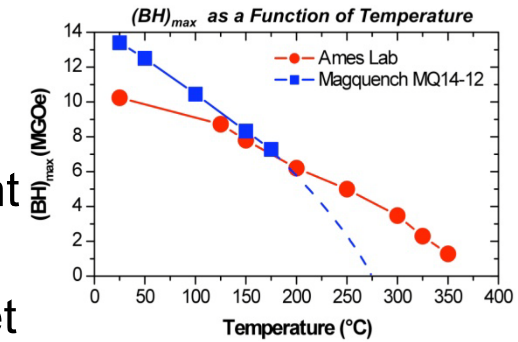
Recommendations:

•Trade-off between magnetic energy density and manufacturing simplicity.

•Develop anisotropic sintered form of Ames HT magnet alloy.

•Compression molding of bonded anisotropic HT alloy particulate should have IPM motor cost advantage.

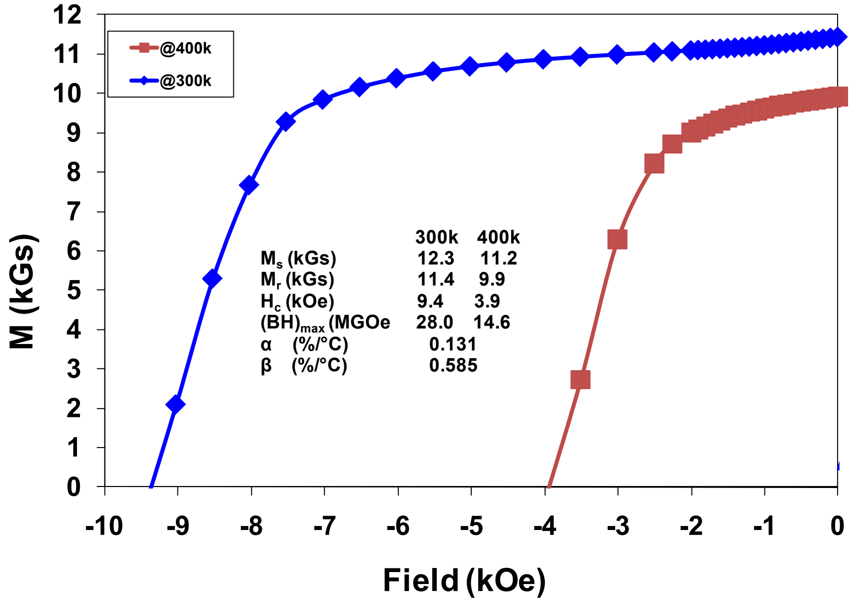
Technical Approach for FY10



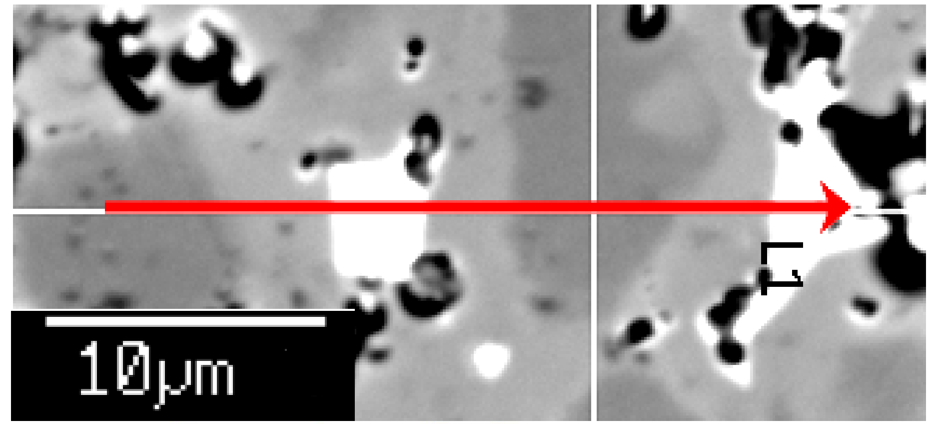
- Task 1: Explore prospects for anisotropic sintered permanent magnets from the MRE-Fe-B alloys using modified **intrinsic** liquid phase sintering with La substitution for Y during magnet consolidation or at reduced temperatures with elevated pressure to bypass RE partitioning problem in high temperature (HT) magnet alloy.
- Task 2: Investigate consolidation of anisotropic sintered permanent magnets from MRE-Fe-B using novel **extrinsic** liquid phase sintering at reduced temperatures with low level Dy addition during consolidation to limit Dy use but to promote coercivity at HT.
- Task 3: Develop enhanced directional growth of nano-crystalline structure in glassy RE magnet alloy flake with uni-axial pressure to enable crushing to anisotropic particulate for bonded aligned magnets.
- Task 4: Utilize invited workshops to help formulate new research thrust on non-RE permanent magnets with selected partners and technology advisors to assess magnet targets for advanced traction motors and initiate progress on BREM thrust goals.

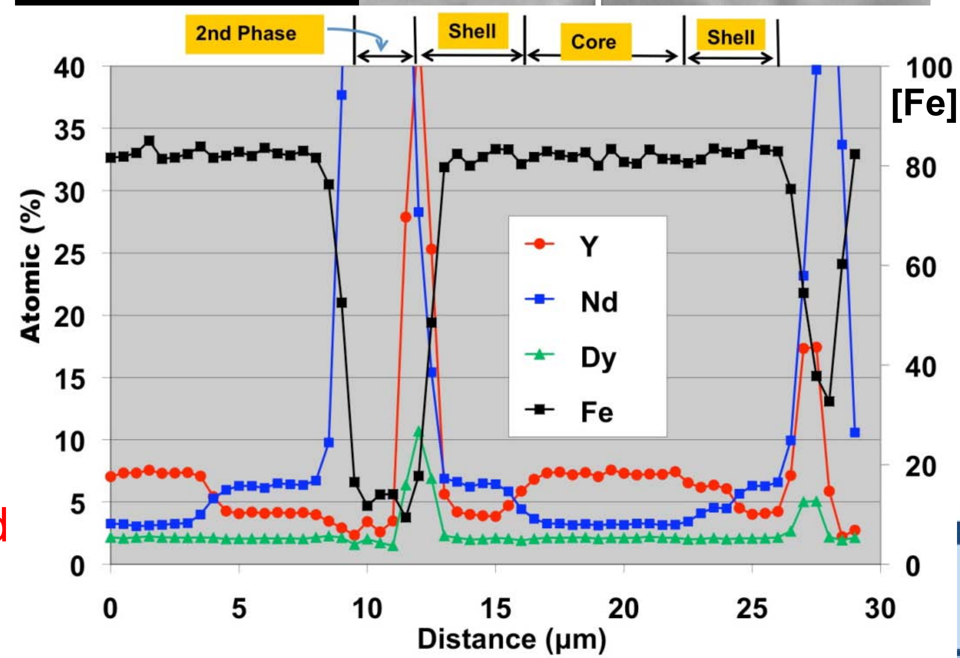
•Approach supports anisotropic (aligned) magnet emphasis recommended by industry expert and begins non-RE magnet discovery and development thrust.

Intrinsic Sintering of Anisotropic MRE Magnets: Use of Typical HT Alloy Results in RE Partitioning



$[Nd_{0.45}(Y_3Dy_1)_{1/4*0.55}]_{2.6}Fe_{bal}B_{1.2}$





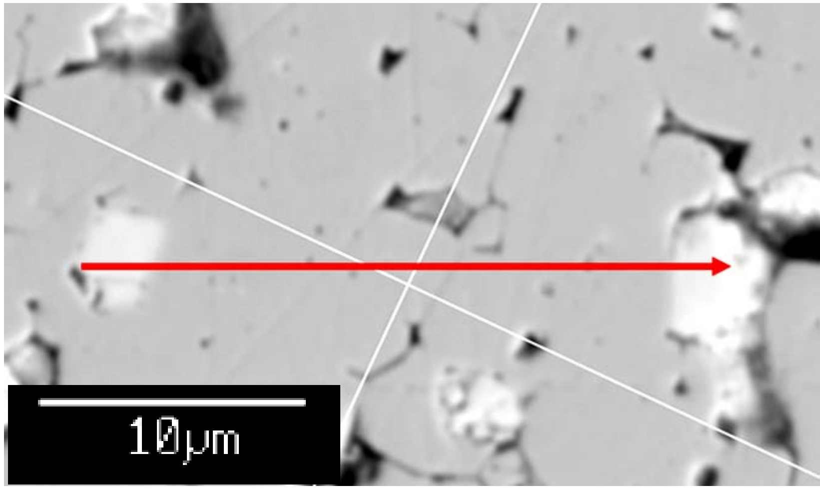
- Sintered MRE magnets have high $(BH)_{max}$ of 28MGOe, but un-expectedly higher temperature coefficients than previous results.
- SEM and Electron microprobe studies show that the 2-14-1 grains develop "core-shell" segregation within 2-14-1 grains on HT sintering: probable cause for poor *high temperature tolerance*.

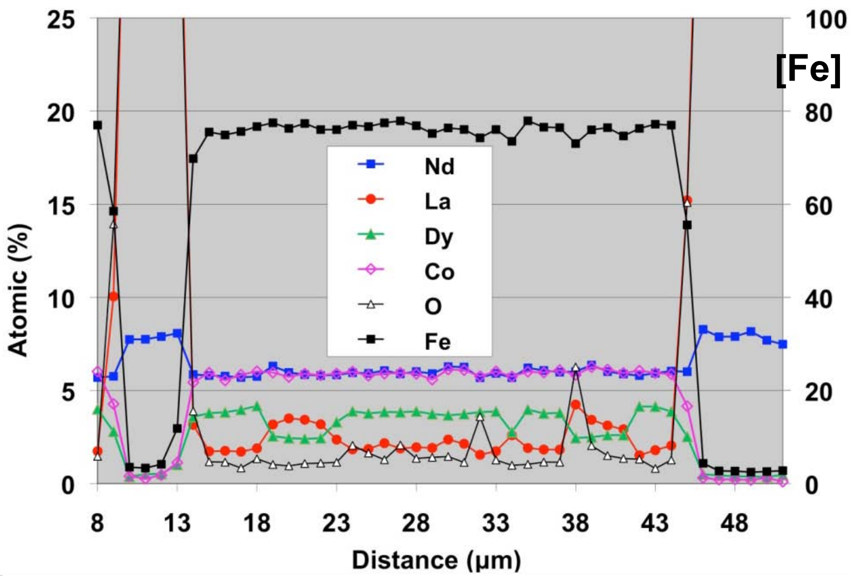
HT sintering needed to achieve high density sintered magnet.

Intrinsic Sintering of Anisotropic MRE Magnets: La Substitution for Y Suppresses RE Partitioning

- We attribute the Nd-Y segregation in the Nd-Y-Dy case to the differences in phase diagrams between the light and heavy RE.
- If true, substituting La for Y should reduce the segregation within grains.
  - Magnetically equivalent in 2-14-1 phase
  - La detrimental for glass formation in rapid solidification, but not bad for strip casting of crystalline alloy precursor for HT sintering
- Results after HT sintering show no Nd partitioning, but some La oxidation.
- Magnetic characterization in-progress.
- Process parameters must be improved to optimize magnetic properties (temperature coefficients?)

$[Nd_{0.45}(La_3Dy_1)_{1/4*0.55}]_{2.6}Fe_{bal}B_{1.1}$





Vacuum hot pressing (VHP) to reduce need for alternative alloying & permit lower T sintering: trials in-progress.

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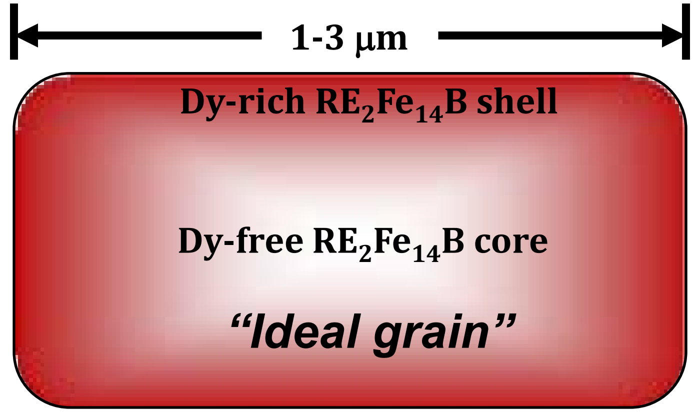
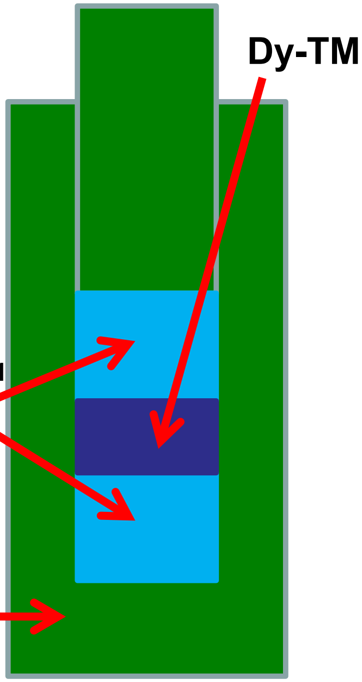
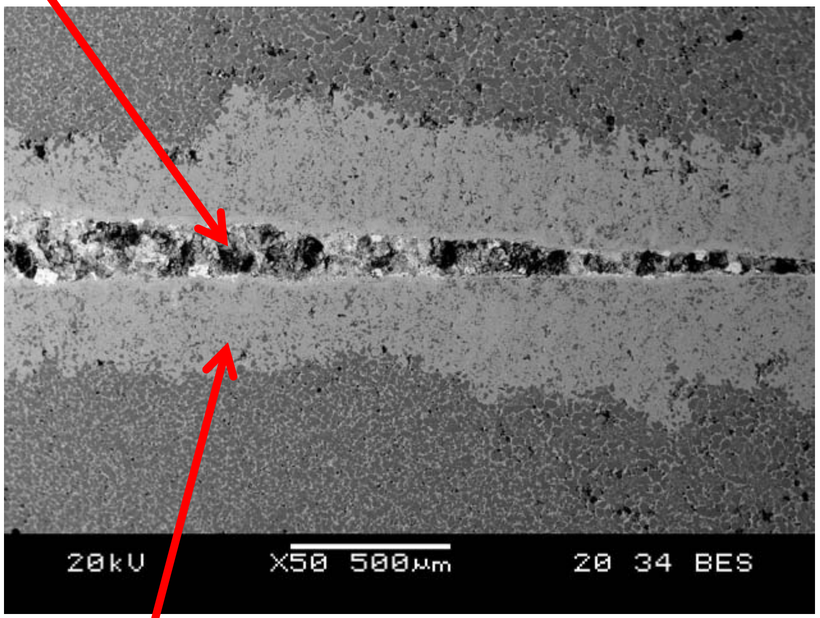
Extrinsic Sintering Aid to Reduce Dy Content/Cost



- Dy portion of HT RE-PM alloy up to 60% of cost.
- Dy-rich shell known to suppress reverse domain nucleation/critical boost to coercivity.---for HT
- Selected Dy-TM alloy for liquid phase sintering effect.
- Started diffusion couple experiments (650˚C,1h) to evaluate the use of Dy-TM alloy as an extrinsic sintering aid to produce Dy gradient on $La_2Fe_{14}B$ grains.
- Initial experiments validated the approach.



Dy-TM remnant

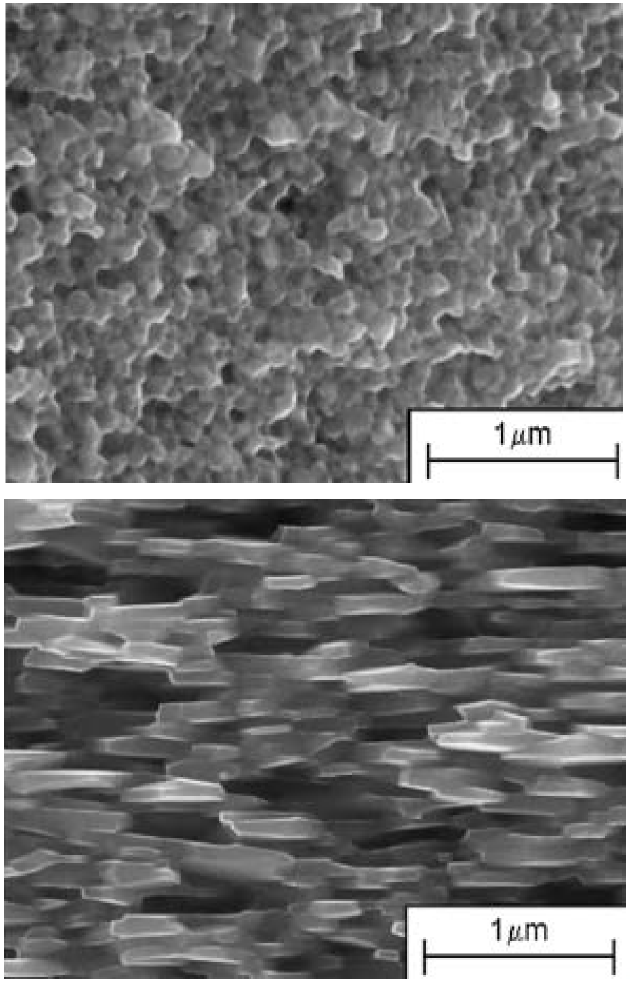


Dy diffusion into 2-14-1 disk (initial result)

Further tests planned with short time/inert capsule, then VHP of blends.

Pressure-Induced Anisotropic Nano-Crystalline Powder: Molding of Aligned Bonded Magnets into IPM Rotor

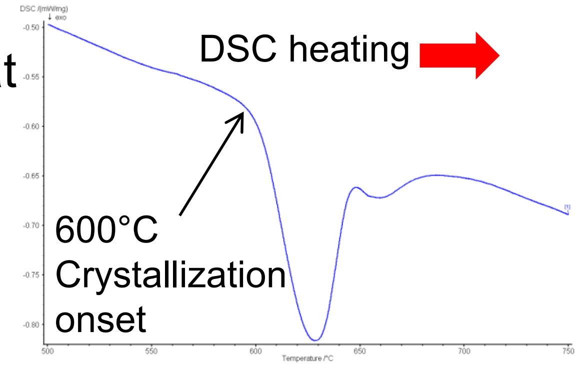
- Produce glassy ribbon of MRE-Fe-B.
- Load die with ribbon/flake (flat orientation) for vacuum hot pressing.
- Apply uniaxial pressure during slow heating to initiate a-axis crystallization.
  - Favored growth direction [ref. W.B. Kamb]
  - Seen in die upsetting process
- Cool rapidly under pressure to restrict further grain growth & coarsening.
- Crush resulting compact to equi-axed particulate for blending with polymer.
- Mold net-shaped bonded magnets under magnetic field.

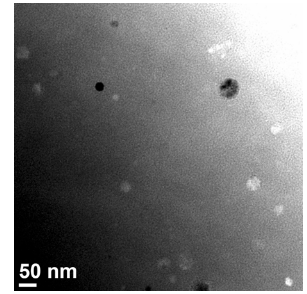


K. Khlopkov et al.

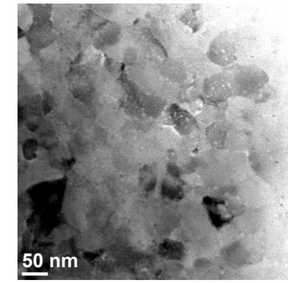
Promising Pressure-Induced Anisotropic Crystallization

- Samples were annealed at 580°C for 1 hour under 110 MPa uniaxial pressure.
- X-ray diffraction shows strong degree of texturing.
- SQUID magnetometer readings show texture.
- Very little coercivity seen.
    - Likely caused by excessive grain growth (need TEM)
- Similar results for both Nd-Fe-B and MRE-Fe-B.
- Microstructure coarsening may be restricted by tight control of VHP parameters & carbide (Ti,Zr) additions.

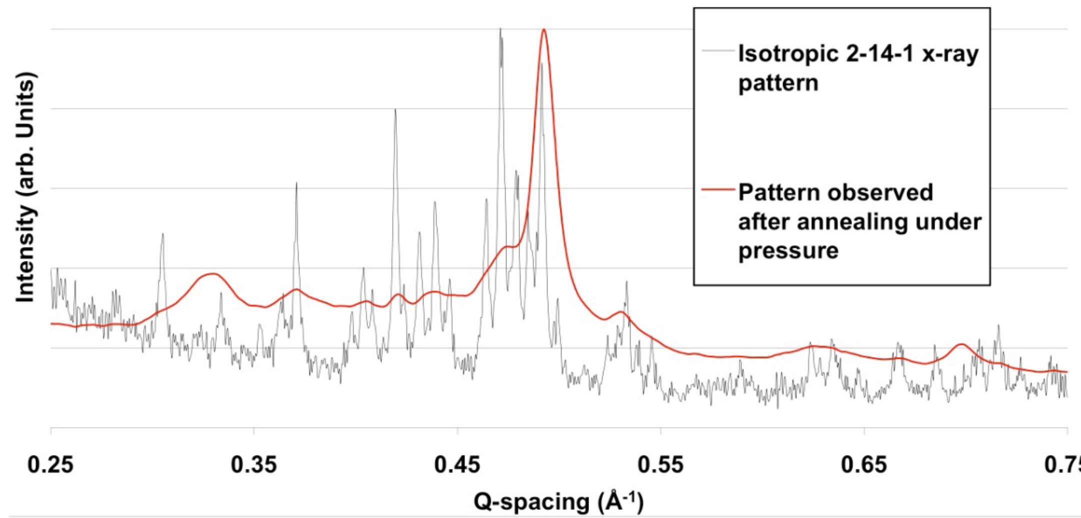




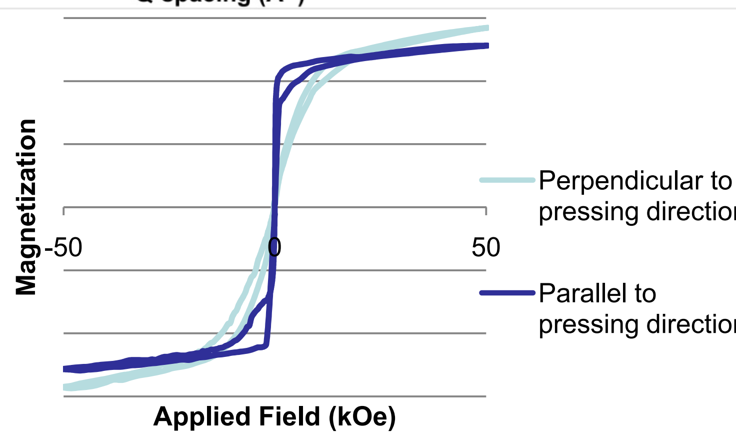
As-Spun



Annealed without uniaxial pressure



To try new induction heated vacuum hot press for better temperature accuracy and faster cooling.



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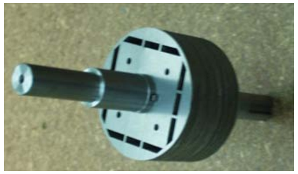
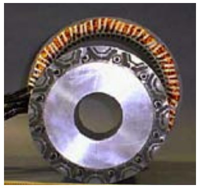
New Thrust: Beyond Rare Earth Magnets (BREM)

The Challenge:

Can high strength permanent magnets be made strong enough without the use of strategic rare-earth metals?





The Questions:

◆What specific magnetic properties are needed from non-RE permanent magnets for advanced electric traction motors?

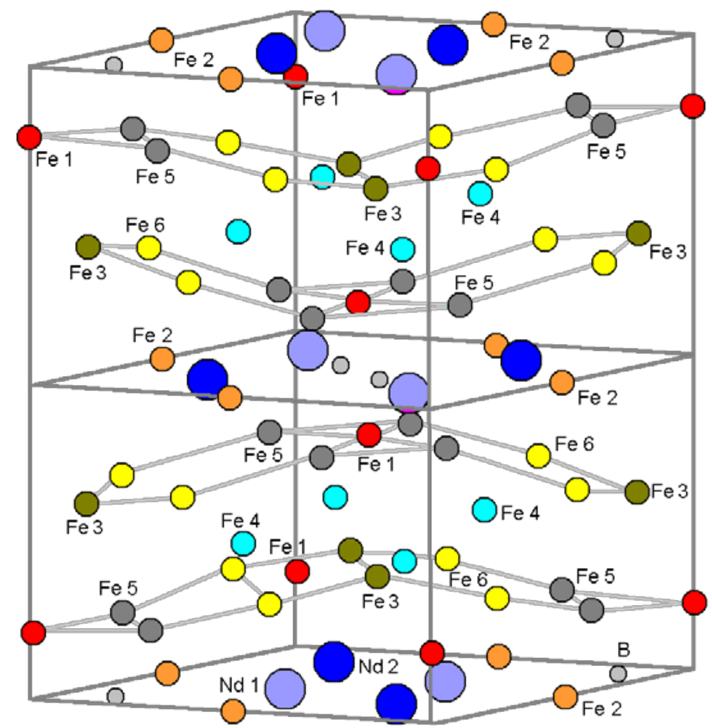
◆Can these magnets be developed by improvement of existing types or must new PM materials be discovered with modern theory and experimental methods?

- Advanced motors, e.g., interior permanent magnet (IPM) machines, offer degrees of design freedom that make it possible to replace magnet torque with reluctance torque in order to reduce magnet requirements
- The greatest challenge for development of non-RE magnets probably involves achieving enhanced coercivity and maintaining it at high temperatures, even though IPM machine designs may reduce vulnerability to demagnetization.

Large mutual benefits for material scientists and machine designers to work together in developing new non-RE permanent magnets.---Prof. Tom Jahns at BREM Workshop, 5-6 November 2009.

Beyond Rare Earth Magnets (BREM):
Approach to Magnetic Materials by Design

- Strategic need to develop alternatives to RE-Fe-B magnets.
- Approach defined to bring modern tools and understanding of magnetism together
  - A multi-disciplinary approach
    - Theory/Synthesis/Characterization
- Each of the disciplines charged to provide close feedback and guidance to the others.
- Maintain interactions with motor designers/magnet industry, e.g., at BREM workshops.
  - Need consistent set of metrics and goals
    - Develop non-RE PM targets consistent with PEEM motor targets



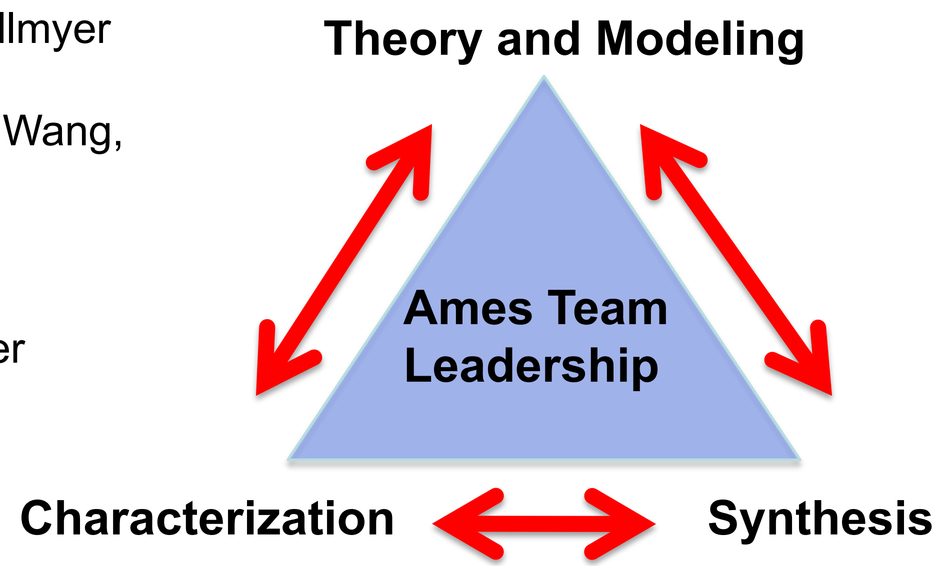
Prototype unit cell structure ($Nd_2Fe_{14}B$), 1984, 64 MGOe (theory)/55 MGOe (actual)

Beyond Rare Earth Magnets (BREM) Approach

Theory and Modeling Group
(ORNL) Malcolm Stocks
(Univ. NE-Lincoln) Ralph Skomski, Dave Sellmyer
(Univ. MD-College Park) Ichiro Takeuchi
(Ames) Kai-Ming Ho, Vladimir Antropov, CZ Wang, Bruce Harmon, Matt Kramer

Characterization Group
(Univ. NE-Lincoln) Jeff Shield, Dave Sellmyer
(Univ. MD-College Park) Ichiro Takeuchi
(Brown Univ.) Shouheng Sun
(Ames) Matt Kramer, Bill McCallum, Bruce Harmon

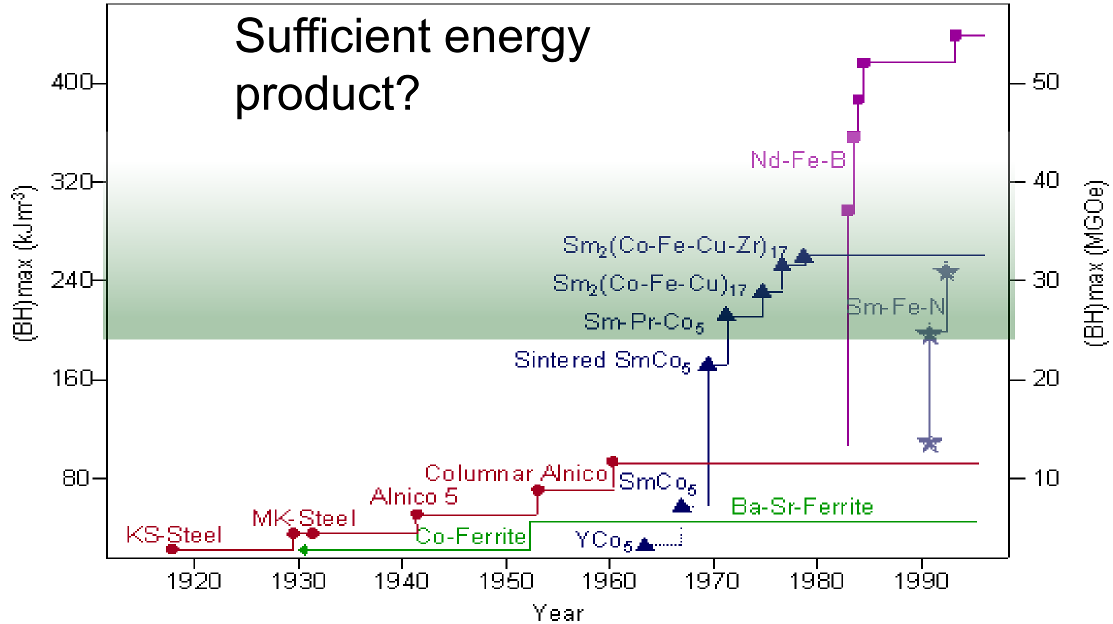
Synthesis Group
(Univ. NE-Lincoln) Jeff Shield, Dave Sellmyer
(Univ. MD-College Park) Ichiro Takeuchi
(Brown Univ.) Shouheng Sun
(Ames) Bill McCallum, Matt Kramer, Iver Anderson

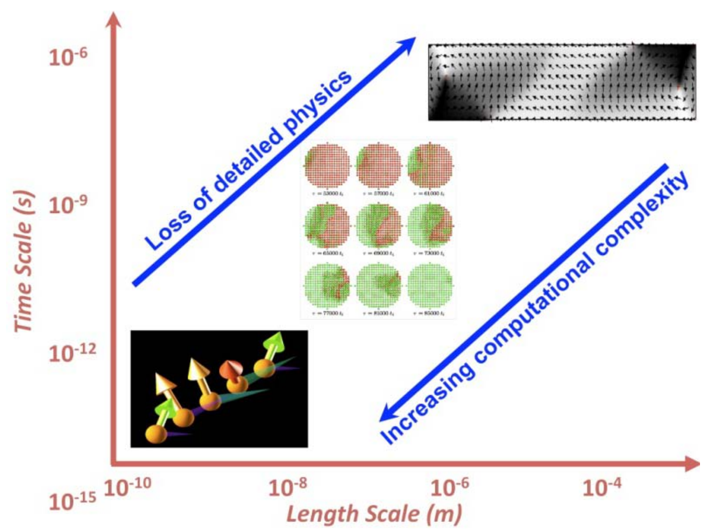


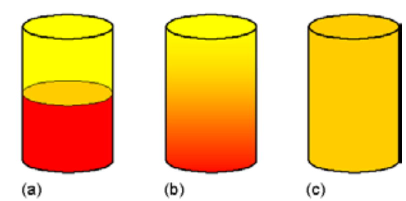
Technology Advisors
(Baldor) Mike Melfi
(Univ. WI-Madison) Tom Jahns)
(Arnold Magnetics) Steve Constantinides

Routes to Better Non-Rare Earth Permanent Magnets

- Improve on known systems, e.g., Alnico.
  - Enhanced knowledge of coercivity mechanisms
  - Enhanced control of composition and microstructure
- Discover new primary monolithic phases with crystalline anisotropy.
  - High Curie temperature
  - High magnetization
  - Magnetic anisotropy
- Promote coercivity with enhanced exchange coupled composite structures.
  - Meso-scale modeling





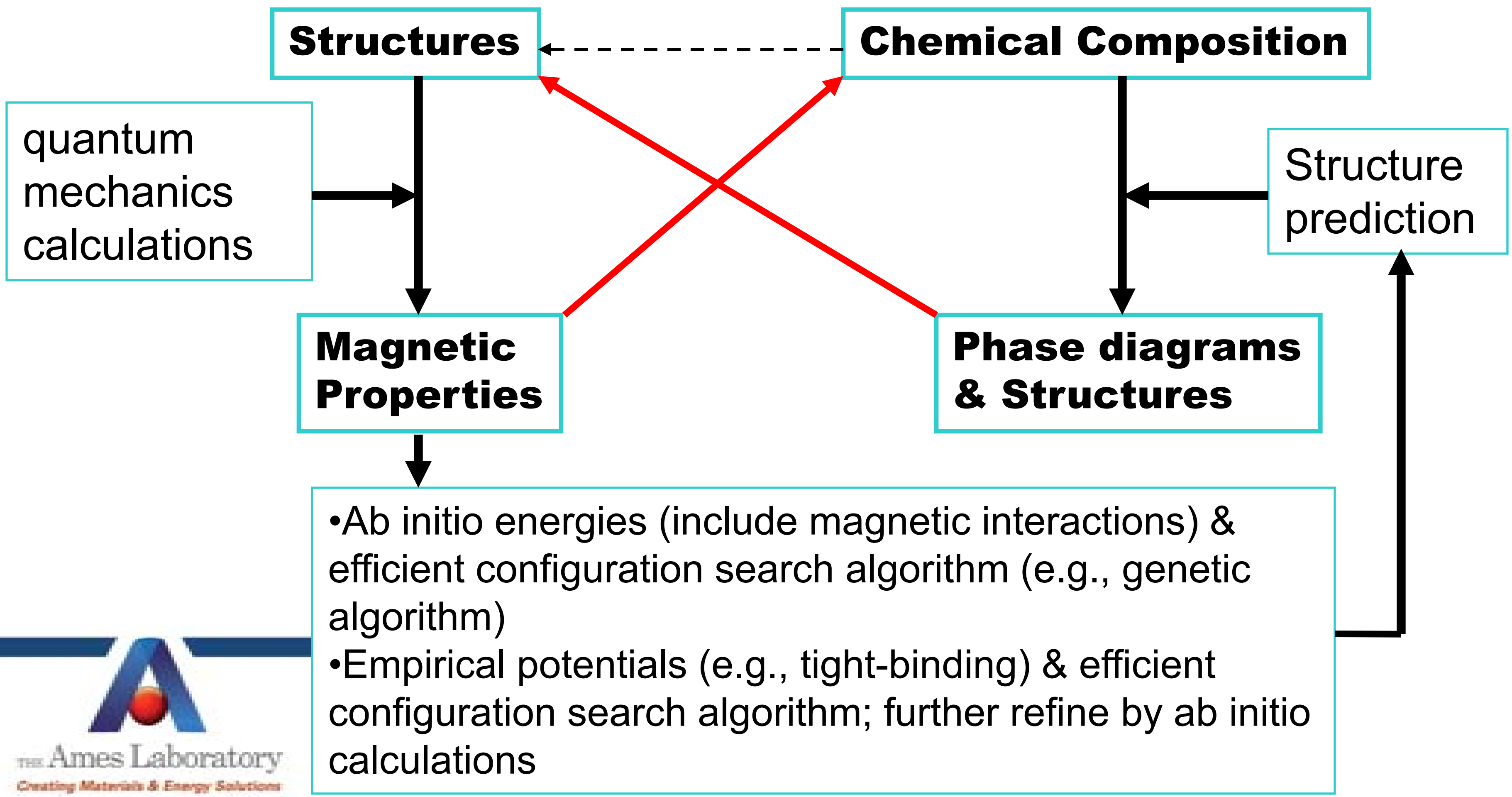


Graded hard phase can improve coercivity of hard-soft composites.

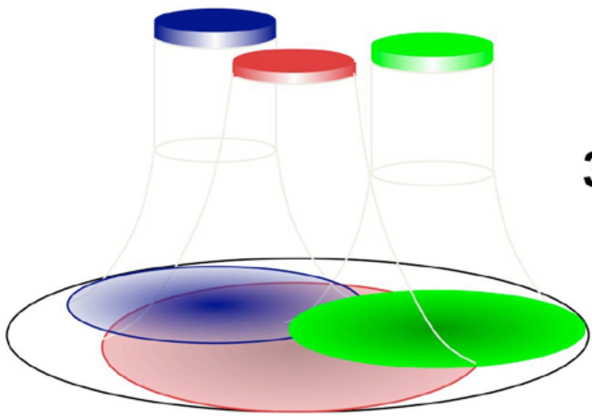
Theory Efforts Started at Ames Laboratory

Two Thrusts:

1. Magnetic properties calculations (initially on Fe-Co, Fe-N, Fe-Co-N)
2. Theoretical phase diagram exploration and structural optimization

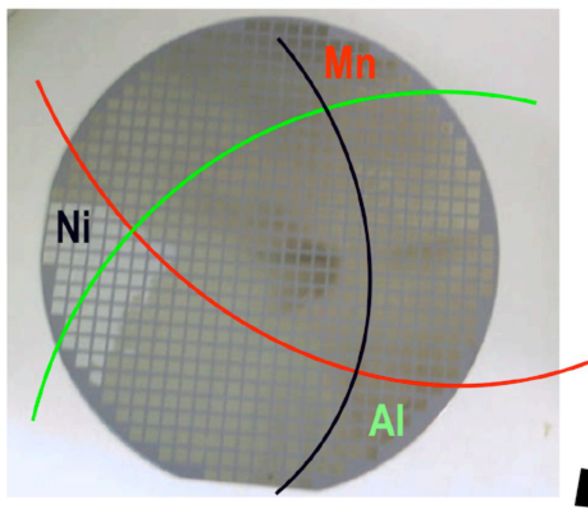


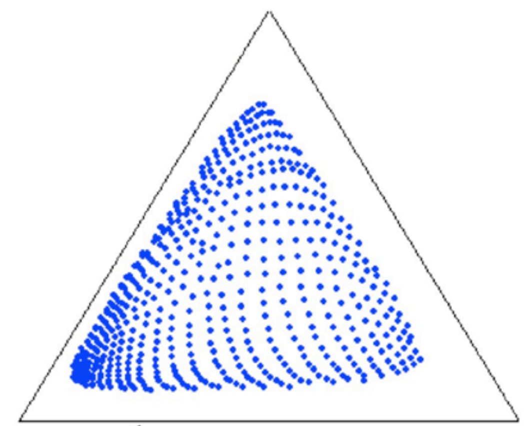
Synthesis/Characterization Approach: Composition Spreads for Initial Ternary Magnetic Alloy Systems



Co-sputtering scheme

3" spread wafer, 300 tiles





Phase diagram

- Composition is mapped on each tile by electron probe (WDS).
- Magnetic properties of tiles by MOKE and SQUID magnetometer.
- High spatial resolution X-ray diffraction to identify structurally.

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---developing collaboration
- Synthesis Partners (Chris Whaling): Automated search of permanent magnet literature.---developing collaboration

BREM Subcontractors:

- ORNL, Univ. Maryland, Univ. Nebraska, Brown Univ.

Portion of 100kg batch of 11HTP Ames alloy flake.

Future Work

FY2010

Aligned/Sintered Magnets

- Better (low O_2) **intrinsic** sintering trials (La replace Y): TEM and SQUID results.
- Induction VHP for **intrinsic** sintering at lower T (Y or La)
- Try Dy-TM as **extrinsic** sintering aid with VHP (Nd-Y or Nd-La in 2-14-1)

Anisotropic Bonded Magnets

- Select induction VHP parameters to stimulate onset of crystallization/avoid coarsening.
- If needed, use TiC or ZrC additions for coarsening control.
- Test multilayer ribbon/flake compacts: extensive TEM/XRD.
- Try moderated melt spinning.

Non-RE Magnets

- Begin evaluation of PM literature search methods and develop search criteria.
- Conduct mid-year workshop to define detailed route.
- Theory/synthesis into binary monolithic anisotropic phases.
- Test synthesis/self assembly of dual phase (spring) types.

FY2011

- Develop robust processing route for anisotropic sintered MRE permanent magnets with HT tolerance, reduced magnet alloy costs, and suited to mass production of drive motors.
- Enhance best approaches (solid-state or solidification) for anisotropic nano-crystalline particulate for MRE bonded magnets with greatly increased magnetic strength.
- BREM Research (brief):

Theory Group

Explore binaries and first ternaries to find anisotropic structures & compositions.

Synthesis Group

Combinatorial synthesis of next anisotropic phases. Nano-particle synthesis/self assembly of model dual phase systems.

Characterization Group

Generate/share magnetic and structural results to guide experimental synthesis and theory groups on next trials.

Summary

•Solid Advances in HT Anisotropic RE Magnets

- ✧ In RE permanent magnet work, two viable pathways to exploit energy density benefits of **anisotropic magnets** are being pursued; anisotropic sintered magnets and anisotropic particulate for bonded magnets, consistent with industry expert recommendations.
- ✧ Rare earth (La) substitution was utilized to suppress a segregation problem during **intrinsic** sintering of a typical experimental mixed RE magnet alloy.
- ✧ Development of a novel **extrinsic** sintering addition to mixed RE magnet alloys holds promise for extremely low Dy use in high coercivity sintered magnets.
- ✧ Pressure-assisted crystallization of glassy ribbons is a promising technology for producing anisotropic particulate for aligned bonded magnets, if closely controlled.
- ✧ Induction heated hot press can help develop both anisotropic RE magnet types.

•Beyond Rare Earth Magnets: Major Thrust

✧Partnership planning workshop held 5-6 November 2009 with full participation of planned team and valuable input from technology advisors and PEEM.

✧Statements of work developed for project and with each partner in collaborative process that defined group interaction process and initial milestones.

✧Full Ames Lab team started joint work (December 2009) and subcontracts for all partners started (April 2010)---Mid-year workshop (13-14 May 2010)

•Encouraging outlook for development of advanced PM (RE and non-RE alloys) to enable efficient/compact electric drives.