Permanent Magnet Development for Automotive Traction Motors

Includes: ***Beyond Rare Earth Magnets (BREM)***

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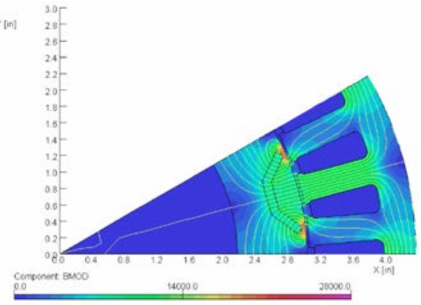


U.S. DEPARTMENT OF ENERGY

Energy Efficiency & Renewable Energy

May 16, 2012

THE Ames Laboratory

Creating Materials & Energy Solutions

U.S. DEPARTMENT OF ENERGY

Project ID #APE015

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Overview

Timeline

- Start - August 2001
- Finish - September 2015
- 79% Complete

Budget

- Total project funding
  - DOE share $10,550K (since FY01)
- FY11 Funding - $2400K
- FY12 Funding - $2400K
- FY13 Funding - $2400K (planned)

Barriers

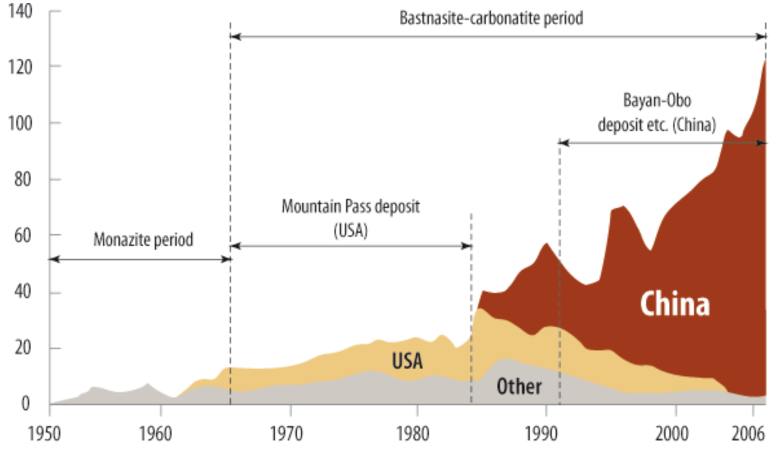
- Higher operating temperature (150-200˚C) and long life (15 yrs.) needed for magnets in PM motors.
- Permanent magnet (PM) energy density increase needed in PM motor (Specific power >1.4kW/kg) to reduce cost (<$8/kW).
- Highly efficient interior PM motors (>94%) require sintered or bonded magnets with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

Partners

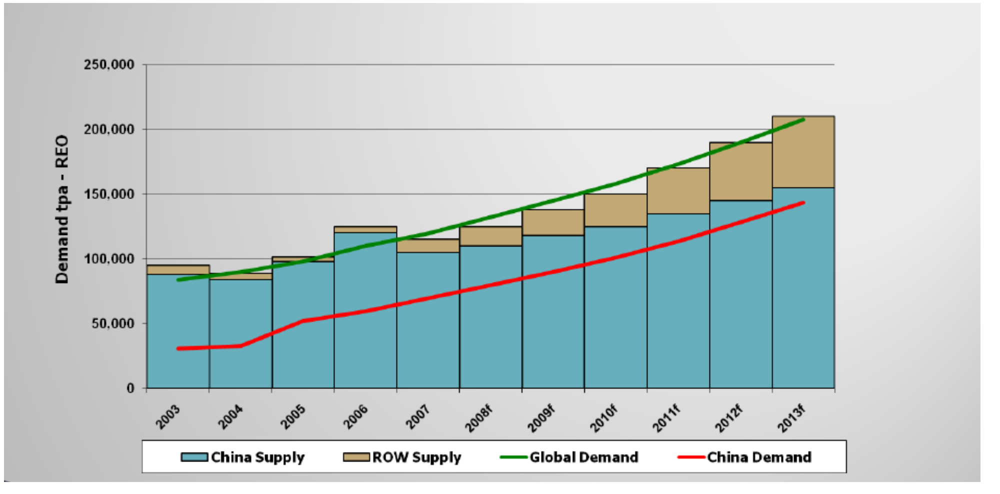
- Baldor, U. Wisc., U. Texas, GM, GE, UQM, Motor Excellence, Synthesis Partners (collaborators)
- ORNL, U. Maryland, U. Nebraska, Brown U., Arnold Magnetics (BREM subcontractors)
- Project lead: Ames Lab

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



The World's Production of Rare Earth Metal Oxides (in 1,000 t). Source: USGS



Project Relevance

Goals

- Develop non-RE permanent magnets with sufficient coercivity and energy product for advanced IPM traction motors.
- Further develop anisotropic sintered rare earth (RE) magnets to achieve highest energy product (4-6X isotropic bonded) and anisotropic bonded RE magnets (2-4X isotropic bonded) with high temperature stability & little or no Dy.

Targets Addressed

The goal of this research is 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

Rising RE cost pressure and on-going reduction of import quotas for RE supplies (particularly Dy) motivates a continuation within this permanent magnet project of a major research effort to elevate transition metal-based permanent magnet designs (modify or discover new) to the realm of the high magnetic strength (especially coercivity) necessary for high torque drive motors.

US/EU/Japan file joint request on March 13, 2012, for negotiations with China at the WTO on expansion of international trade in RE and REO.

Milestones for FY11 and FY12

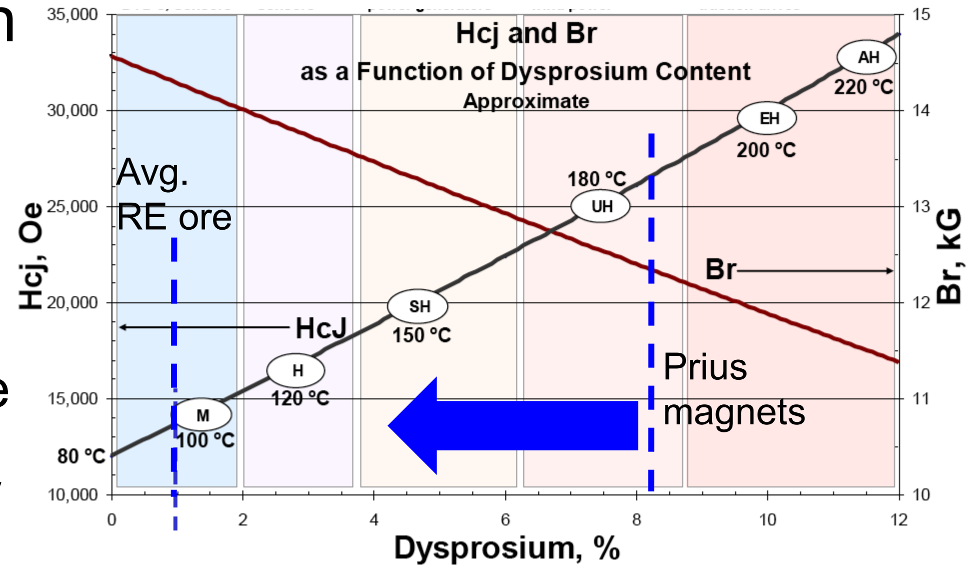
Month/Year	Milestone or Go/No-Go Decision
Sep-11	Milestone: Conduct initial search for new monolithic high performance non-RE permanent magnets, reporting results in papers and generating intellectual property, if needed. Milestone: Start development of enhanced coercivity in existing Alnico type magnets with BREM research team by enhancing crystallization and precipitation alignment and interface straining. Milestone: Pursue anisotropic sintered MRE-Fe-B permanent magnets with pressurized intrinsic sintering at reduced temperature and explore extrinsic additives to eliminate Dy use.
May-12	Milestone: Conduct sixth regular BREM workshop with team to exchange results and refine directions for non-RE magnet work. Milestone: Complete study of aligned solidification patterning in MRE magnet alloy ribbon with low Dy to accentuate anisotropy in crystallized particulate for bonded magnets.
Sep-12	Milestone: Complete analysis of commercial Alnico: alloy influences on columnar solidification development and spinodal partitioning and ultimate reduction of spinodal scale. Milestone: Theoretical tools expanded for the investigation of potential new Fe-Co-X phases on clusters and supercomputers. Milestone: Extend experimental investigations of Co-X, Fe-X, & Fe-Co-X systems (X=e.g., W, Ta, Mo, Hf) with combinatorial synthesis, cluster deposition, and chemical synthesis

Approach:

RE Permanent Magnets for high temperature with little or no Dy

New high strength anisotropic mixed rare earth (MRE) magnets will be developed with high temperature (HT) stability & little or no Dy, **using Y substitutions** and unique processing to meet the cost and requirements for advanced interior PM electric traction motors.

Typical Dy additions to $Nd_2Fe_{14}B$

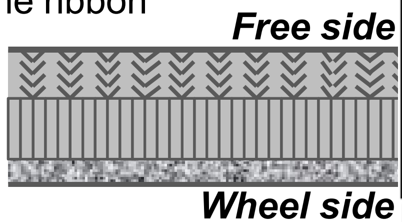


- Anisotropic bonded RE magnets (no Dy)
  - Through-thickness aligned ribbon solidification from Ag addition for unique alignment of cellular dendrites.
  - Refine cells by enhanced melt spinning to boost coercivity.

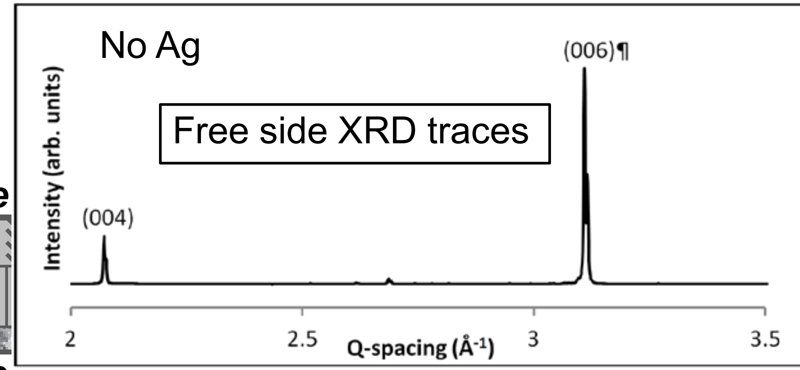
- Anisotropic sintered RE magnets (reduced Dy)
  - •Diffuse coating of DyF_3 "paint" to MRE 2-14-1 grain boundaries; higher coercicity/lower Dy content.
  - •Sintering at lower temperature (low T_m melt) in press for directional crystallization of glassy ribbon without RE segregation.

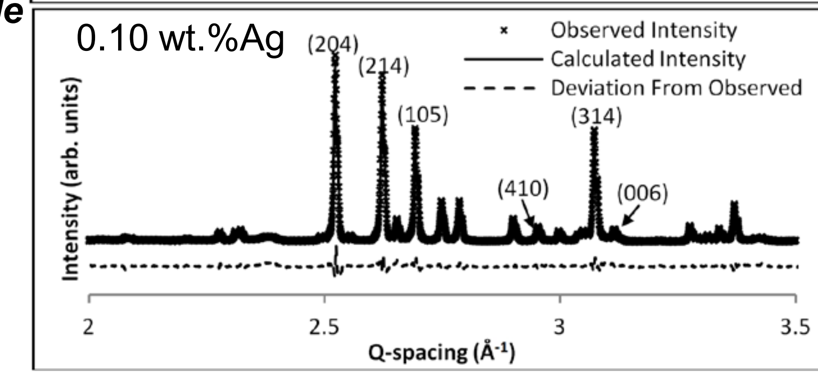
Accomplishment: Direct Texturing Strategy (Ames Lab)

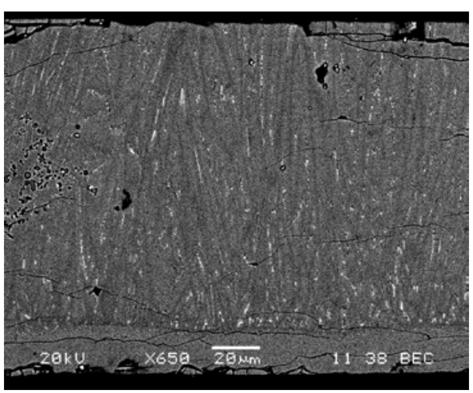
- Low wheel speed (5m/s) melt spun Nd-Y based 2-14-1 produces three distinct regions
  - Caused by variance in solidification front velocity through the thickness of the ribbon
  - Fine equiaxed zone
    - Lack of texture
  - Columnar cellular region
    - C-axis texturing
  - Dendritic region
    - Secondary arms can break off, reducing texture



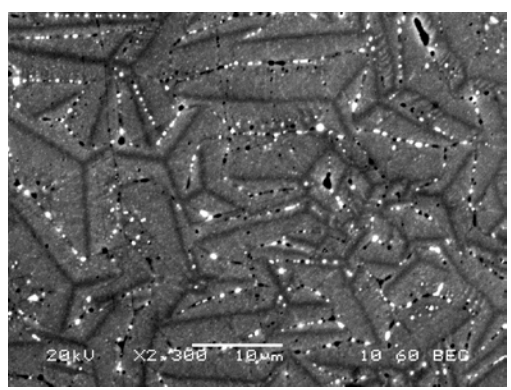
- Alloyed with Ag to stabilize/extend cellular part
- Did not reach goal of fine (1-3μm) spacing of cells extended through-thickness of ribbon.
- Mild crushing of ribbon made particulate.
- Embedding and alignment of particulate within polymer or metallic (low T_m) matrix
  - Improved anisotropic bonded magnet



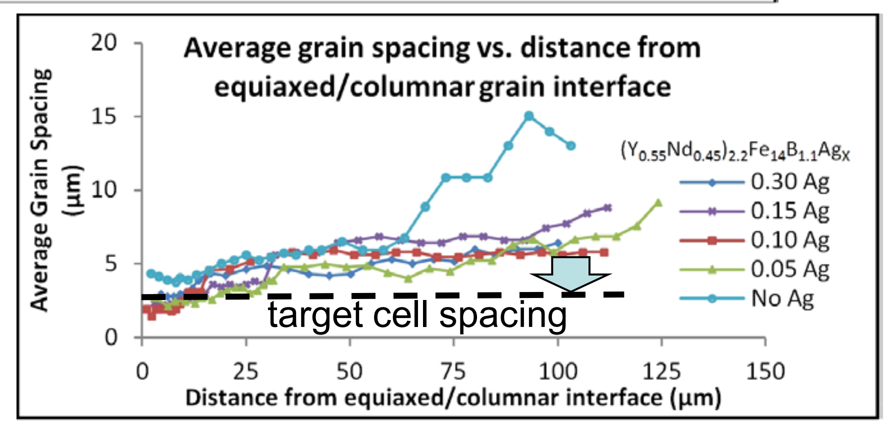




SEM cross-section, melt-spun ribbon, 0.10 wt.%Ag added.



SEM free side, melt-spun ribbon, 0.10 wt.%Ag added.

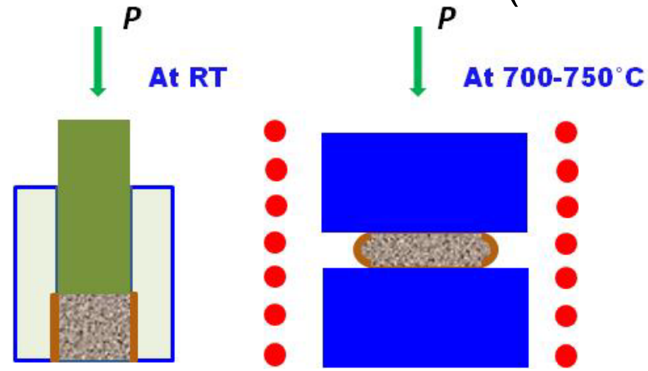


Summary of results for Ag additions in MRE magnet (no Dy) at 5m/s wheel speed.

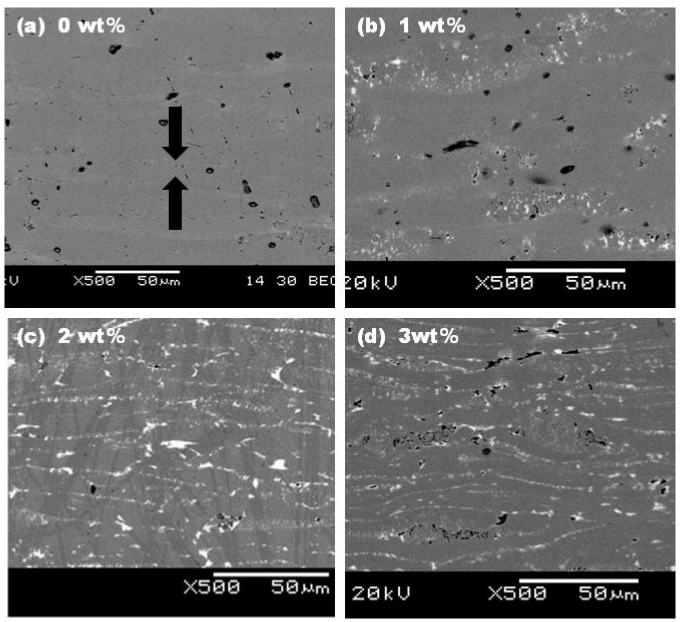
Accomplishment: Anisotropic MRE-Fe-B Magnets Fabricated by Vacuum Hot Deformation (VHD)

(Ames Lab)

- **Compared to isotropic polymer bonded PMs, anisotropic bonded magnets with enhanced $(BH)_{max}$ perform more effectively for lightweight, compact high torque electric driver motors (EDMs).**
- **Anisotropic magnets were fabricated by a single stage hot deformation method from isotropic $MRE_2(Fe,Co)_{14}B$ ribbons mixed with Zn powder as an additive.**

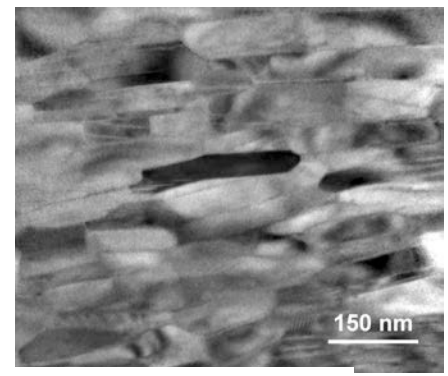


➢**SEM images of VHD samples with different Zn contents**

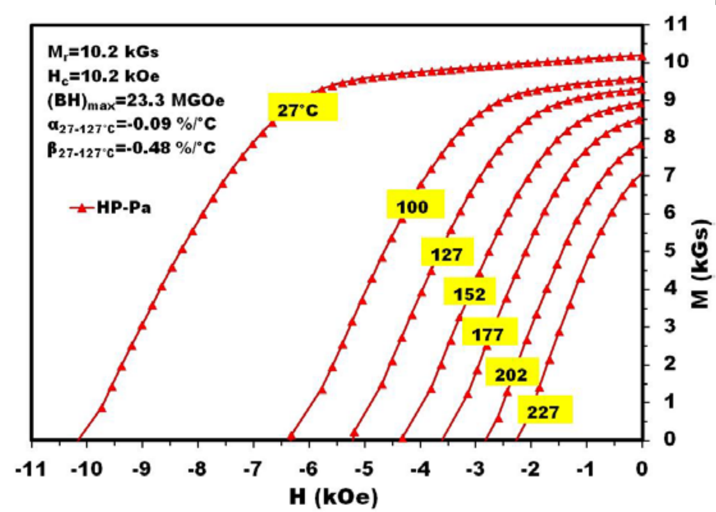


- **The microstructure consists of elongated shape particles (dark grey areas) and a grain boundary phase (white areas), and the long axis of the particles is perpendicular to the pressing direction.**
- **The average particle size is reduced with increasing Zn contents.**

➢**TEM image of VHD sample, 1 wt.% Zn**



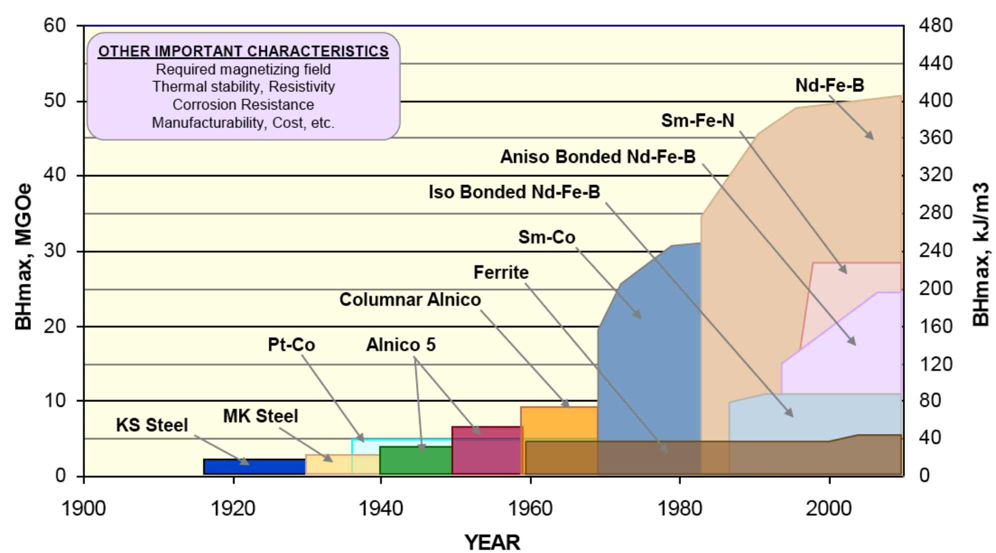
- **Hot deformation processing on the ribbon samples results in a stress-induced preferential grain growth along a direction perpendicular to the pressing direction..**



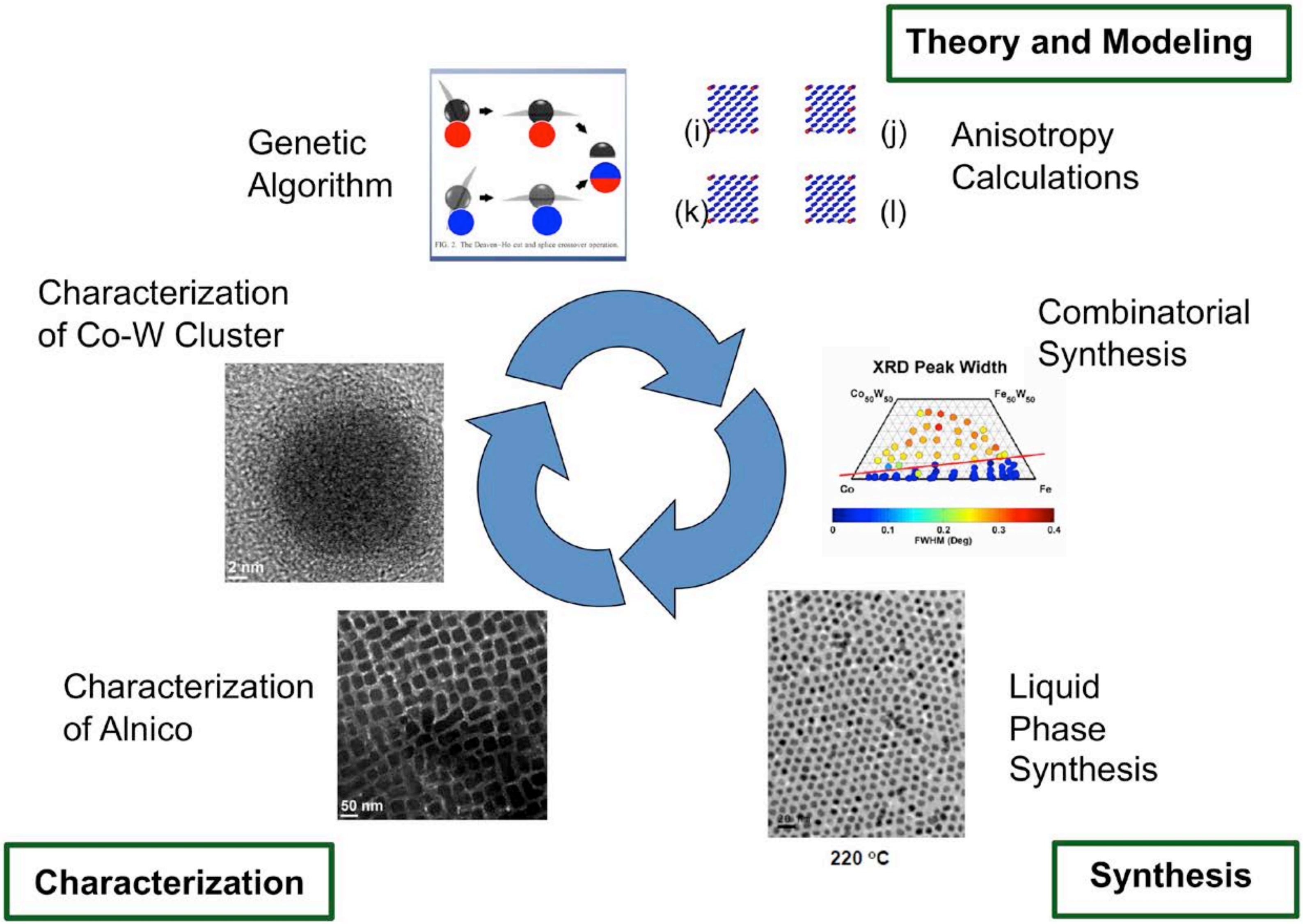
Approach: *Improved Non-Rare Earth Permanent Magnets*

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 best known non-RE system: Alnico
  - Enhanced knowledge of coercivity mechanisms
  - Enhanced control of composition and microstructure
- Discover new Fe-Co based hard magnetic phases
  - High Curie temperature
  - High Magnetization
  - Magnetic anisotropy

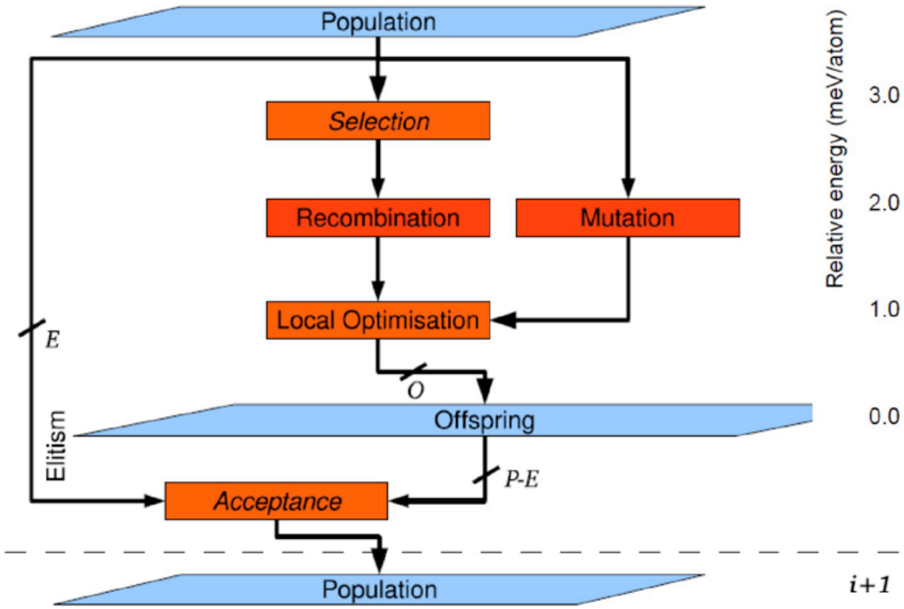


Approach: *Improved Non-Rare Earth Permanent Magnets*

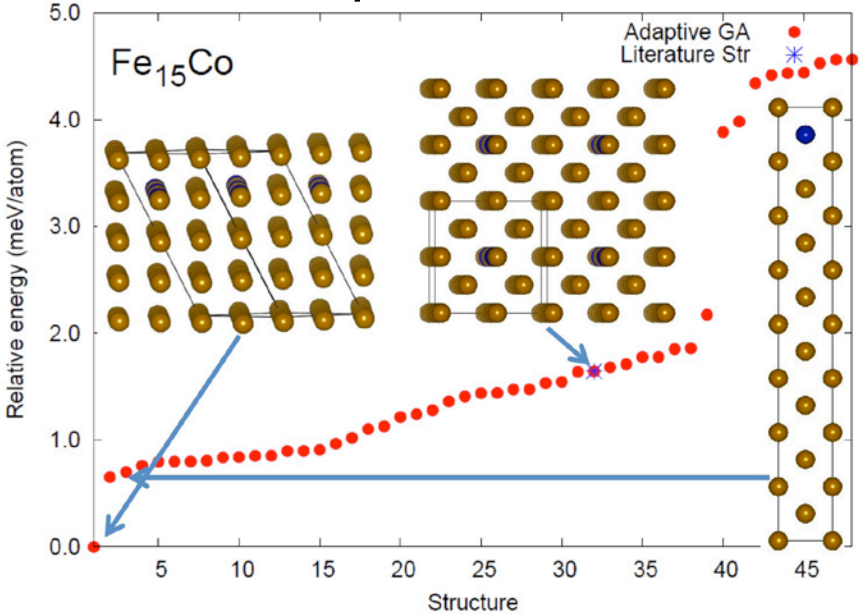


Accomplishments: Genetic Algorithm (GA) for global structure optimizations (Ames Lab)

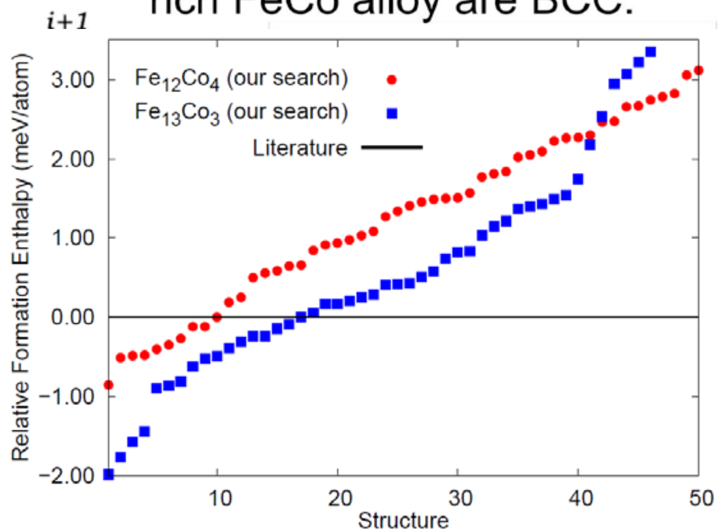
Find stable structure/calculate magnetic properties. Any low energy structures with non-cubic symmetry & high magnetic anisotropy?



- Pick two clusters from the pool.
- Rotate them randomly
- Cut through the z=0 plane
- Paste atoms above z=0 from A and those below z=0 from B
- Shift cluster along z-direction to have correct match in number of atoms



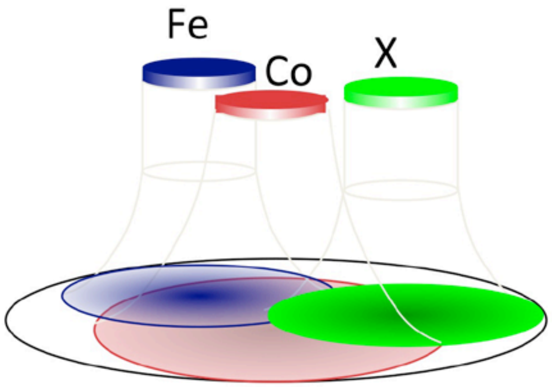
Initial low energy structures of Fe-rich FeCo alloy are BCC.



Accomplishments: Combinatorial Investigations

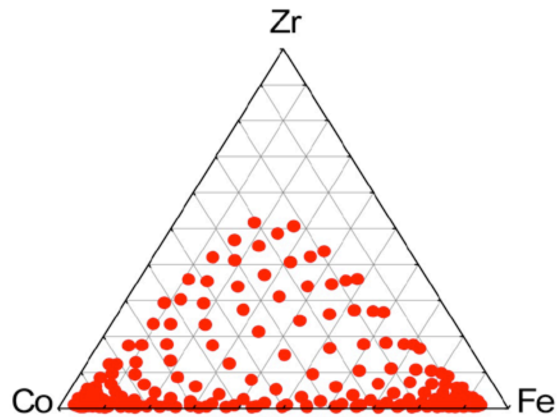
(Univ. of Maryland)

H_c up to 3 kOe observed in some compositions (out-of-plane)



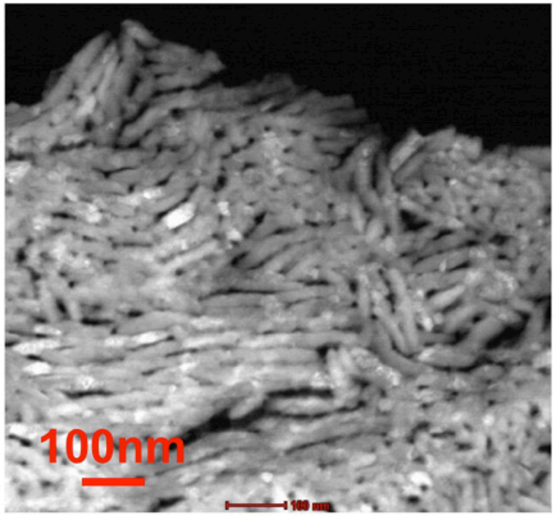
Co-sputtering scheme

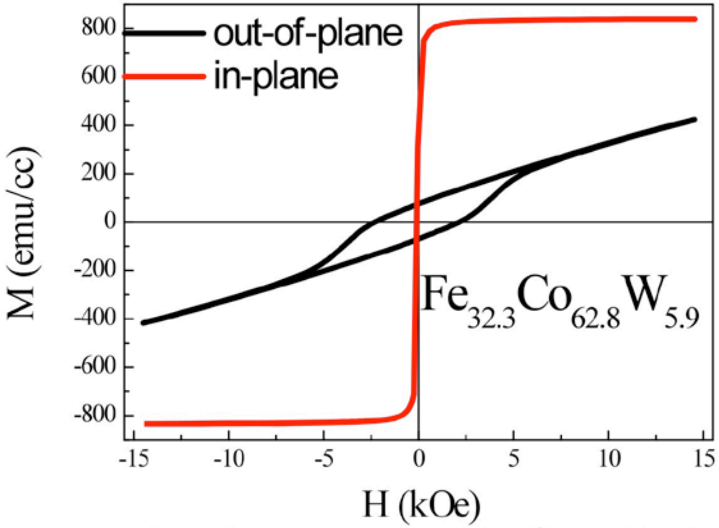
Fe-Co-X (X = W, Mo, Zr, Hf,…)



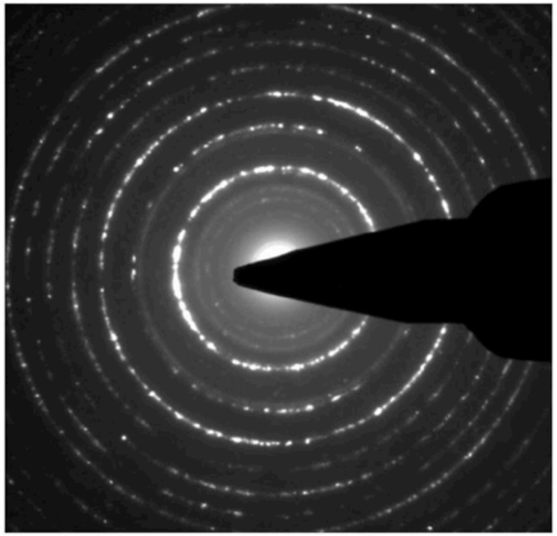
Latest library: Fe-Co-Zr

$Fe_{58.2}Co_{39.5}W_{2.3}$





Typical low W conc. Fe-Co-W behavior: H_c enhancement in out of plane

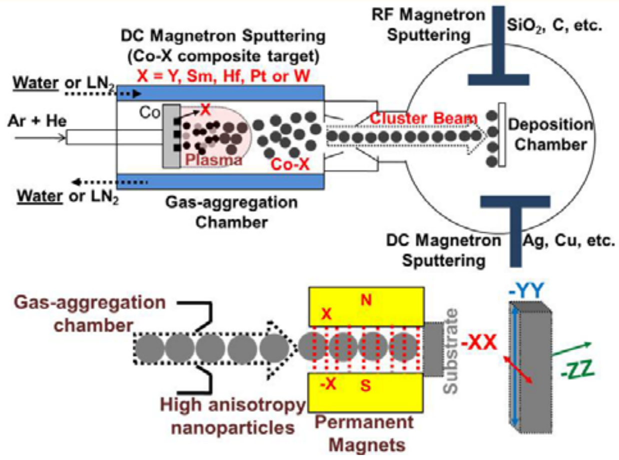


Planar TEM of Fe-Co-W reveals BCC platelet structure

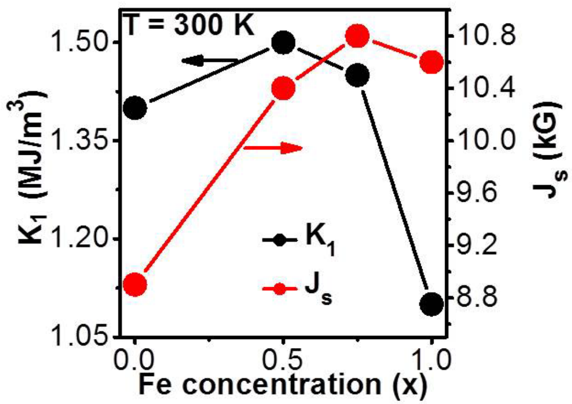
Accomplishment: High-Anisotropy $HfCo_7$ Clusters and Alloys

(Univ. of Nebraska)

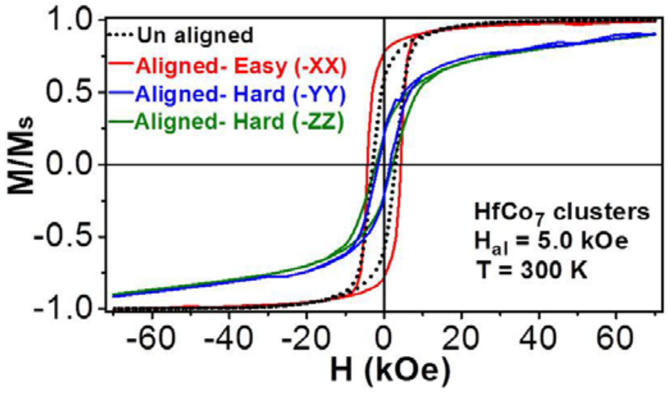
Fabrication & Alignment of High-Anisotropy Nanoparticles



K_1 & J_s of $HfCo_{7-x}Fe_x$ Alloys



Aligned $HfCo_7$ Clusters



Summary

- $HfCo_7$ nanoclusters fabricated and aligned in a $\vec{B}$ field.
- Alloying with Fe shows an increase of K_1 and J_s to significant values.

Accomplishment: Magnetic Nano-particles from Solution Chemistry

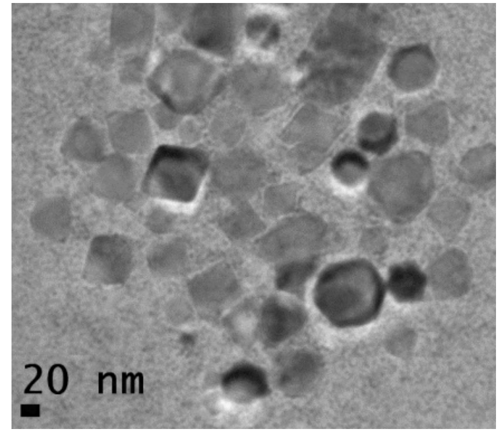
(Brown Univ.)

From CoFeW-O to CoFeW: making W-CoFe-O Nanoparticles

- We added tungsten acetylacetonate, $W(acac)_3$, during the synthesis of $CoFe_2O_4$ to make W-doped $CoFe_2O_4$ nanoparticles.

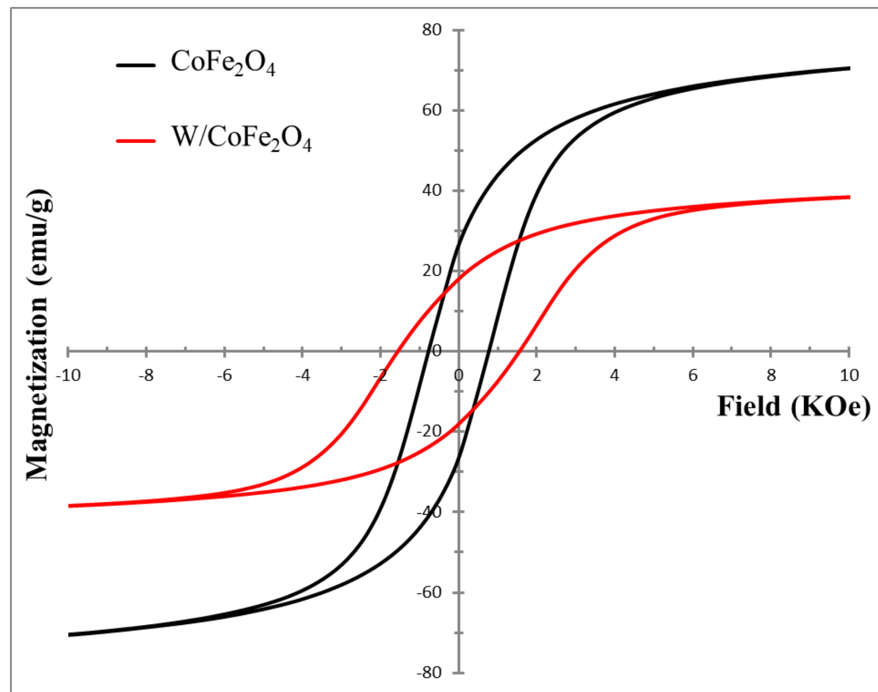
- Initial tests showed that we had not achieved the desired size and shape control yet (see the TEM image). However, preliminary results showed the coercivity enhancement after these particles were annealed at 600C under Ar for 3 h.

- **Our next step: to synthesize W-CoFe-O nanoparticles; to reduce them (with Ca) into WCoFe alloy nanoparticles; and to study their magnetic properties.**



TEM of W-doped $CoFe_2O_4$

Fe/Co/W = 7/2/1



Alnico Microstructure/Magnetic Properties Relationship

Highest energy product from columnar microstructure.

Grains grow preferentially in the [001] direction.

Improves final alignment of the precipitates.

Arnold Alnico 5-7 casting

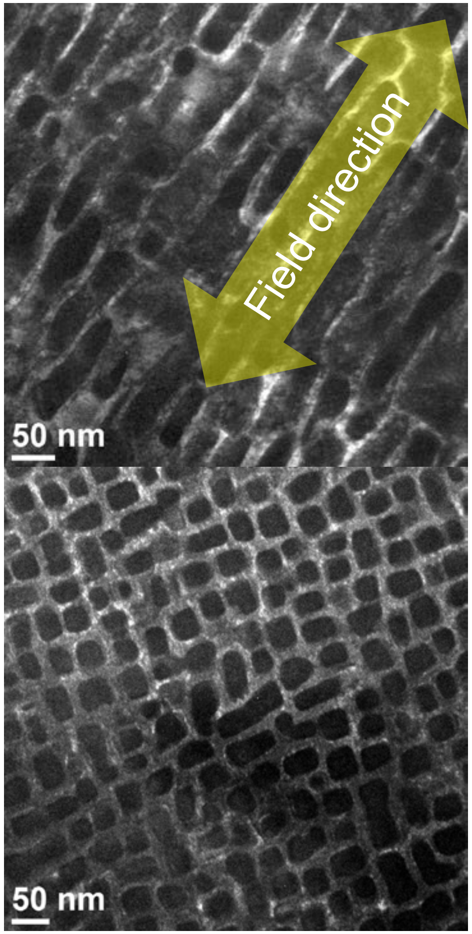
Fe-Co rich precipitates in NiAl matrix phase.

- 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)

Accomplishments: Magneto Crystalline Anisotropy of Alnico "Sandwiches" (ORNL)

Ab initio Electronic Structure Methods

DFT-LSDA with Relativistic treatment of Kohn-Sham-Dirac (KSD) equation

KSD equations solved using Screened Korringa-Kohn-Rostoker (SKKR) method:

Green's function method, exact treatment of the semi-infinite host

Calculation of Magneto-Crystalline Anistotropy Energy [MAE]

$$\Delta E_{band} \approx K\cos^2(\vartheta): \quad \frac{\partial \Delta E_{band}}{\partial \vartheta} = -K\sin(2\vartheta)$$

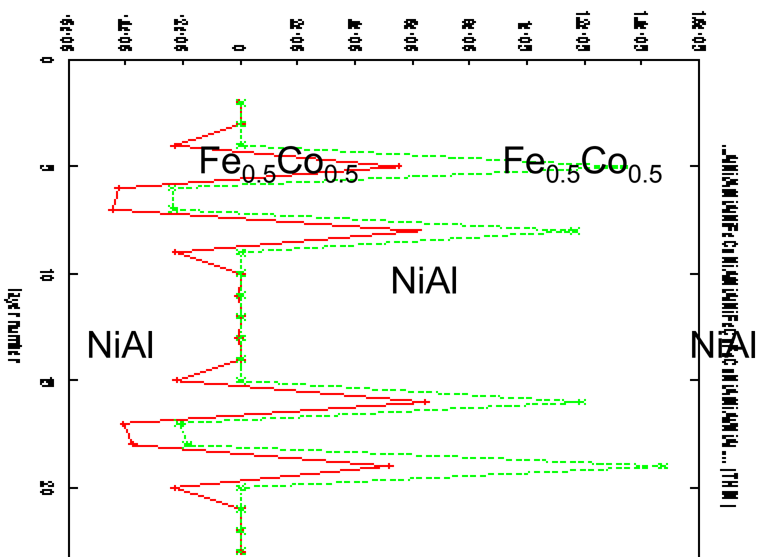
$$K > 0 \Rightarrow \text{Perpendlr}$$

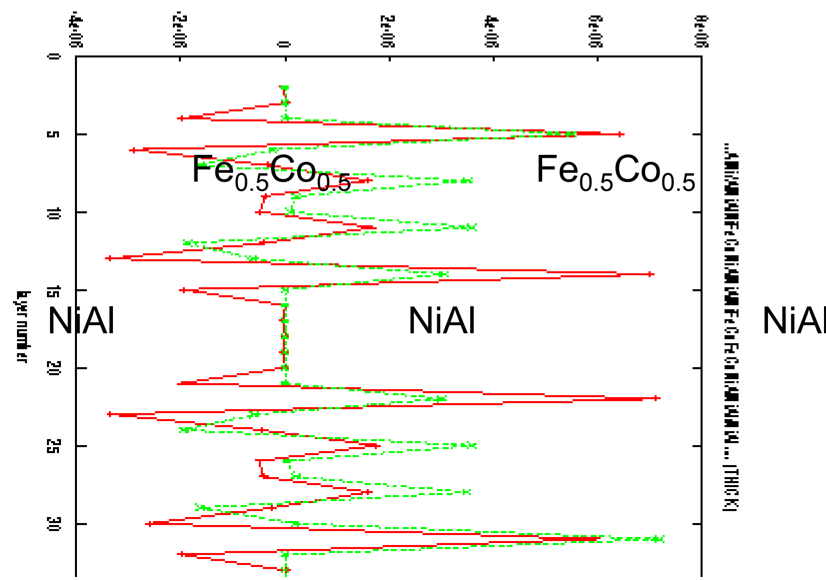
$$K < 0 \Rightarrow \text{Parallel}$$

$$D_{\pi/4} = \left.\frac{\partial \Delta E_{band}}{\partial \vartheta}\right|_{\vartheta=\pi/4} = -K$$

Agreement with DFT results for finest spacing.

Result: Large MAE at interface between between very thin solid solution $Fe_{0.5}Co_{0.5}$ layers sandwiched between NiAl. Decreases with increasing $Fe_{0.5}Co_{0.5}$ thickness

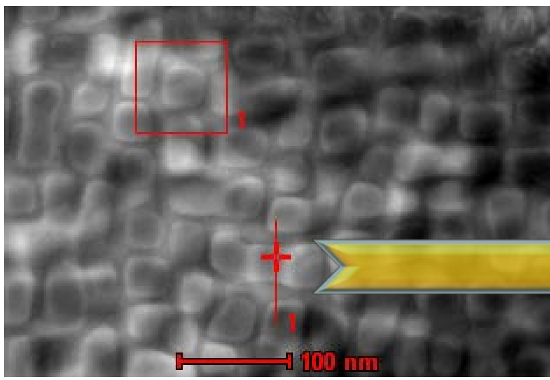


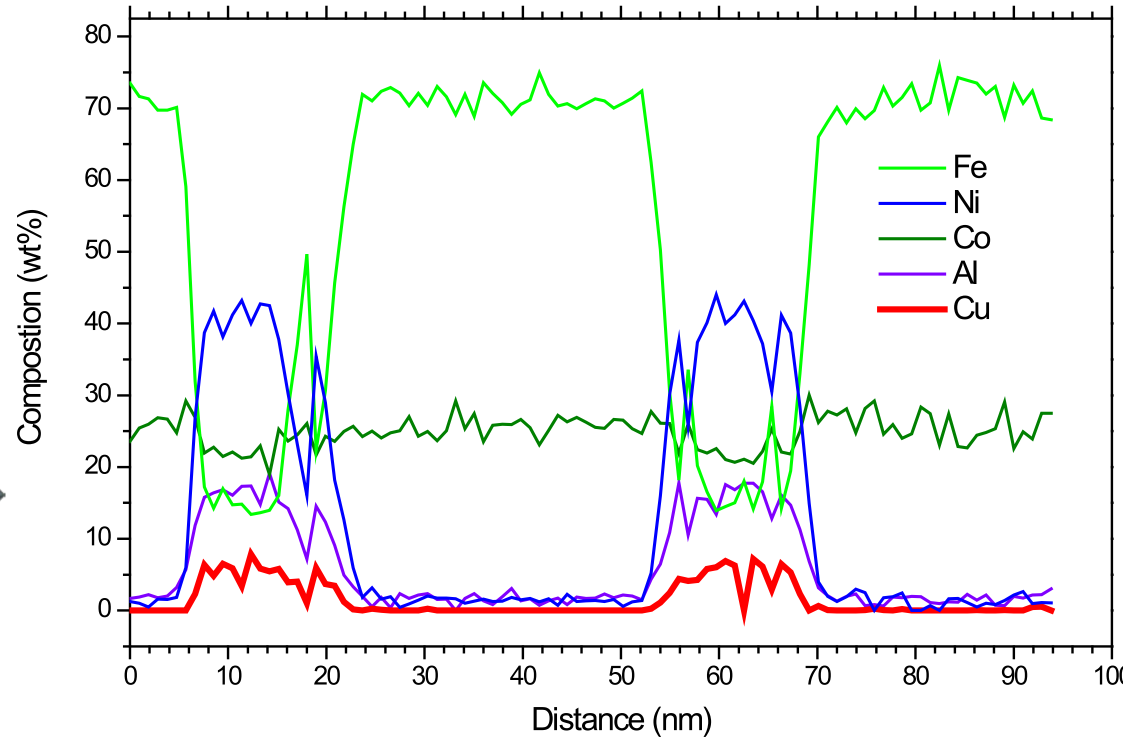


Accomplishment: Verified Chemical Partitioning in the Spinodally Decomposed Alnico 5-7

(Ames Lab with Arnold Magnetics)

High fraction of Co & Fe in the AlNi region suggest considerable improvement can be made in magnetic properties of this alloy



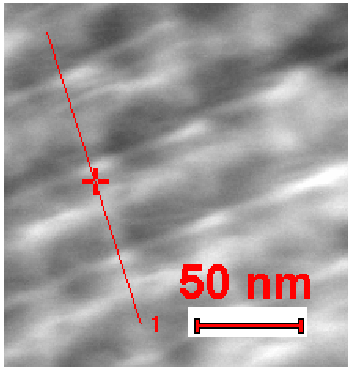


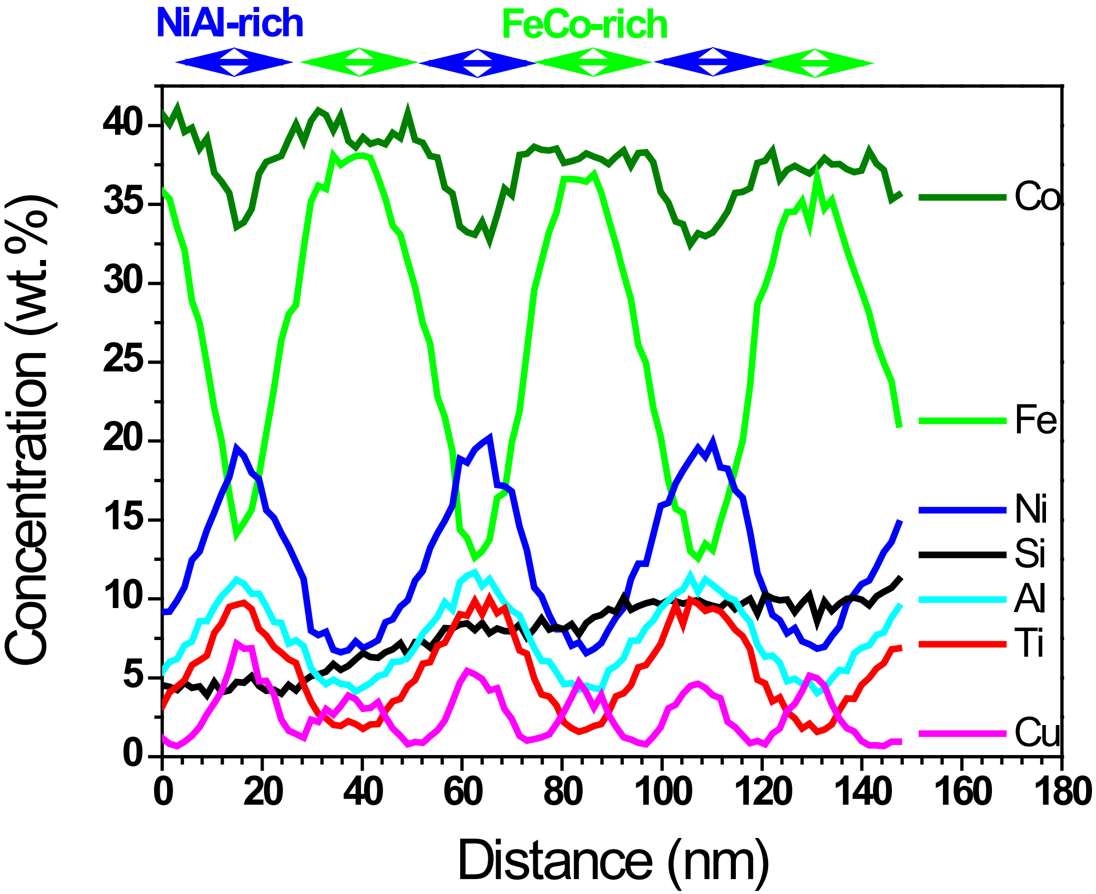
To assess how optimized the current state-of-the-art alnico alloys, we analyzed the nano-chemistry of a high-grade Alnico 5-7 from Arnold Magnetics.

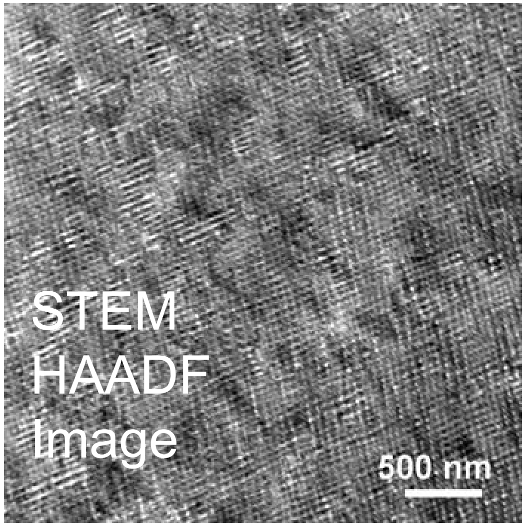
While 50 nm Fe-Co cells are well-formed, the degree of chemical ordering is far from ideal. While highly variable, the overall Co+Fe in the AlNi phase appears to be as high as 30 wt.%.

Accomplishment: Investigated Chemical Partitioning in Spinodally Decomposed Alnico 8

- Thinner 'AlNi' regions
- Less sharp boundaries
- **Cu-trapped in the Fe-Co region**







Note presence of tweed-like nanostructure (LHS) compared to more brick-like (actually columns) in the Alnico 5-7.

For better Alnico: Reduce Co-Fe content in AlNi.
Sharpen chemical gradient at interface.
Produce narrower, more regular array.

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, 2012 VT-PEEM Motor/Magnet partner (project lead).
- Unique Mobility (Jon Lutz): Advanced motor design, 2012 VT-PEEM Motor/Magnet partner (project lead).
- Univ. Texas-Arlington (Ping Liu): Nano-composite magnet design, DARPA partner.
- 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.

imagination at work

UQM TECHNOLOGIES

ARNOLD® MAGNETIC TECHNOLOGIES

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 FY12 Highlights

RE Anisotropic PM

- Improve rapid solidification processing of aligned magnetic microstructures with minor alloying to enable demonstration of anisotropic bonded magnets from MRE-Fe-B alloys without Dy.
- Enhance processing of sintered (full density) aligned permanent magnets from MRE-Fe-B alloys to permit maximum energy product to be realized at 200˚C with reduced Dy.

BREM

- Complete analysis of commercial Alnico.
  - Investigate alloy influences on columnar solidification development and on completion of spinodal partitioning.
  - Explore ultimate reduction of spinodal decomposition scale.
- Use of theoretical tools will be expanded for the investigation of potential new Fe-Co-X phases on clusters and supercomputers.
- Extend experimental investigations of Co-X, Fe-X, & Fe-Co-X systems (X=5d and 4d, e.g., W, Ta, Mo, Hf) with combinatorial synthesis, cluster deposition, and chemical synthesis
- Maintain WebEx® sharing of results and hold Spring Workshop.

FY13 Plans

RE Anisotropic PM

- Pursue processing of aligned magnetic particulate to make anisotropic bonded magnets from MRE-Fe-B alloys without Dy
- Develop optimized sintered aligned magnets from MRE-Fe-B alloys for max. energy product at 200˚C & low Dy.

BREM

- Based on theoretical guidance, pursue promising regions of ternary Fe-Co-X systems for further investigation by full suite of experimental synthesis methods.
- Provide detailed characterization results to allow improved selection of compositions and bulk magnet processing approaches.
- Maintain WebEx contact and bi-annual workshops with team

FY11-12 Summary for High Temperature RE PM

- Unique through-thickness aligned solidification patterns resulted from Ag-doping of MRE magnet ribbon (Dy-free), but finer cells needed for anisotropic bonded magnet particulate.
- "Diffusion" (grain boundary alloyed) MRE sintered anisotropic magnets with 5.3wt.% Dy had same β as the best commercial Nd-based $Nd_2Fe_{14}B$ magnets (>8% Dy) that are used in motors up 200˚C (EH grade), but with 46% less Dy, i.e., large cost reduction.
- Strong and dense anisotropic magnets of MRE (low Dy) magnet alloys were hot pressed at 725˚C to promote aligned nano-crystalline grains, demonstrating concept of combined intrinsic and extrinsic binder, but grain size needs further control for maximum coercivity.

FY11-12 Summary for BREM Project Thrust

- Analysis of commercial Alnico is proceeding to determine the effect of additives for texture development during directional solidification and to map the parameter space for spinodal decomposition to improve coercivity.
- New processing or alloying ideas for Alnico 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 and composition and crystallization control is improving.
- Chemical synthesis of Co-X and Fe-X based magnet alloy nano-particles has continued in development.

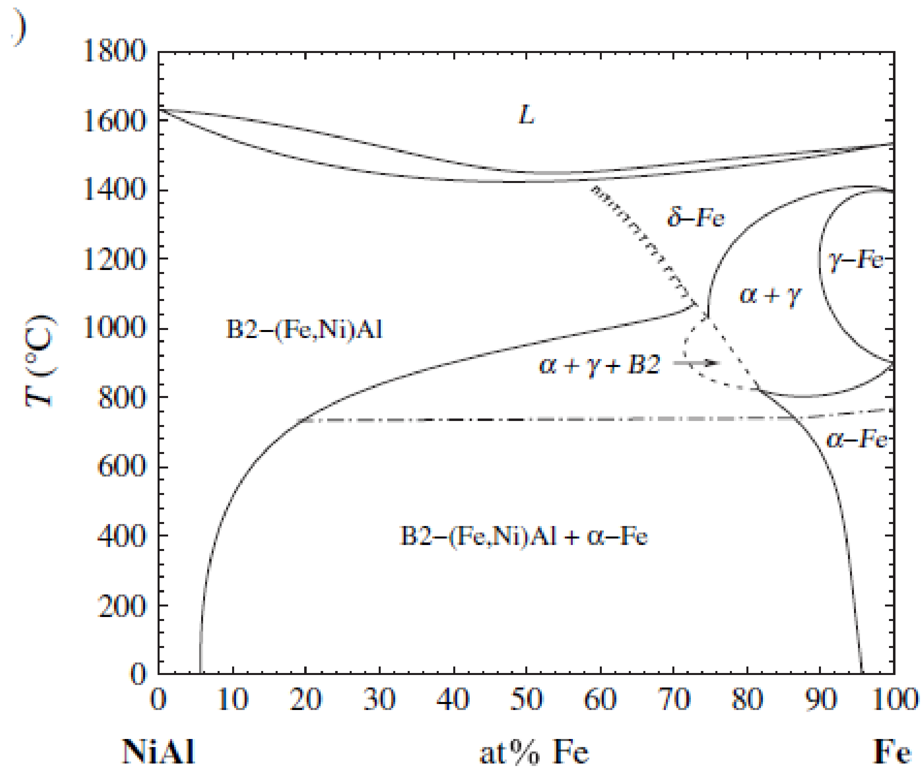
Technical Back-Up Slides

(Note: please include this "separator" slide if you are including back-up technical slides (maximum of five). These back-up technical slides will be available for your presentation and will be included in the DVD and Web PDF files released to the public.)

The Alnico System

- Spinodal alloy based on the Fe-NiAl System
- Co additions promote higher T_c
- Additional alloy additions promote partitioning and control microstructure
- Typical composition:

	Al	Ni	Co	Cu	Fe
At %	15.6	12.5	21.4	2.5	48



Eleno, Luiz, Karin Frisk, and Andre Schneider. "Assessment of the Fe-Ni-Al system." *Intermetallics* 14 (2006): 1276-1290

Accomplishments: Electronic Structure Calculations

(Ames Lab)

Density Functional Theory approach (FPLMTO, FLAPW, ASA)

Of 5d elements W and Ta considered initially as candidates for commercial magnets (considering cost, safety and availability).

Main results:

Magnetic anisotropy strongly depends on symmetry of W atomic arrangement

ordered Fe-W systems

given concentration of W

An increase of uniaxial anisotropy noted at 10-15 times of ideal bcc-Fe simple cubic.

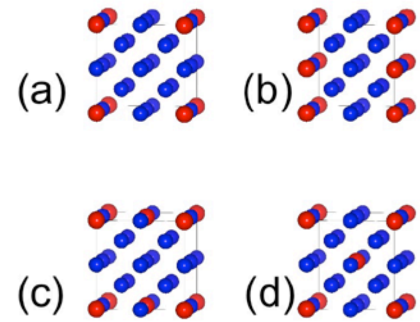


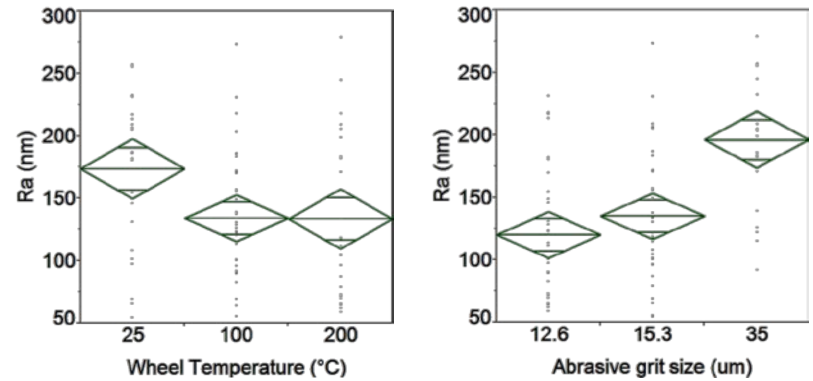
Figure (a) shows arrangement of W atoms in $Fe_{15}W$. Other arrangements of W in Fe show smaller effect. Calculations of other 5d atoms show smaller effect.

Implies: Artificial growth of such an ordered system (which is not a ground state) is desirable if such level of anisotropy is to be obtained.

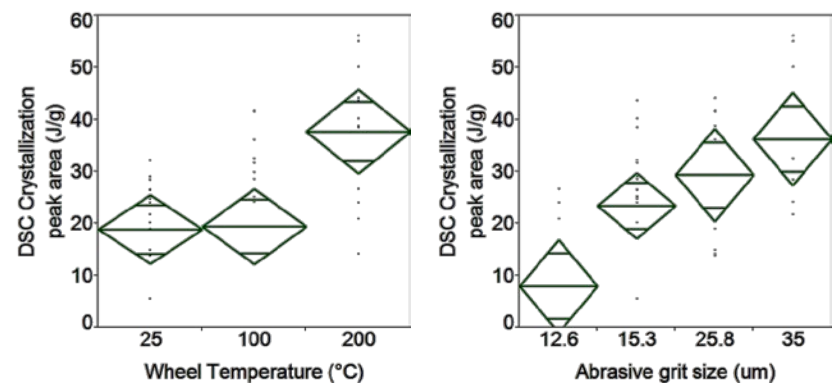
Effects of wheel temperature and surface finish on ribbon properties

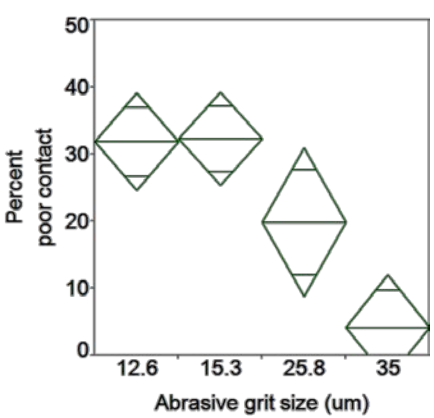
- Ability to form amorphous material in $Nd_2Fe_{14}B$+TiC greatly affected by surface conditions of the melt-spinning wheel
  - Can allow for greater control of ribbon processing
- Crystallization energy (amorphous content) significantly increased at elevated wheel temperature (200° C) for moderate wheel speeds (12-25 m/s)
- Crystallization energy also increased with increasing grit size
  - Likely linked to ability of melt to wet the wheel surface (poor contact fraction decreased with increasing grit size)

Effects of wheel temp. and surface prep. on ribbon wheel side surface roughness (as measured by optical profilometry)



Effects of wheel temp. and surface prep. on ribbon amorphous content (as measured by DSC)





Region of good contact

Region of poor contact