U.S. DEPARTMENT OF ENERGY

Energy Efficiency & Renewable Energy

Development of Radically Enhanced alnico Magnets (DREaM) for Traction Drive Motors

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Ames Laboratory (USDOE)

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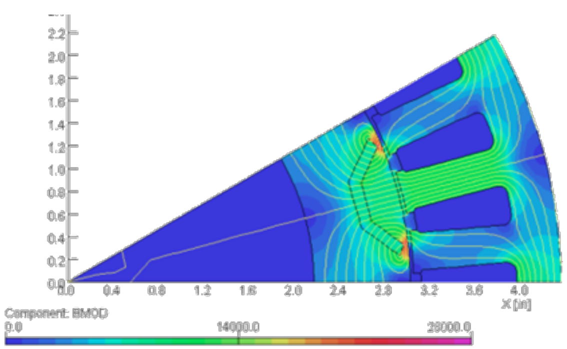
Project ID # EDT015



The Ames Laboratory
Creating Materials & Energy Solutions
U.S. DEPARTMENT OF ENERGY

Overview

Timeline

- Start – October 2014
- Finish - September 2018

  50% Complete

Budget

- FY 15 Funding - $1900K
- FY 16 Funding - $1900K

  (actual)
- FY17 Funding - $1900K

  (planned)

*2020 VT Targets

Barriers & Targets*

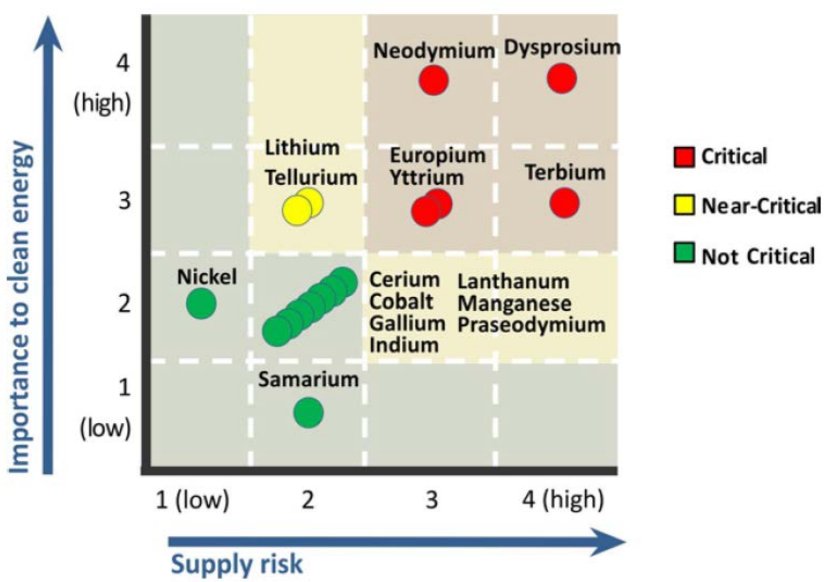
- High energy density permanent magnets (PM) needed for compact, high torque drive motors (specific power >1.6kW/kg and power density >5.7kW/L).
- Reduced cost (<$4.7/kW): Efficient (>94%) motors require aligned magnets with net-shape and simplified mass production.
- RE Minerals: Rising prices of rare earth (RE) elements, price instability, and looming shortage, especially Dy.
- Performance & Lifetime: High temperature tolerance (180-200˚C) and long life (15 yrs.) needed for magnets in PM motors.

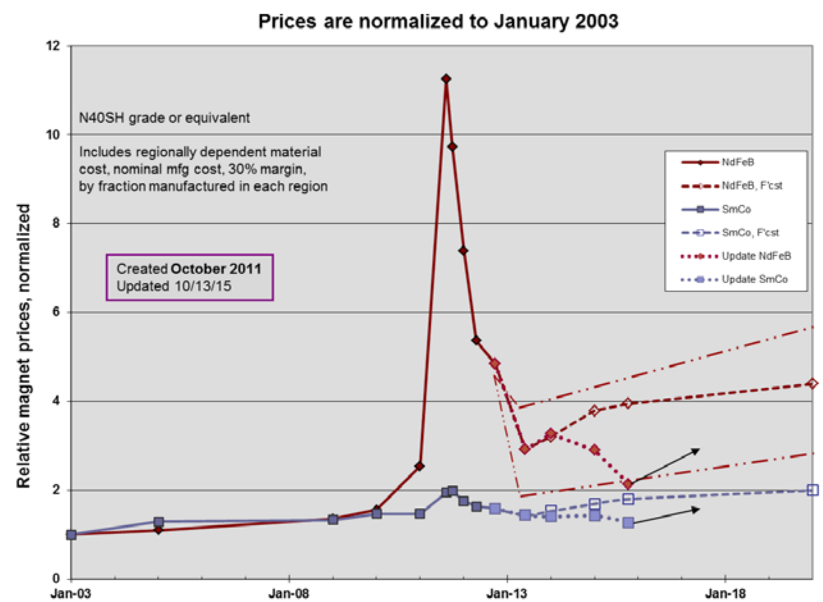
Partners

- Baldor, U. Wisconsin, NREL, Ford, GM, GE, UQM, Synthesis Partners (collaborators)
- ORNL, U. Nebraska, Arnold Magnetic Tech. (DREaM subcontractors)
- Project lead: Ames Lab

Project Relevance/Objectives

- To meet 2020 goals for enhanced specific power, power density, and reduced (stable) cost with mass production capability for advanced electric drive motors, improved alloys and processing of permanent magnets (PM) must be developed.
- Rising RE cost trend and unpredictable import quotas (by China) for RE supplies (particularly Dy) motivates this research effort to improve (Fe-Co)-based alnico permanent magnet alloys (with reduced Co) and processing methods to achieve high magnetic strength (especially coercivity) for high torque drive motors.
- **Objectives for the fully developed PM material:**
  - ✓ Provide competitive performance in advanced drive motors, compared to IPM motors with RE-PM.
  - ✓ Eliminate use of RE, e.g., Nd, Dy, in high performance PM due to global strategic RE supply issues.
  - ✓ Achieve superior elevated temperature performance (180-200˚C) to minimize motor cooling needs.





FY16 DREaM Tasks

2015 Oct	Nov	Dec	2016 Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep

Develop enhanced alnico (non-RE) magnets

Focused Theory and Simulation:

Expand beyond previous equilibrium Monte-Carlo modeling development for Al-Ni-Fe-Co (baseline alnico) to encompass a simplified alnico 8 with Al-Ni-Fe-Co-Ti with composition variations and temperature dependence in collaborative efforts with experiments.

Intrinsic magnetic property calculations to obtain parameters for magnetic nano- and meso-scale simulations.

Develop phase field models for simulation of morphology evolution and magnetic behavior at micron-scale, including magnetic field application.

Synthesis of Test Samples:

Well-controlled bulk magnet samples will be prepared to achieve designed levels of nano-structure and microstructure variation and to permit testing of at least one of the theoretical pathways to improve alnico coercivity.

Develop low-Co alloy for lower cost alnico-8 with increased coercivity.

Produce a bulk alnico magnet of a sub-final size and same shape of the prototype magnets desired by a motor industry partner

Characterization:

Develop capability to store refined data rapidly from advanced structural characterization.

Magnetic and microstructural characterization of extensive series of experimental alnico 8 and alnico low-Co-8 alloy system samples to verify effects on nano-scale and micron-scale microstructure.

Temperature and frequency dependent measurements will be performed involving magnetic properties and other parameters of permanent magnets

Thermal and mechanical properties of baseline commercial samples will be analyzed.

Key Deliverable: A bulk (sub-sized) alnico magnet with properties exceeding commercial magnets delivered to an industrial partner

Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
	Work shop						Work shop				

Milestones

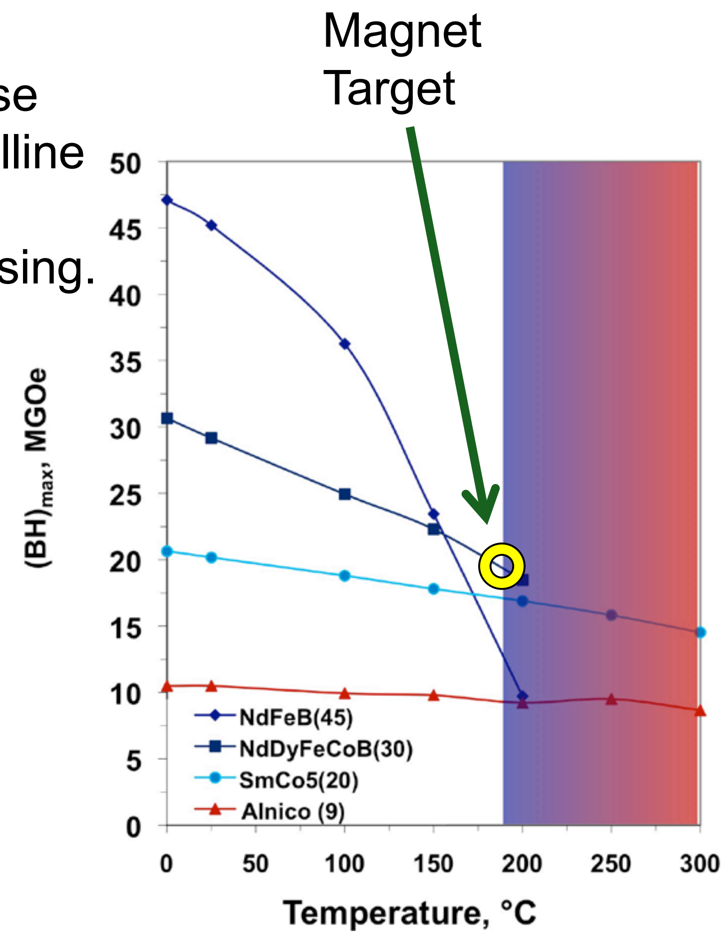
Project Duration: FY15 – FY18 **Overall Objective (all years):** Design and synthesize a high energy product alnico PM competitive with RE-PM (cost/MGOe/kg), but with sustainable supply and cost outlook in bulk near-final shapes by mass production methods.
FY16 Focus: Optimize nano-structure and microstructure of bulk samples from thermal-magnetic and annealing processing to reproducibly fabricate alnico-8 type alloy with Hci > 2020 Oe (commercial). Validate theoretical modeling and correlated with magnetic properties and the observed nano-structure changes.
Key Deliverable: Bulk, sub-sized alnico magnet with improved magnetic properties (vs. 8HE and/or 9) produced and delivered to UQM for specification of test magnets for advanced motor system.
Go/No Go Decision Point: Does bulk sub-sized alnico magnet have improved magnetic properties compared to alnico 8HE and/or alnico 9 or not?
FY 18 Focus: Develop refined low-Co alloy with reduced cost that undergoes spinodal transformation to produce desired nano-scale pattern and exhibits same higher levels of magnetic properties when subject to similar thermal-magnetic and annealing treatments.
Deliverables: Bulk alnico magnet samples made with reduced cost low-Co alnico alloy.

DREaM Overall Approach/Strategy

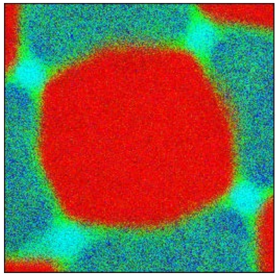
Near-term non-RE Magnets: Best RE-free magnets (alnico) further enhanced (coercivity) by low-Co alloy design and bulk powder processing improvements using detailed and innovative analysis of micro/nano structure-magnetic property relationships, extensive theory results, and critical industry input.

Long-term non-RE Magnets: Advances in Fe-Co-X magnet systems will be shifted to "super-alnico" for added tetragonal distortion of Fe-Co magnetic phase for a further boost of coercivity from magnetocrystalline anisotropy, coupling theory with synthesis/characterization and bulk magnet processing.

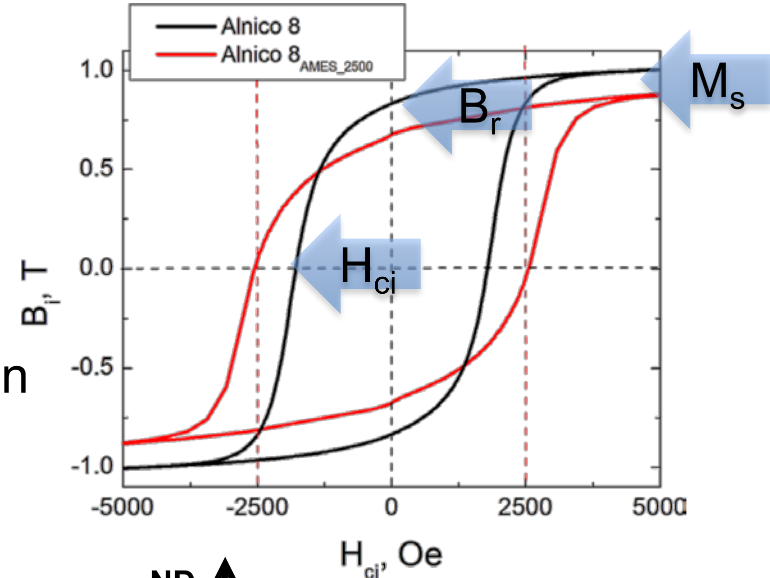
		Alnico 8	Alnico 9
aspect ratio		~ 10:1	> 10:1
fraction bcc phase (f)		0.53	0.53
Fe:Co in bcc phase		0.54	0.60
mole % Fe+Co in bcc		0.84	0.91
~M_s (KG) for bcc based on Fe:Co		23.8	23.9
Fe:Co in intermetallic		0.24	0.27
mole % Fe+Co in bcc		0.36	0.40
B_r (KG)	measured	8.2	10.6
	calculated	10.6	11.5
Hc_i (Oe)	measured	1860	1500
	calculated	3205	3715
BH_{max} (MGOe)	measured	5.3	9.0
	calculated	17.0	21.4



Alloy Design Requisites

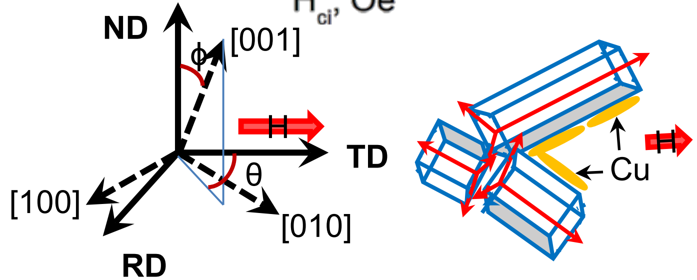


- Maximize saturation magnetization (M_s)
  - Fine tuning of the alloy chemistry to maximize the volume fraction of FeCo phase.



- Maximize coercivity (H_{ci})
  - Spinodal as fine as possible while insuring complete chemical separation

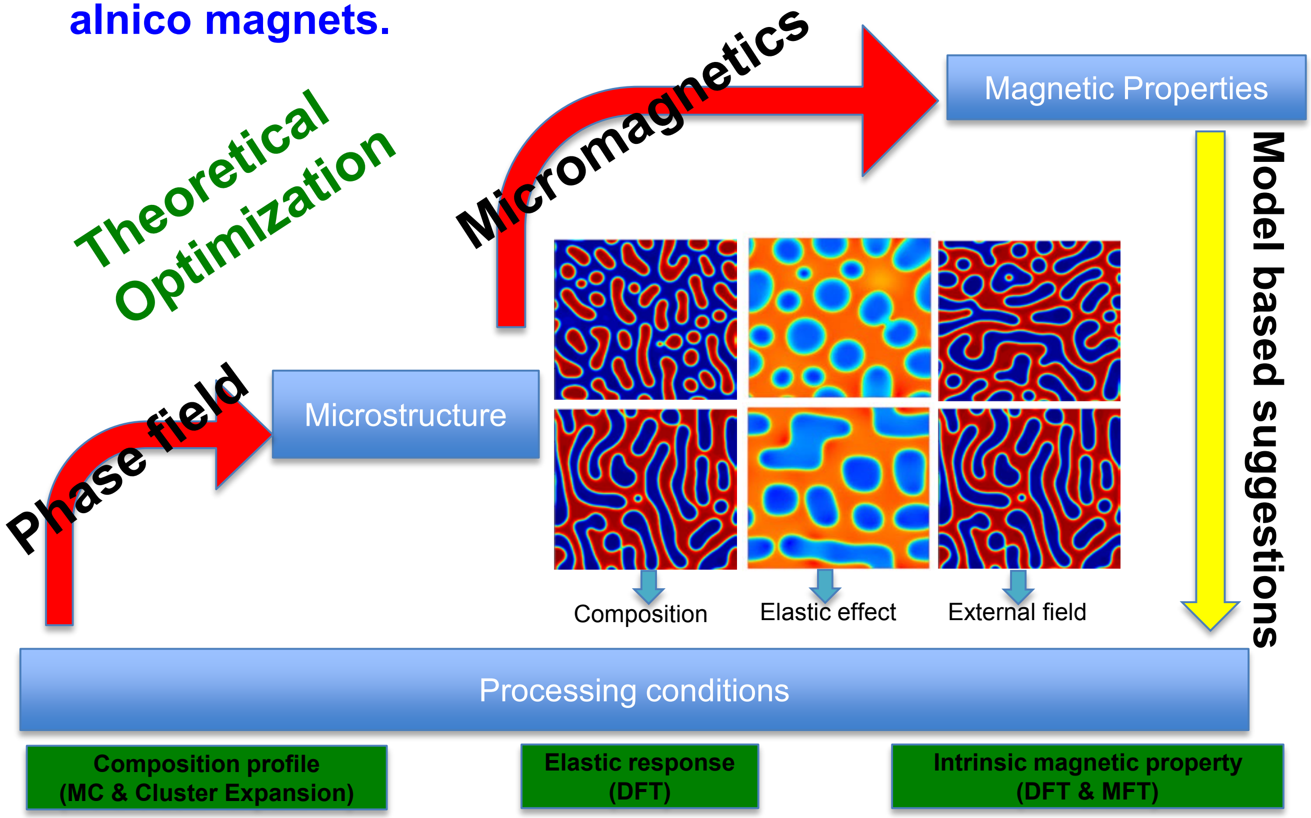
- Maximize Remanence (B_r)
  - Align <100> to the orientation of the field annealing

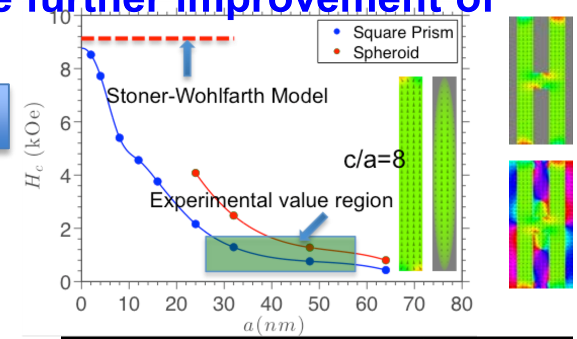


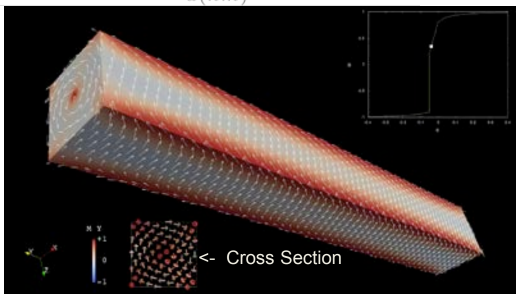
$H_{// <100>} \sim \cos(\theta) \sin(\phi)$

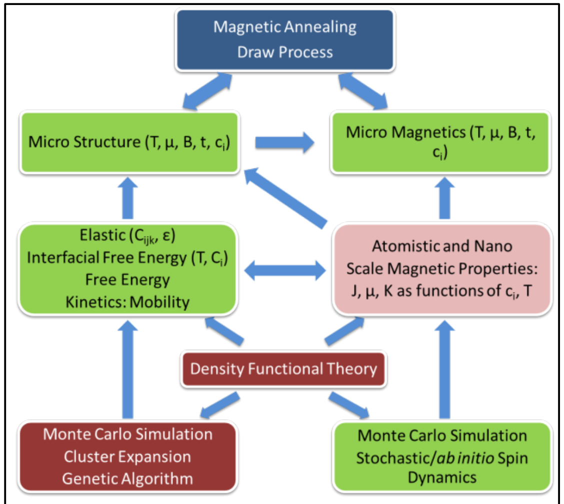
Technical Accomplishments in Theory and Modeling

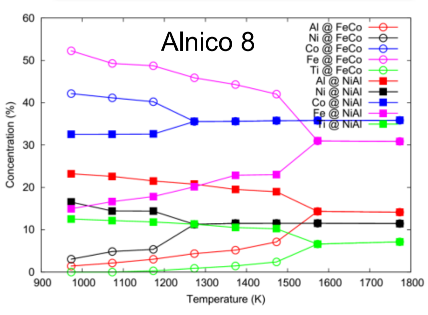
- **Current alnico magnets took decades to optimize by trial and error.**
- **A comprehensive multi-scale modeling tool can speed up the further improvement of alnico magnets.**

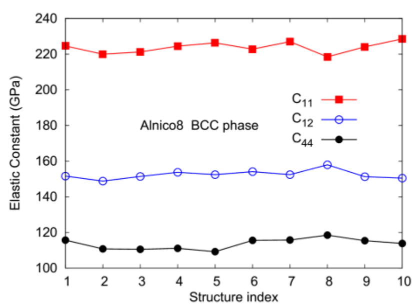


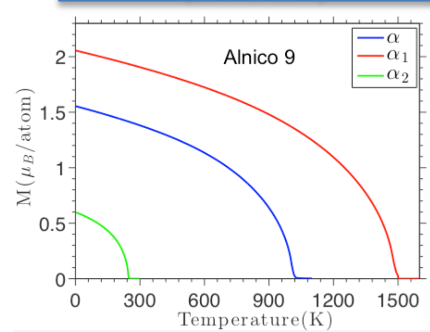






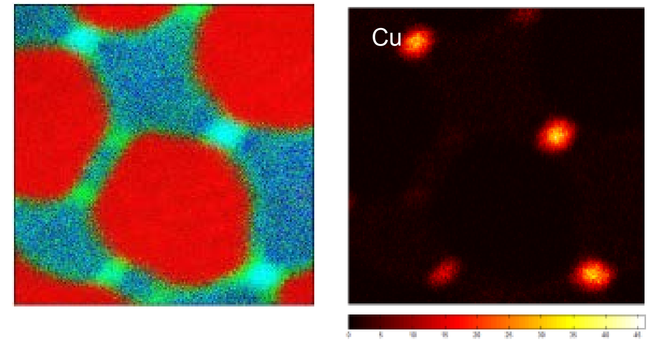




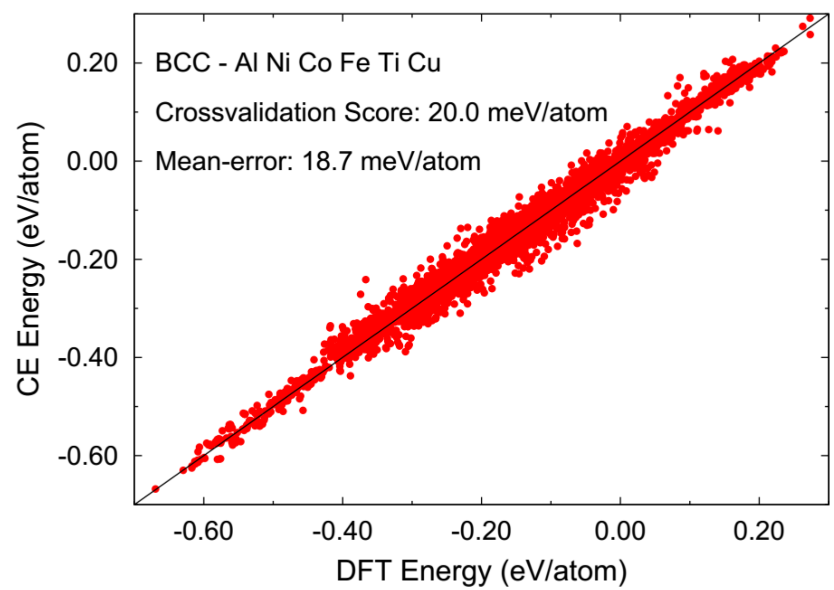


Monte Carlo Simulation Taking Cu Into Account

- **Experiment observations:**
  - There is Cu rich area connecting magnetic needles.
  - Cu why does it form at specific points
  - Cu rich phase is first in BCC then transforms to FCC then elongates during the draw.
- Cluster expansion terms needed to perform Monte Carlo (MC) simulations.
- Database includes 5500 structures.
- MC simulations are running.



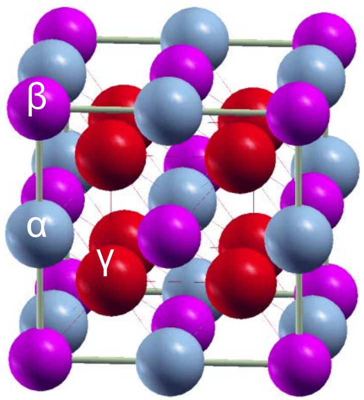
Element maps of alnico 9



Cluster expansion fitting including up to 3rd NN pairs and 3rd NN triplets to DFT database

Cu may play an critical role in spinodal spacing and isolation of the FeCo needles

Magnetic properties of $L2_1$ alnico-9 ($Al_{25}Ni_{23}Fe_{10}Co_{27}Ti_{15}$)



Our goal is to find atomic magnetic moments and exchange interactions in $L2_1$ and $D0_3$ structures (AlNi-phase).

$L2_1$ (AlNi) structure : α-site (Fe+Ti) : (1/2,1/2,1/2)
β-site (Al, □) : (0, 0, 0)
γ-site (Co+Ni): ±(1/4,1/4,1/4)

	Magn. Mom. (μ_B) $L2_1$
Al	-0.03
Fe	2.83
Ti	-0.07
Co	0.56
Ni	0.07

Heisenberg model

$$H = -\sum_{i \neq j} J_{ij} \vec{e}_i \vec{e}_j$$

where J_{ij} is exchange interaction between atoms *i* and *j*;
$\vec{e}_i$ Correspond to direction of magnetic moment of atom *i*

$(J_0)_{nm}$ – effective exchange interaction of moment of one magnetic atomic species (Fe and Co) with all other Fe and Co atoms in meV

$(J_0)_{nm}$	Fe	Co
Fe	39	148
Co	148	12

Interaction between the FeCo and L21 and degree of chemical separation appear key to understanding why coercivity is so sensitive to thermal processing

Alloy electronic structure was calculated using KKR Coherent Potential Approximation (KKR CPA), as it implemented in Munich code

Phase-field modeling for magnetic materials

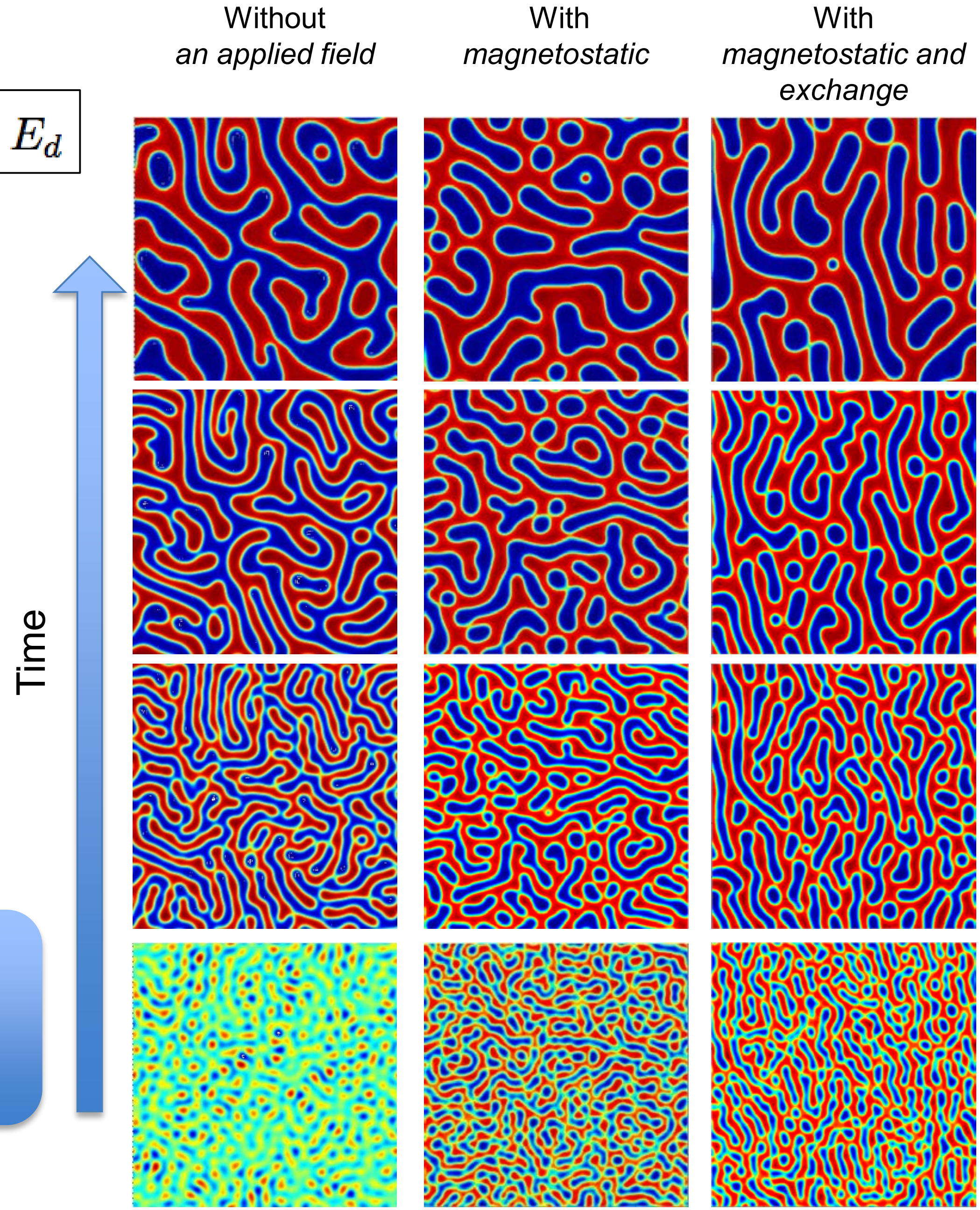
Magnetic energy terms:

$$E_{mag} = E_{ext} + E_{exch} + E_{an} + E_{mstr} + E_d$$

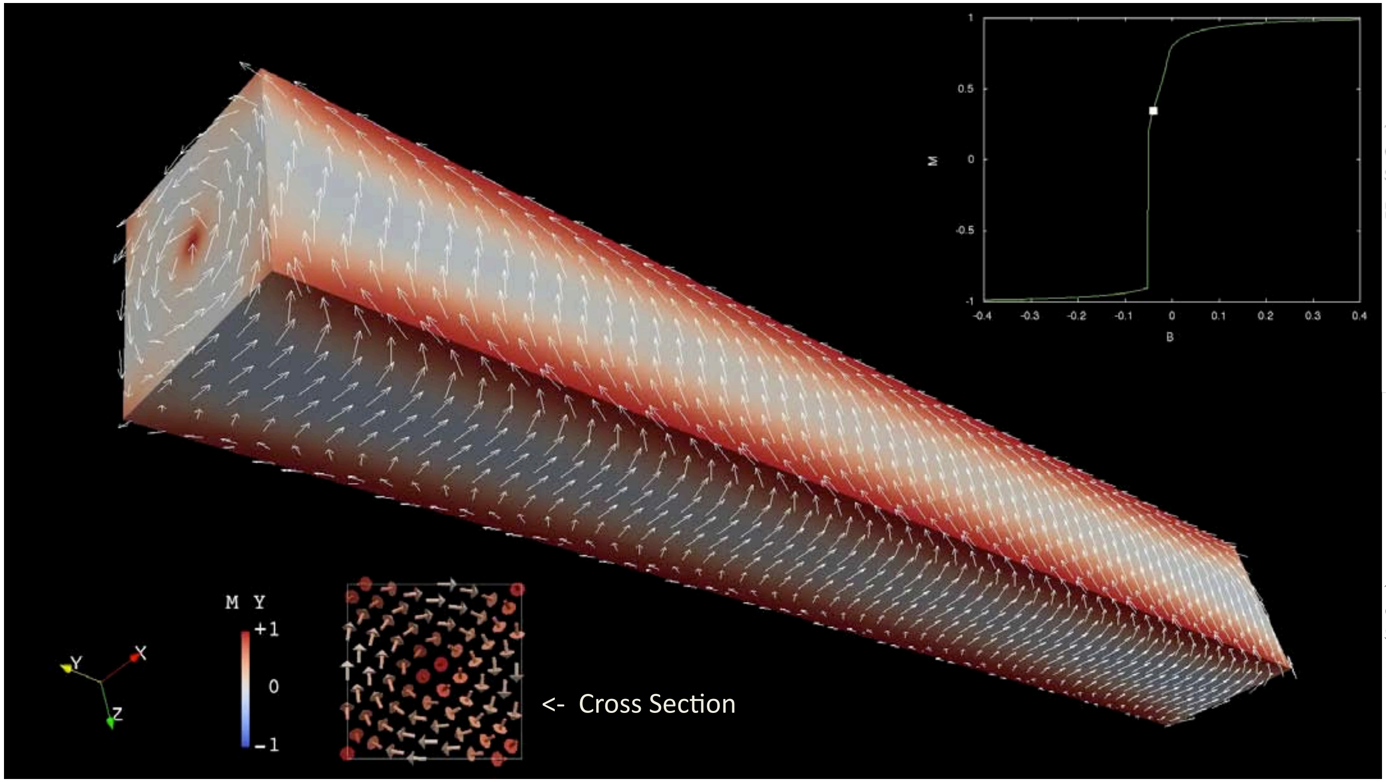
E_{ext} : Zeeman
E_{exch} : Exchange
E_{an} : Magnetocrystalline anisotropy
E_{mstr} : Magnetostriction
E_d : Magnetostatic

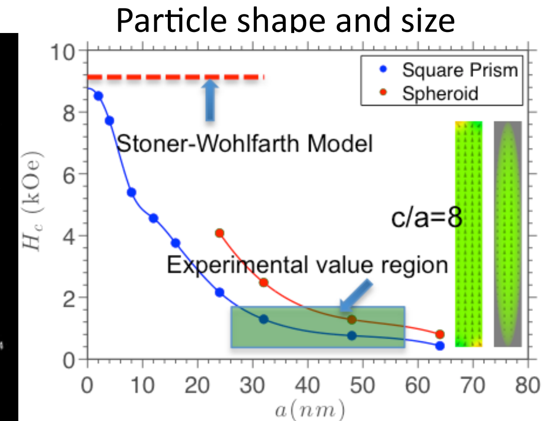
	B ↑↑	↑↑ B
E_{ext}	=	
E_{exch}	=	
E_{an}	=	
E_{mstr}	Small	
E_d	>	

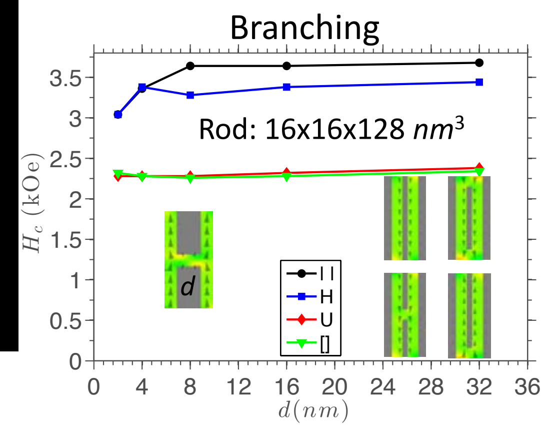
It is the magnetostatic term(E_d) with the exchange field driving elongation of the spinodal.



Micromagnetic simulation





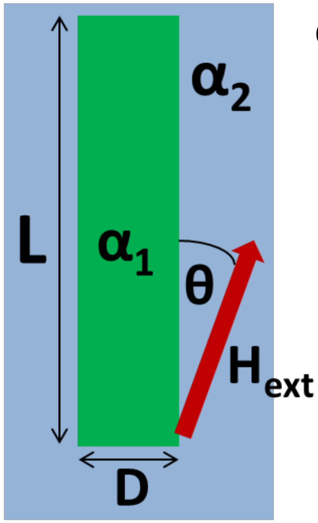


We investigate the effect of size, shape, aspect ratio, alignment and branching on magnetic properties.

- The mechanism of magnetization reversal inside each individual particle deviates from the uniform spin rotation (SW model).
- Curling starts at corners of the two ends of the Rod. Particles with spheroid shape have a higher coercivity than those with other shapes.
- Coercivity quickly decreases with increasing particle size. With a=25~65 nm, the deviation of H_c values from SW value is about factor 5~20.
- H-shape branching is less detrimental than U- or O- shape branching in decreasing coercivity.

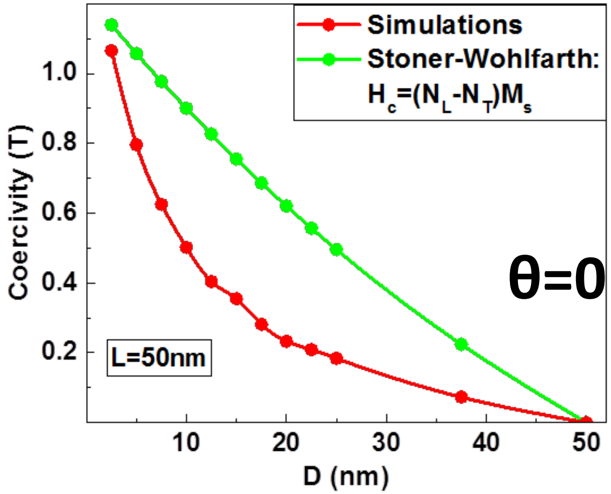
Micromagnetics: Noninteracting needles

Cuboidal needles

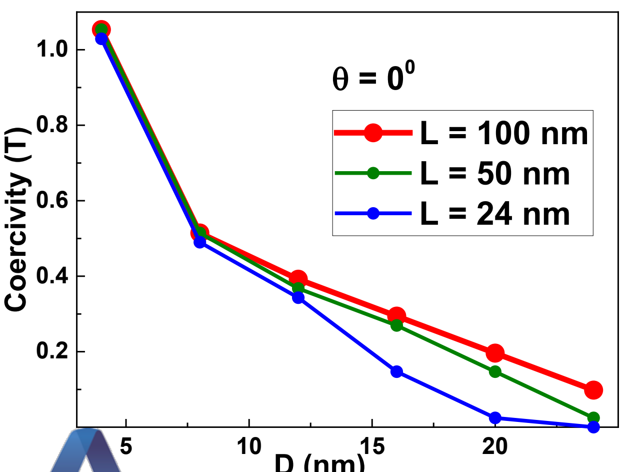


Stoner-Wohlfarth overestimates coercivity

Full numerical simulations needed



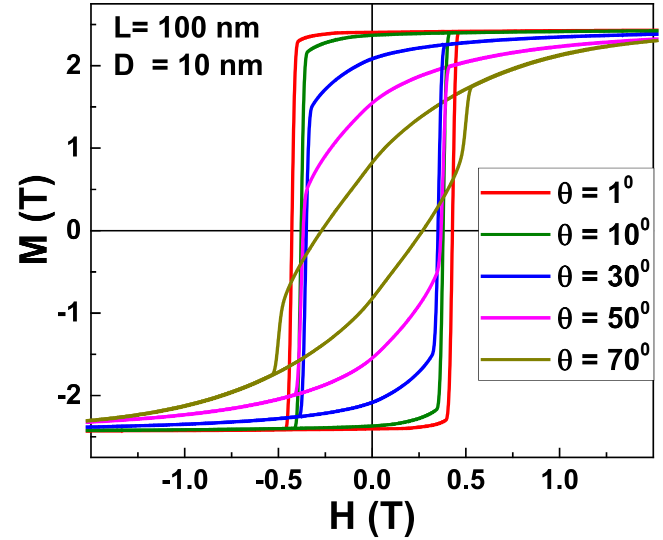
Optimization of microstructure parameters

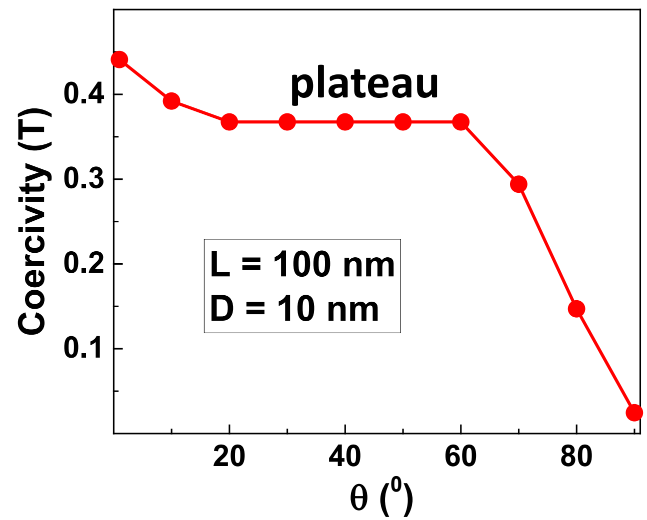


Weak dependence on the needle length if the aspect ratio > 50%

Quantifying how small and how well aligned the Fe-Co needles guides synthesis

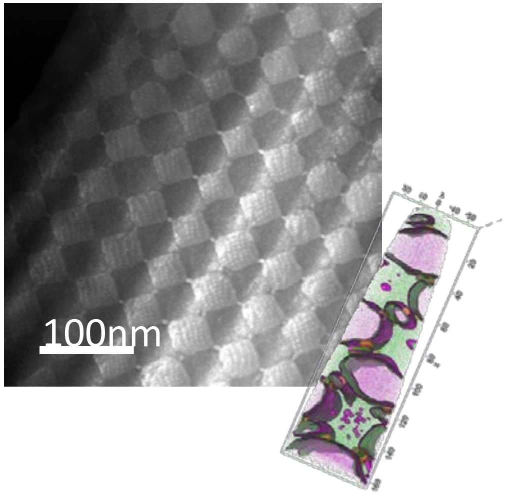
Grain misalignment



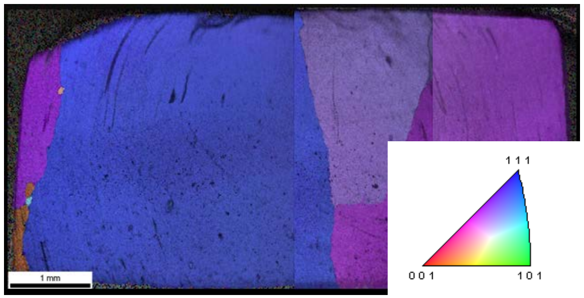


Coercivity changes significantly only after 60^0 misalignment

Technical Accomplishments in Synthesis of Bulk Magnetic Samples



- Reduce Co content
  - Near term low hanging fruit
- Optimize processing and chemistry to enhance coercivity
  - Magnetic and thermal anneals
- Sintering grain aligned alnico
- Introduce anisotropy
  - Distortion to Fe-Co

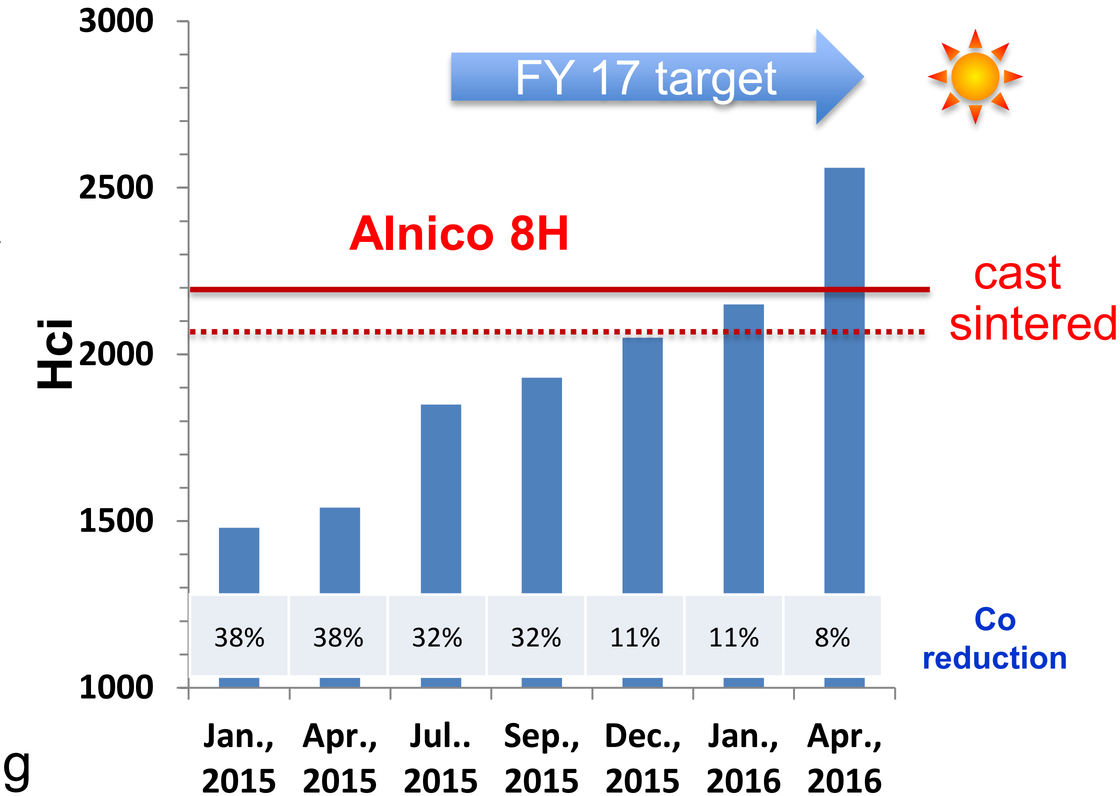


Co-lean alnico

Co high cost and price variability

- Co traditionally added to increase corecivity and high T stability.
- New knowledge of the chemistry and phase relationships enables design lower Co content without losing Hci.
- Chemical substitution is limited
    - Further improvements will require optimization of processing

Equi-electronic substitution of Co



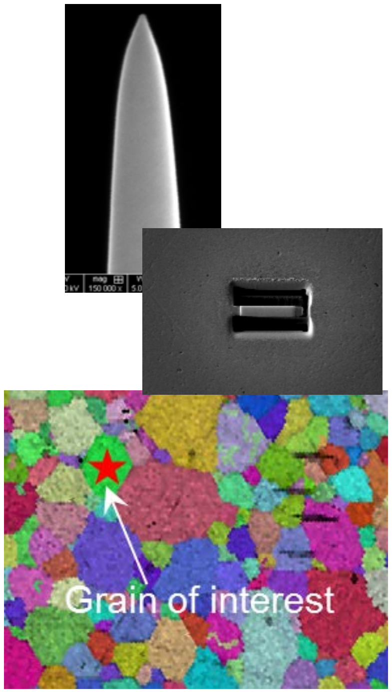
Trick more Co to stay where it is needed

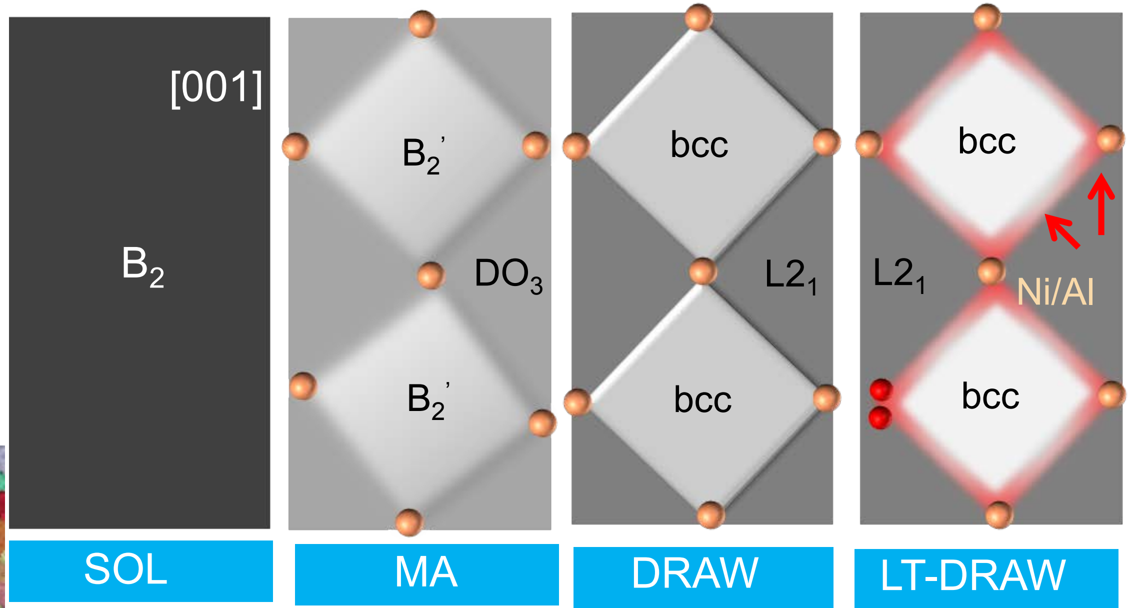
$Fe_{38.4}Co_{34}Ni_{12.6}Al_{13.7}Ti_{8.8}Cu_{2.5}$

~37% Co reduction

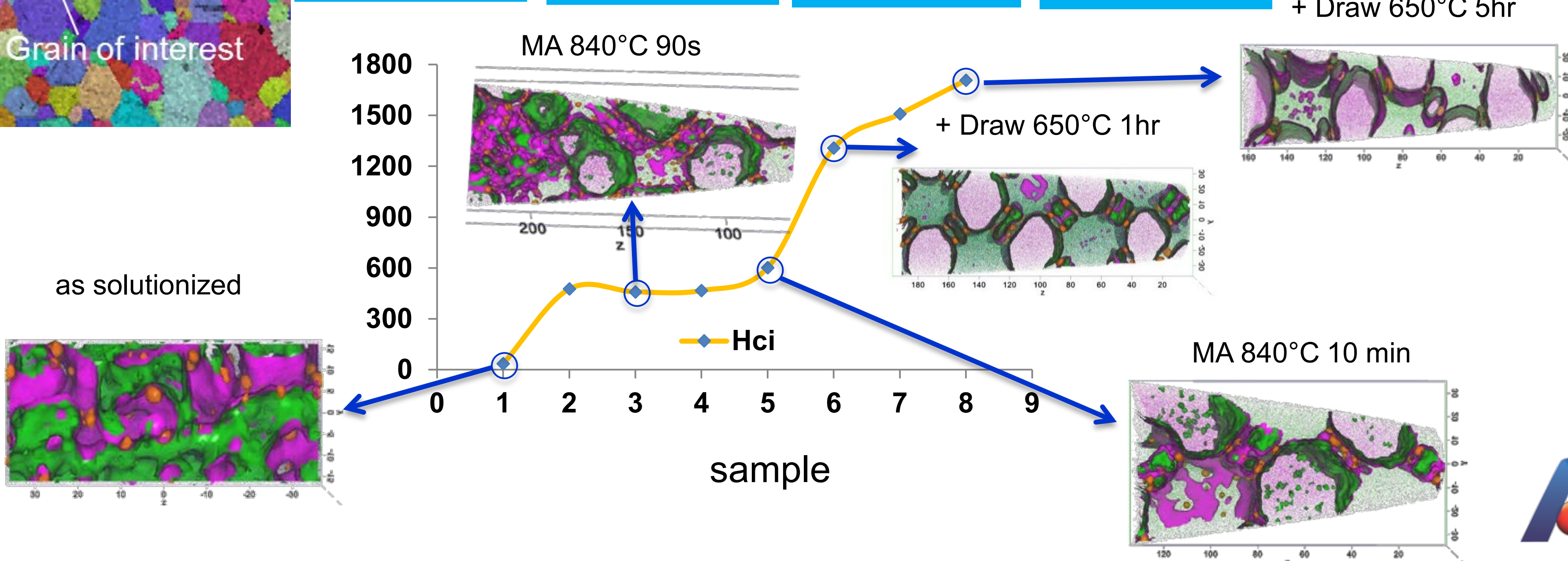
$Fe_{35}Co_{21.5}Ni_{19.0}Al_{15.0}Ti_{7.5}Cu_{1.5}$

Technical accomplishments in
Optimized processing and chemistry to enhance coercivity

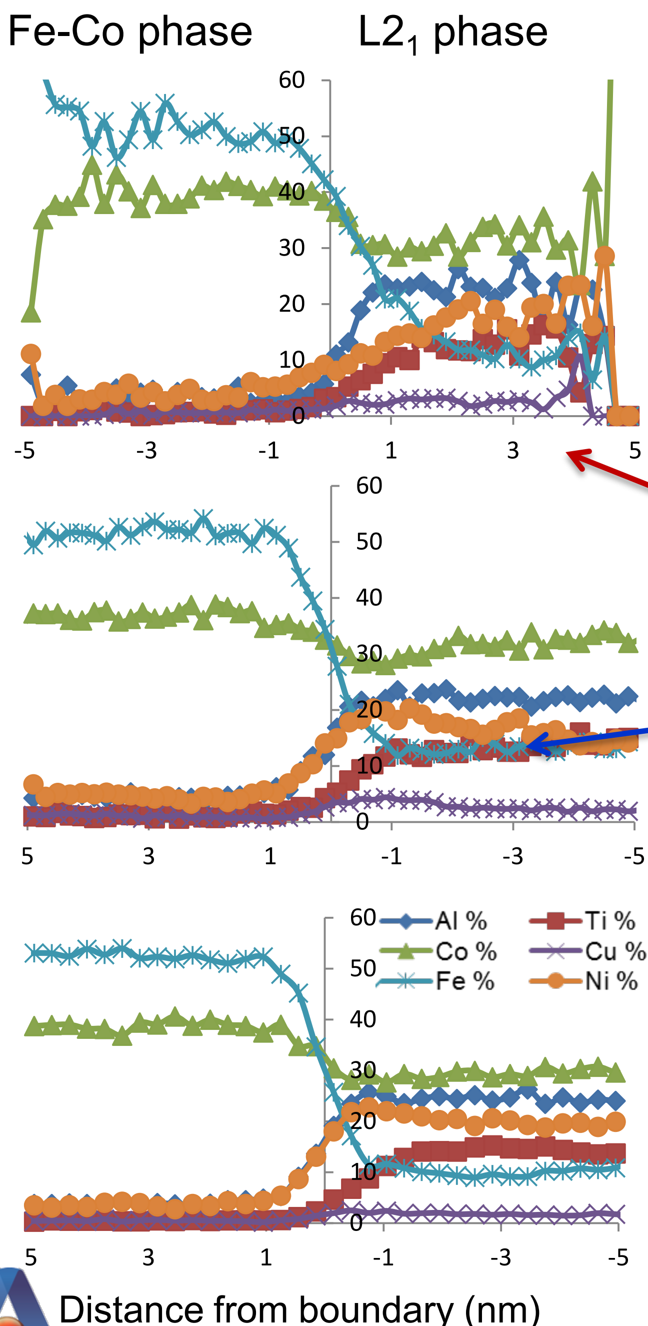


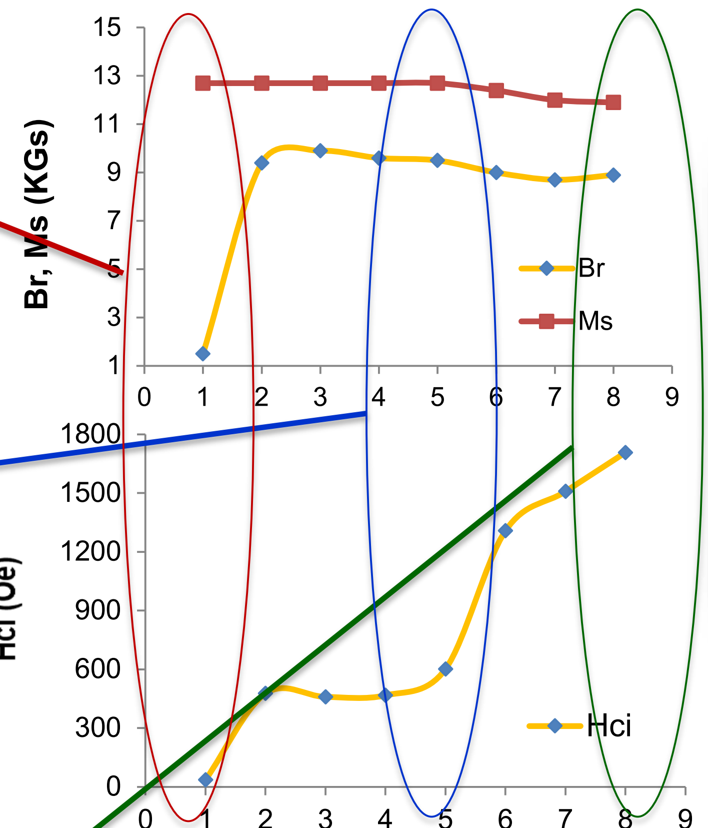


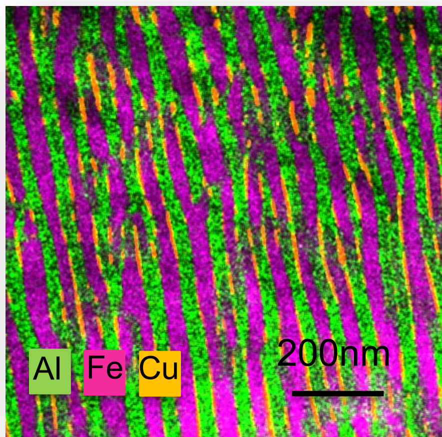
Series of samples alnico 8 were examined using 3DAP and TEM at critical points of the processing



3DAP chemical profiles and TEM microstructure will provide quantitative validation of the atomistic modeling



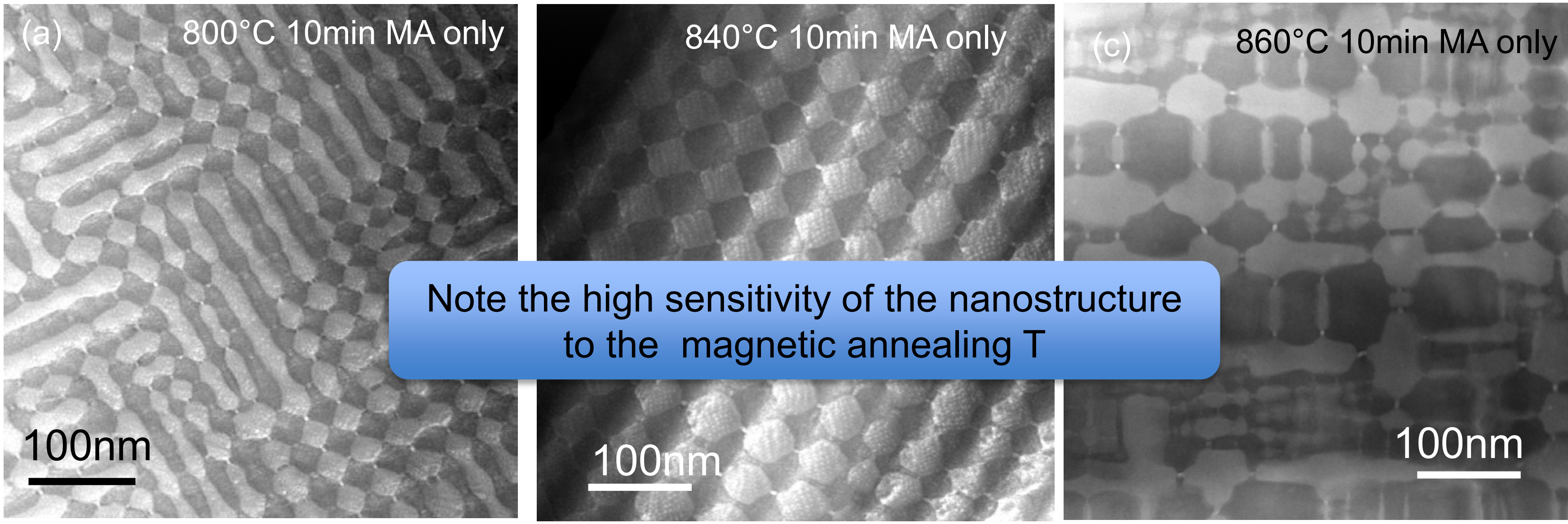




2D projection of a 3D chemical map of alnico 8

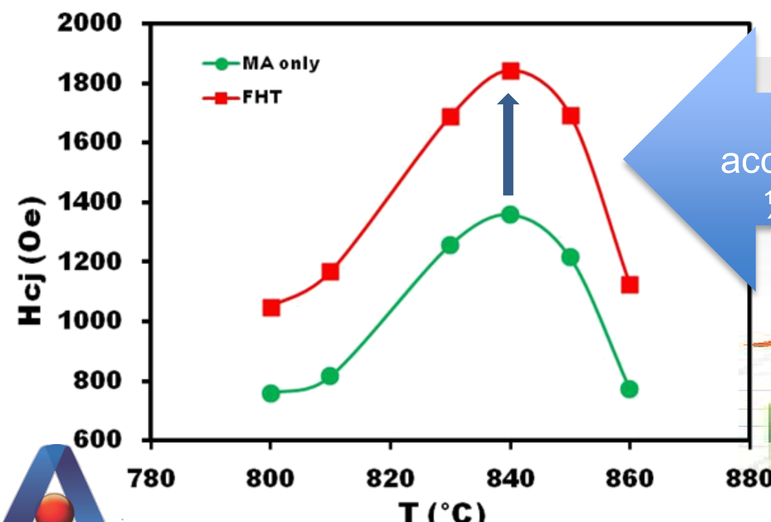
3D tomography will provide validation of the phase field modeling and inputs for the micromagnetic calculations

Effect of magnetic annealing temperature

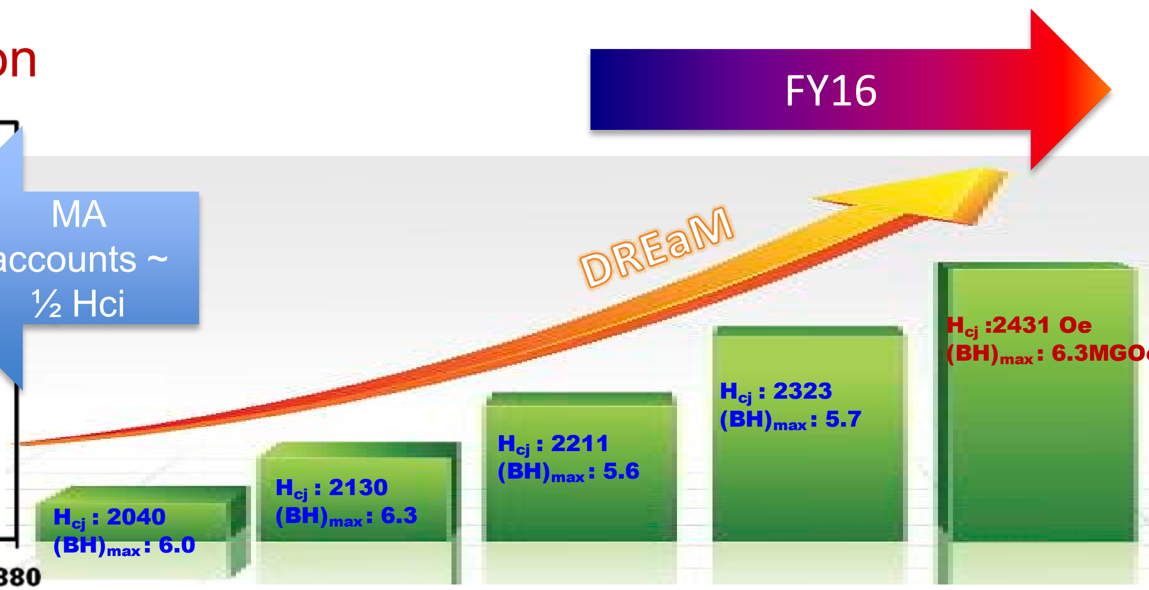


Note the high sensitivity of the nanostructure to the magnetic annealing T

Magnetic property optimization

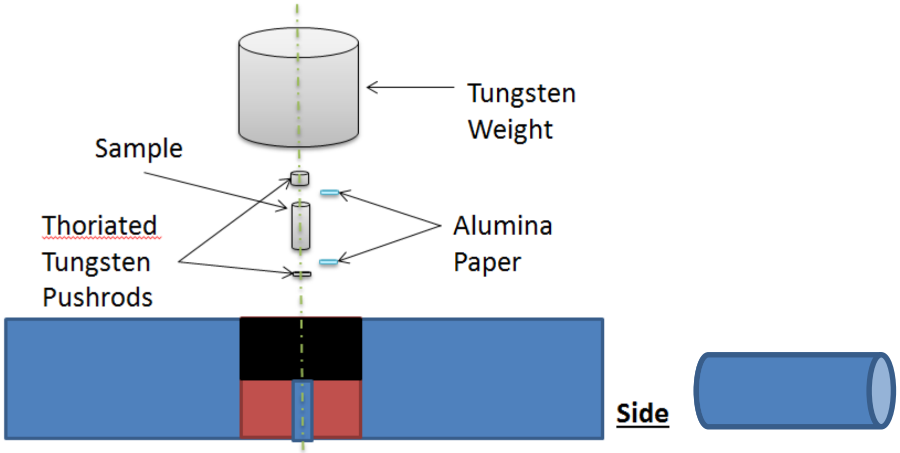


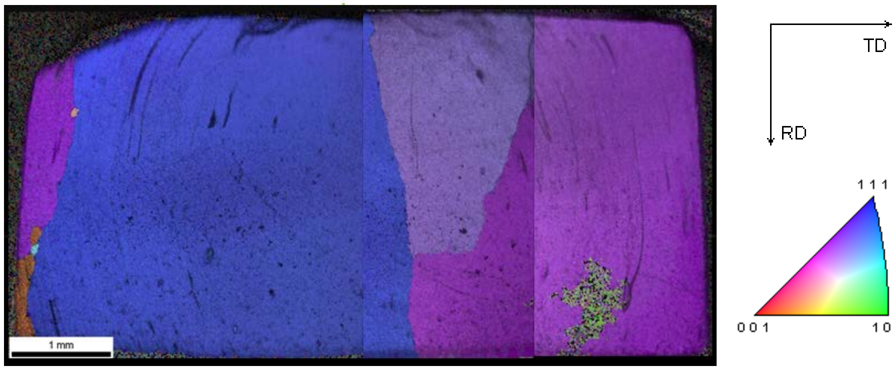
MA accounts ~ ½ Hci



Technical Accomplishments in Texture Alignment

- Solid state texture development utilizing abnormal grain growth condition
  - Grain rotation in high strain situations loads > 100g
  - Grain boundary energy biasing in low/no strain situations with loads < 100g
- Different resultant texture depending on mode utilized
- [111] typical with sheer banding and grain rotation
- [114]/[115] appears common with GB biasing, which is only ~16-19 degrees from optimal



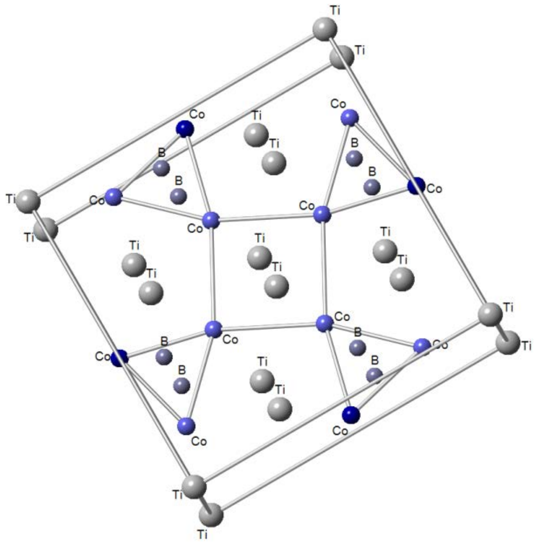


900g grain rotation

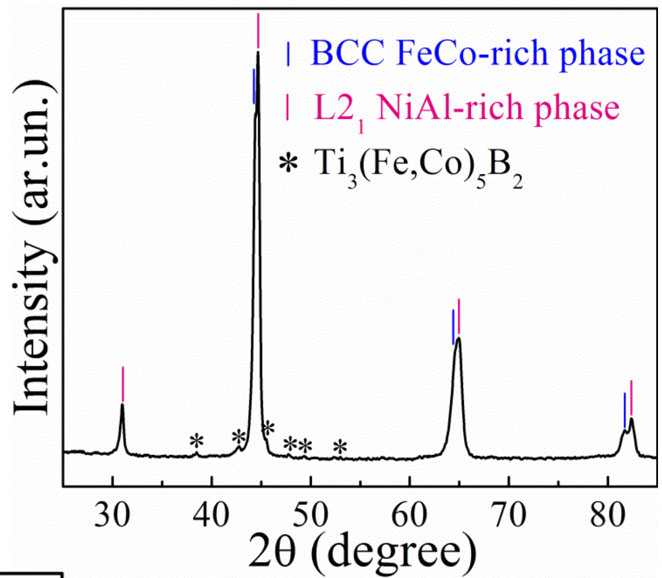
Provisional patent: Solid State Grain Alignment of Heat Treatable Permanent Magnets in Near-Final Shape (March 31, 2016)

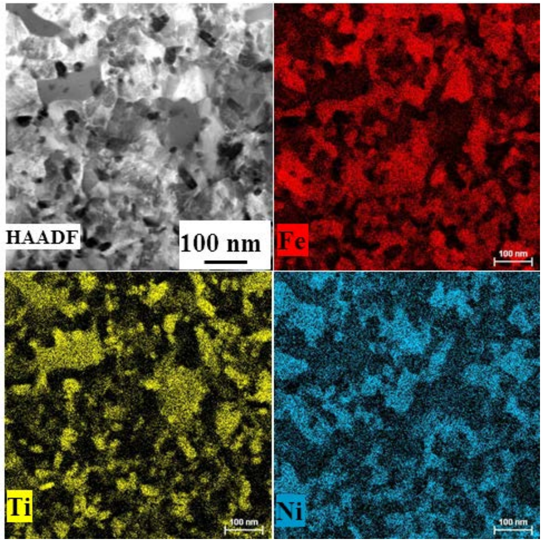
Technical Accomplishments in Anisotropy in alnico 8

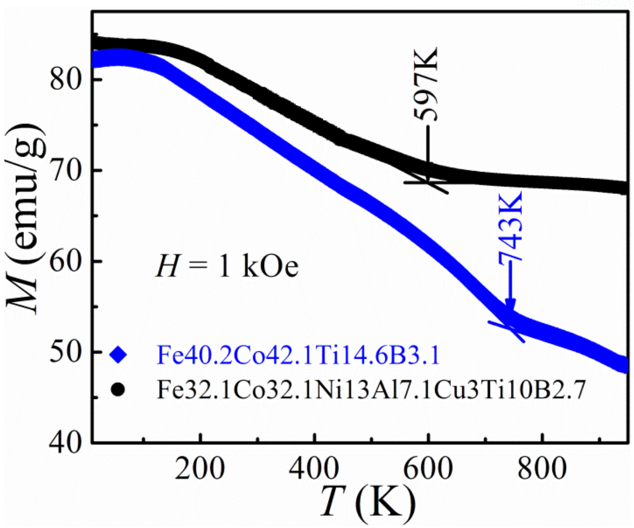
Structure of tetragonal $Ti_3Co_5B_2$



Amorphous Fe32.1Co32.1Ni13Al7.1Cu3Ti10B2.7 annealed (750°C, 10 min.)







Zhang, AIP Adv. **6**, 056001(2016).

Summary

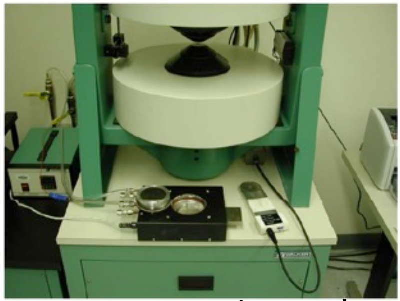
Tetragonal $Ti_3(Fe,Co)_5B_2$ phase with high T_c

Equiaxed alnico 8 and used to generate H_c.

Next steps: Develop bulk processing.

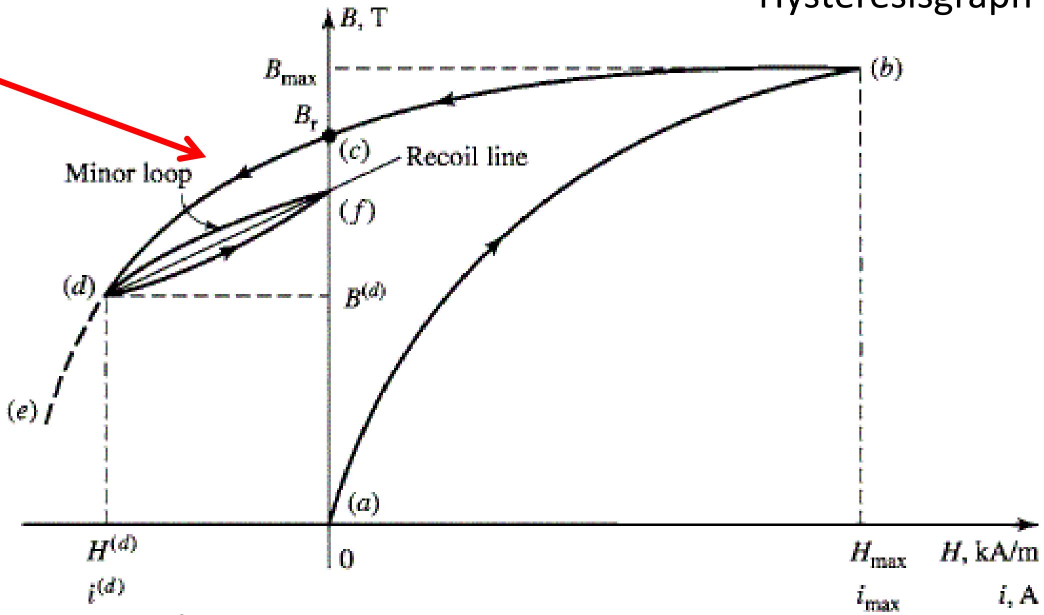
University of Nebraska Lincoln

Technical Accomplishments in Electrical and Magnetic Measurements



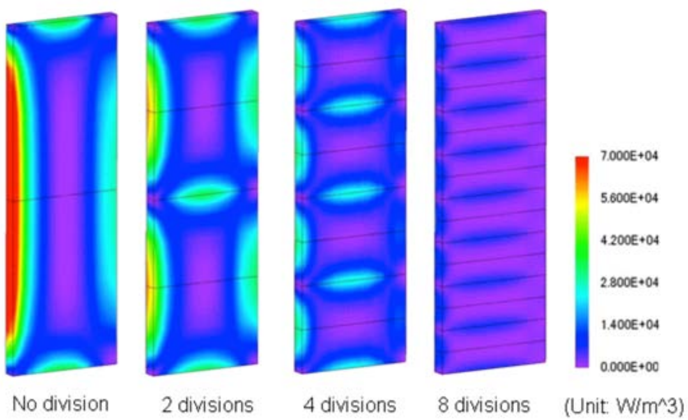
Hysteresisgraph

- B-H hysteresisgraph testing
  - Permeability
  - 4-quadrant B-H testing
  - Recoil testing – to determine magnetic field at which B_r is reduced permanently



- Resistivity and Eddy Current loss analysis
  - Important in considering the use of magnet segments in motor or generator designs to minimize eddy current losses.

Eddy current loss in magnets for various number of segments



Source: https://www.jmag-international.com/catalog/22_IPMotor_MagnetLoss.html

Classic Eddy Current Loss

$$P_e = (\pi f d B)^2 / 6 \rho \rho_e$$

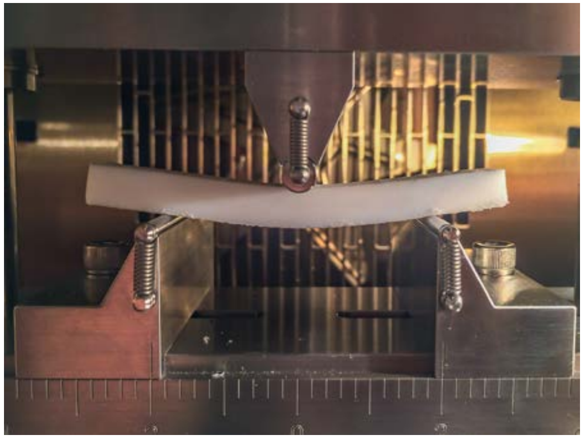
f: frequency
d: sheet thickness
B: flux density
ρ: density
ρ_e: specific elec. resistivity

Technical Accomplishments in Thermal Mechanical Properties

Base line testing of thermal/mechanical properties
Improve impact resistance
Improve motor assembly reliability
for managing thermal loads

- **Compression Testing**
  - 25.4 mm long, 9.5 mm diameter cylinder samples
  - Fine-grain samples tested at -40°C, 25°C, and 150°C
  - Coarse-grain samples tested at 25°C
- **Transverse Rupture Testing**
  - 3 mm x 3 mm x 32 mm beam samples
  - Follow ASTM B528-12 test standard
  - Fine-grain samples each tested at -40°C, 25°C, and 150°C
  - Will calculate transverse rupture strength:

Compression Test Fixture



Transverse Rupture Test Fixture

Response to Previous Year Reviewers' comments

- "The reviewer thought that the technical quality of the work is great, but that communicating a clear plan was not done well."

A number of reviewers were very complimentary on the achievements we have made but would like to set more targeted metrics to insure we do not get 'lost in the weeds'. This includes more integration with end users to flowdown the minimum properties needed. In the current FY, we have established a clearer set of intermediate goals to provide more granularity in the targeted metrics. This can be accomplished by setting near and long term goals: Improved coercivity with lower Co; Fully dense sintered alnico with improved texture; Produce prototype magnets designed by industry partner.

- The overall message of AlNiCo being viable was delivered, but sheer number of variables and options presented was excessive."

This is where the theoretical efforts have proven valuable. Design of a magnet is a complex set of engineering compromises. Theory efforts are designed to provide a a quantitative guide alloy optimization. While motor designers always want more of both coercivity and remanence, specific designs are more sensitive to one or the other. We are on a ***clear trajectory to enable discrete optimization*** *based on motor design rather than motor optimization around material limits.*

- The reviewer would like to see the game plan that leads to 20 MGOe. Although the future work is good and great progress is being made, this reviewer would just like to see how the project team would get to the end goal."

We now have a clear understanding of the broad materials optimization pathways. Improved coercivity requires reducing the Fe-Co needle diameters and sharpening the chemical gradient between the magnetic and non-magentic phases. Increasing remanance requires maintaining the volume fraction of the Fe-Co phase while increasing the grain alignment. Reducing the needles to ~ 15nm while maintaining current volume fraction with a well grain aligned alloy will meet the supplier's magnet performance target.

Ames Lab Partners/Collaborators for FY2016

Leadership Team: Iver E. Anderson, Matthew J. Kramer: AL

DREaM Team:

K.M. Ho, C.Z. Wang, V. Antropov, and T. Wang: AL

R. Skomski, D. Sellmyer and J. Shield: Univ. Nebraska-Lincoln

M. Eisenbach and M. Stocks: ORNL

S. Constantinides: Arnold Magnetic Technologies, Inc.

Collaborators:

- Baldor (Mike Melfi): Electric motor manufacturing technology, DREaM technology adviser.
- Univ. Wisconsin-Madison (Tom Jahns): Electric machine design, DREaM technology adviser.
- Synthesis Partners (Chris Whaling): Automated search of permanent magnet literature, DREaM project adviser.
- General Electric (Frank Johnson): Non-RE magnet technology and motor design, started in 2012, VT Motor/Magnet partner (prime).
- UQM Technogies Inc. (Josh Ley): Advanced non-RE PM motor design, started in 2012, VT Motor/Magnet partner (prime).
- Univ. Delaware (George Hadjipanayis): Development of high-energy permanent magnets, ARPA-E partner (prime).
- Case-Western Reserve Univ. (Dave Matthiesen): Transformation enabled nitride magnets absent rare earths, ARPA-E partner (prime)

Remaining Challenges and Barriers

- Coercivity levels continue to be increased while Co content is decreased compared to commercial alnico magnets, but higher energy density will require ability to improve grain alignment while reducing nano-structure further.

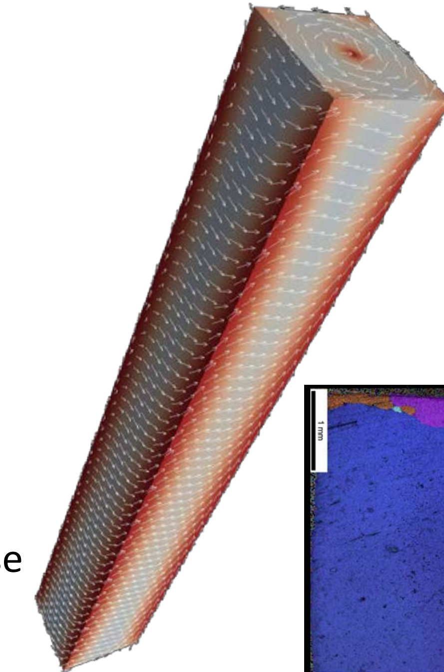
- Significant understanding of the role of magnetic processing of alnico microstructure and nano-structure for enhancing magnetic properties has been achieved but a clear mechanism explaining the longer, lower temperature anneal and nearly a 2x in coercivty remains elusive.

- We have establish the ability to routinely produce, dense, fine grained samples using binder-assisted compression molding to a variety of shapes with anisotropic magnetic properties but need to extend this to grain aligned parts with controlled crystallographic orientation.

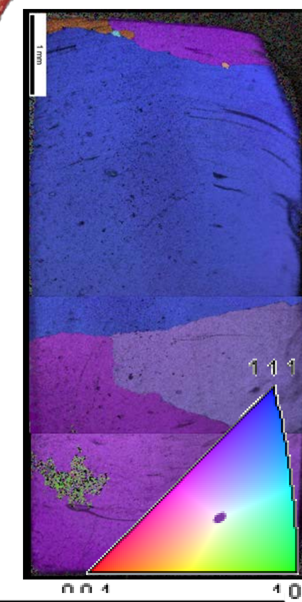
- To enable extensive experiments on compression molding and other bulk magnet fabrication methods, additional gas atomized pre-alloyed powder must be produced with high purity and desired composition.

Remaining FY16 DREaM Tasks

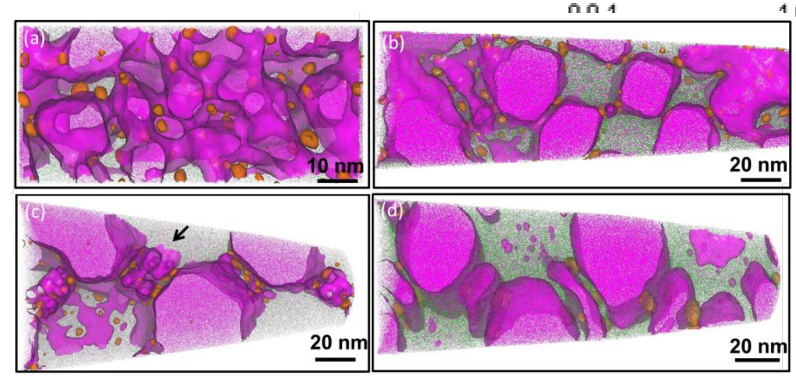
Develop Focused Theory & Simulation: The theory efforts will continue to establish a clear set of kinetic models to predict evolution of the various competing phases. This information is being validated by targeted set of carefully designed experiments and characterization using state-of-the-art tools. The data is moving ‘upscale’ to inform mesoscale models to predict the effect of processing on microstructure and magnetic properties.



Synthesize Test Samples: Demonstrate the ability to produce fully dense and grain aligned magnet. Then produce bulk magnets of a sub-final size/shape (for UQM) will be made with learning from processing/characterization results with preferred nano-structure and microstructure. [SMART milestone] [Demonstration of bulk prototype alnico magnets with improved magnetic properties and mechanical properties for use in an advanced UQM motor system will be done under separate VT project.]



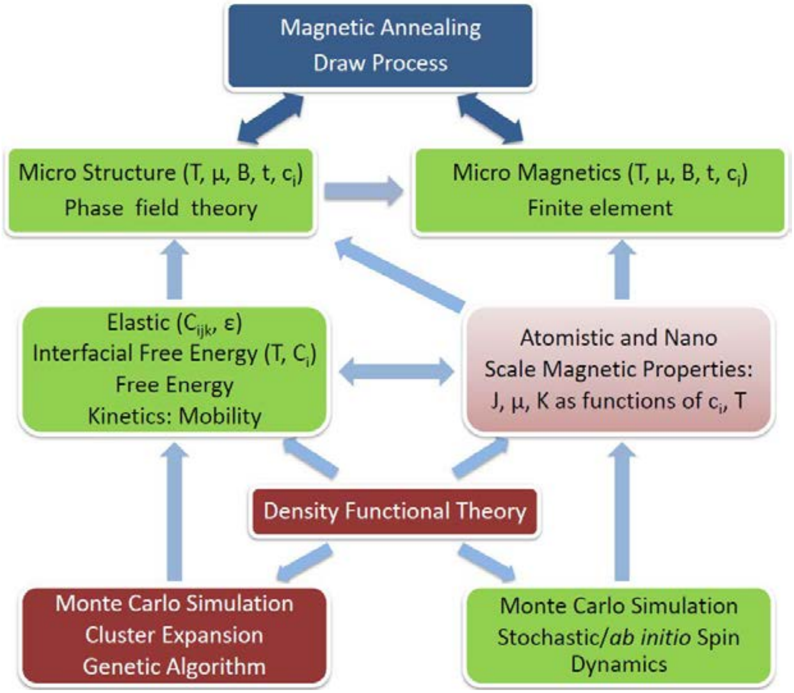
Perform Characterization: Map out a clear set of diffusion profiles as a function of processing parameters: magnetically annealed and draw, linking to specific magnetic properties.



Future (proposed) FY17 DREaM Detailed Tasks

Promote DREaM Team Interactions: Maintain regular WebEx discussions on specific project progress and conduct two face-to-face workshops per year with research team.

Develop Focused Theory & Simulation: Use theory methods to improve cluster expansion models to 6-element Al-Ni-Fe-Co-Ti-Cu systems (alnico 8 and 9) to permit realistic phase equilibria. M-C simulations & enabling kinetic M-C to begin on spinodal & annealing. Verify with experimental results and use for calculating magnetic properties and driving forces to extend phase field and micromagetic microstructure calculations.



Perform Characterization: Continue characterization of extensive series of alnico 8 and low-Co samples to verify theory predictions/actual effects from alloy & processing variations and correlating magnetic properties and nano-structure. Utilize new NREL collaboration to add magnet mechanical property data. Expand ORNL studies to include temperature dependent magnetic properties and FEM for motor design.

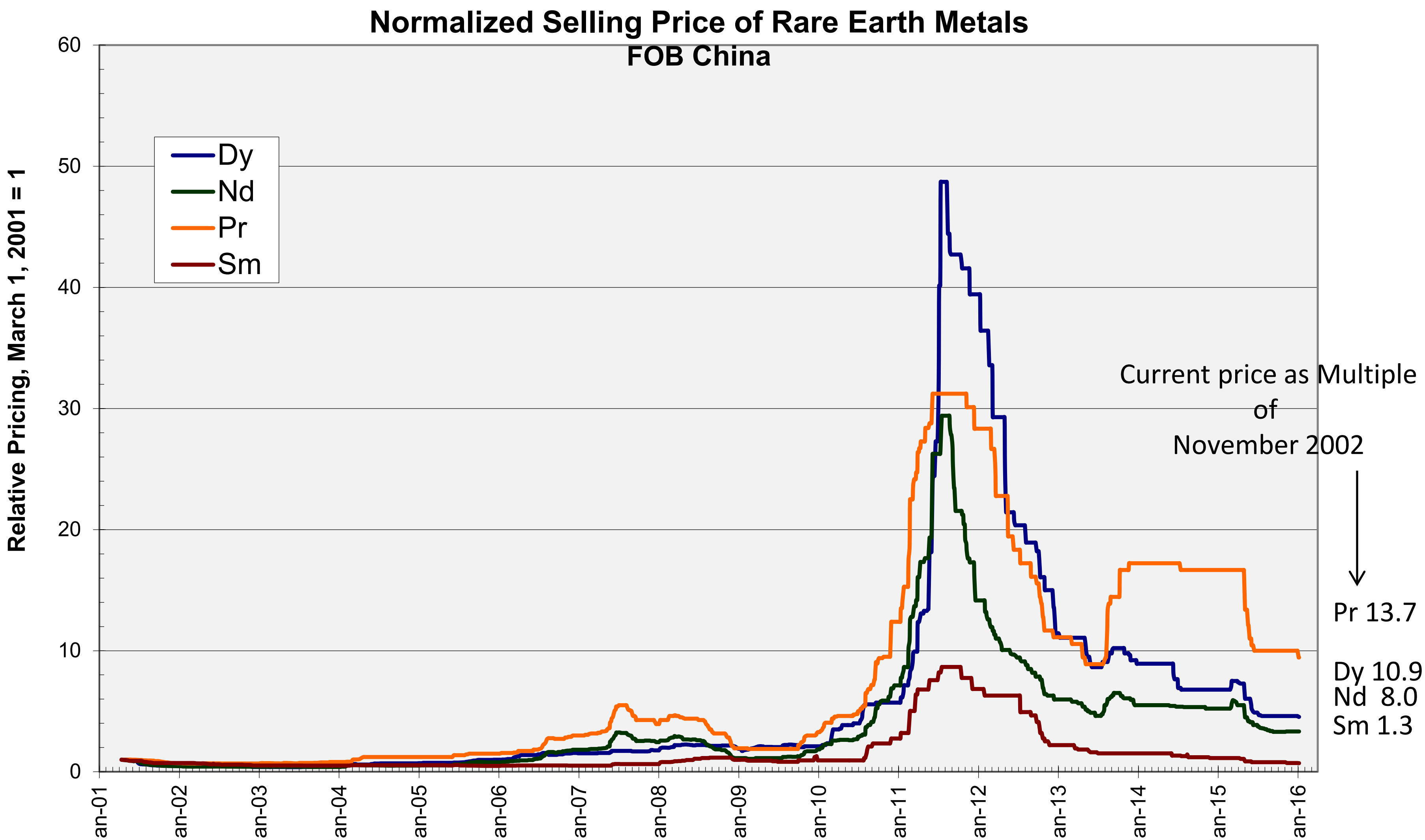
Synthesize Test Samples: Bulk samples with nano-structure variations made to continue pursuit of modified alnico alloys, using magnetic and thermal processing parameters for pre-alloyed powder (alnico 8, refined alnico "low-Co"). Refine methods to gain control over texturing effects in sintered bulk magnets to further improve magnetic properties. Analyze and report results of high magnetic field experiments on nano-structure and magnetic properties. [SMART milestone, complete September 30, 2016]

Summary

- **Coercivity > 2500 Oe (alnico 8H ~ 2170 Oe)**
- Co decreased while maintaining coercivity
  - New pathways show even more promise
- Bulk sinter and grain aligned demonstrated
  - Patent filed
- Near-net shaped, half scale motor magnets fabricated
- Modeling providing useful guidance

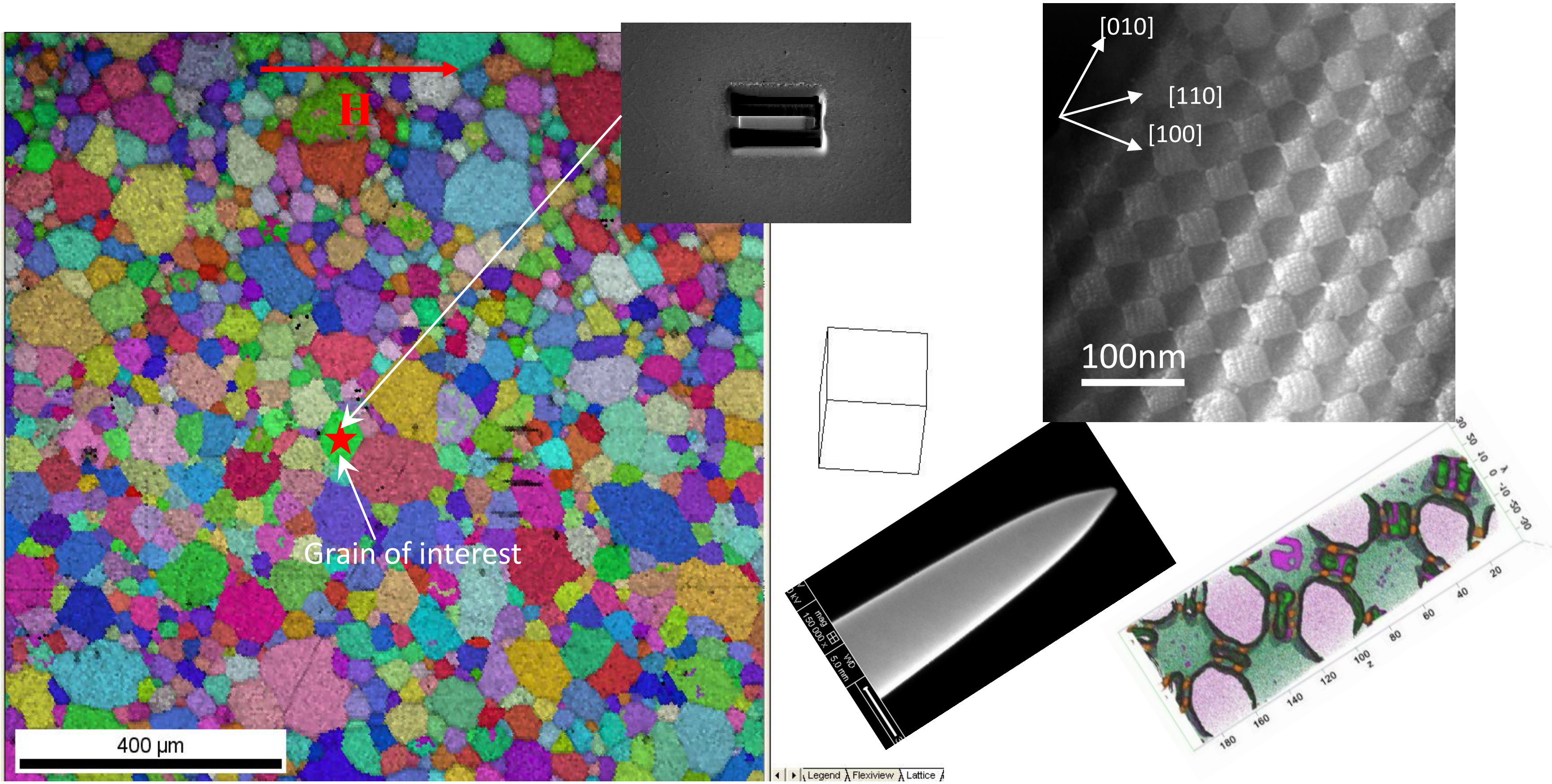
Technical Back-Up Slides

Rare earth metal prices (normalized)



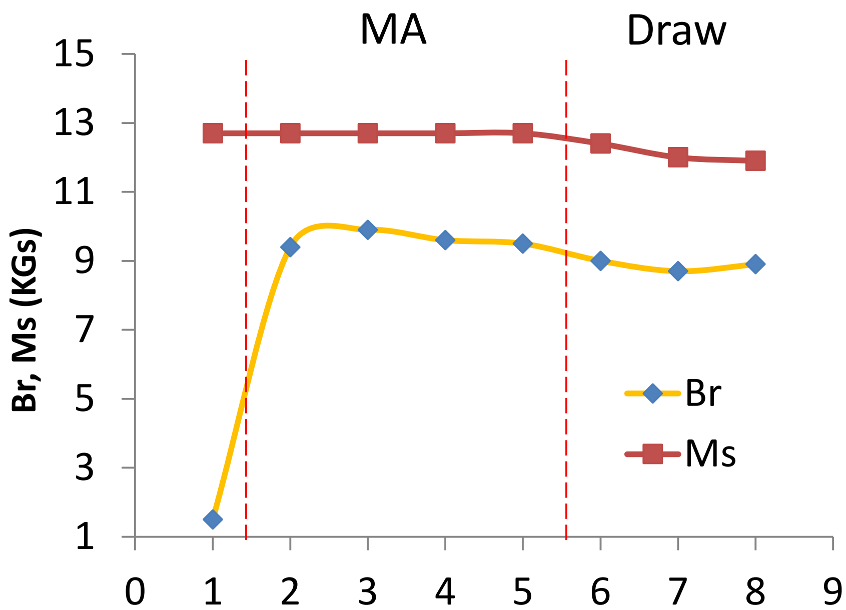
ARNOLD® MAGNETIC TECHNOLOGIES

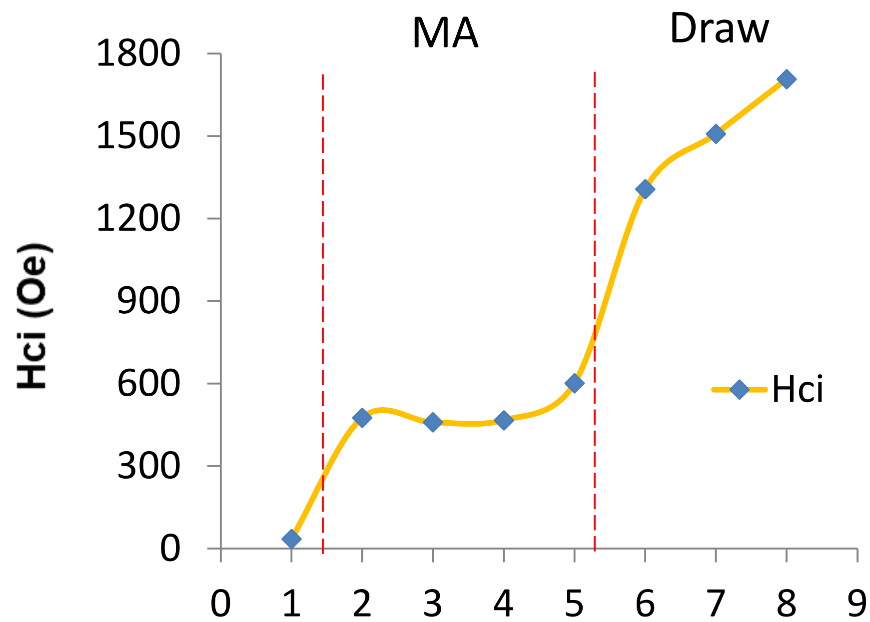
Diffusion Profiles from MA and Draw



- Grains with its [100] direction parallel l to the external magnetic direction and [110] direction parallel to the liftout direction was intentionally selected to capture as many interfaces as possible and avoid the effect of grain orientation..

Magnetic properties





1. as solutionized
2. HIP-A1-1-M840°C-30s
3. HIP-A2-1-M840°C-90s
4. HIP-A4-2-M840°C-5min
5. HIP-A4-2-M840°C-10min
6. HIP-A4-5D1-M840°C-10min-650°C 1hr
7. HIP-A4-6D3-M840°C-10min-650°C 3hrs
8. HIP-A4-7D5-M840°C-10min-650°C 5hrs

Same sample was processed sequentially from solutioinizing, magnetic anneal and draw and 3D atom probe, TEM and magnetic measurements were made

Mechanical Testing

- **Compression Testing**
  - 25.4 mm long, 9.5 mm diameter cylinder samples
  - Fine-grain samples tested at -40°C, 25°C, and 150°C
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- **Transverse Rupture Testing**
  - 3 mm x 3 mm x 32 mm beam samples
  - Follow ASTM B528-12 test standard
  - Fine-grain samples each tested at -40°C, 25°C, and 150°C
  - Will calculate transverse rupture strength:

$$TRS = (3 \times P \times L)/(2 \times t^2 \times w)$$

where:

TRS = transverse rupture strength (MPa)

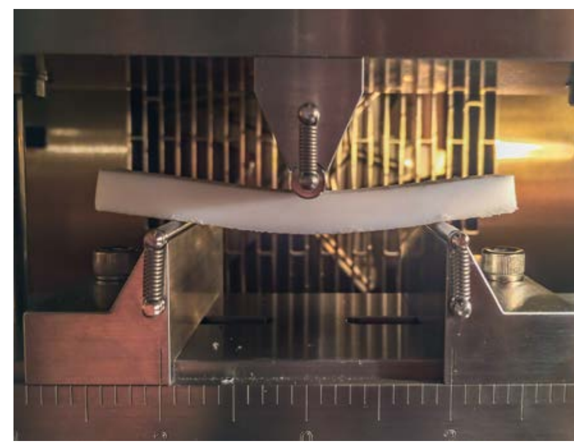
P = force required to rupture specimen (N)

L = Distance between supporting rods (25.4 mm)

w = specimen width (mm)

t = specimen thickness (mm)

Compression Test Fixture



Transverse Rupture Test Fixture

Recent related works from other groups: Interstitial Carbon/Boron doped FeCo

Carbon doped FeCo alloy

Theoretical prediction: Phys. Rev. B 89,144403 (2014)

- Carbon doped Fe-Co alloys form in a wide range of concentrations, in analogy with the formation of martensite in steels.
- The alloys have a stable tetragonal distortion.
- MAE up to 0.75 MJ/m^3.

Experimental progress: J. Appl. Phys. 116, 213901 (2014)

- 2 at. % of Carbon leading to the formation of a spontaneously strained phase with 3% tetragonal distortion. $(Fe_{0.4}Co_{0.6})_{0.98}C_{0.02}$ films have MAE above 0.4 MJ/m^3.

Boron doped FeCo

Theoretical prediction: J. Phys. D: Appl. Phys. 47 (2014)

- MAE up to 0.8 MJ/m^3

Conclusion

- A large increase of MAE in bulk Fe-Co rich phase is possible.
- Interface anisotropy can be significant.