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

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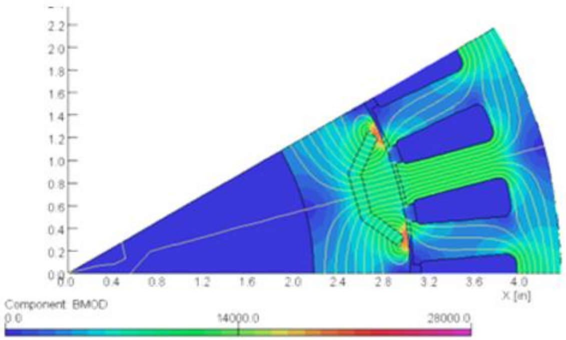


June 6, 2017

Project ID # EDT015

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

Overview

Timeline

- Start – October 2014
- Finish - September 2018

75% Complete

Budget

- FY 15 Funding - $1900K
- FY 16 Funding - $2500K
- FY 17 Funding - $1100K
- FY 18 Funding - $1100K (planned)

OAK RIDGE National Laboratory University of Nebraska Lincoln ARNOLD MAGNETIC TECHNOLOGIES

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.

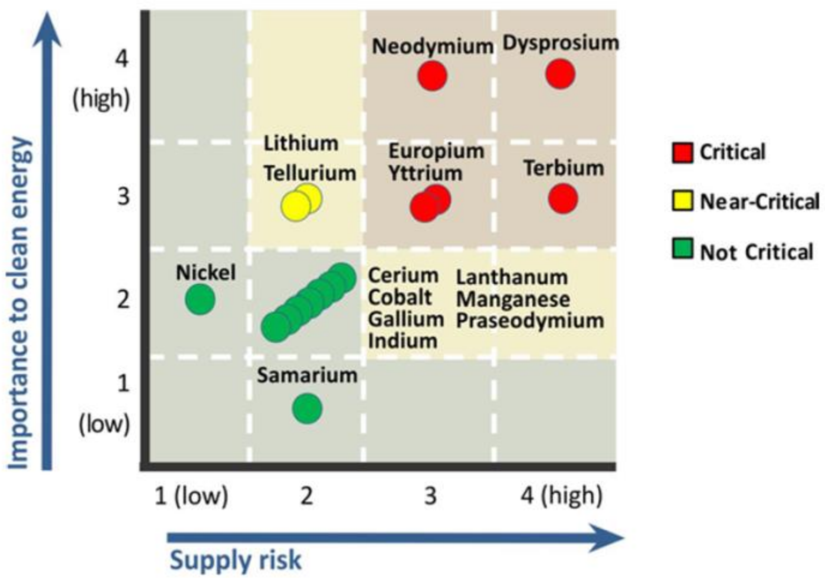
Partners

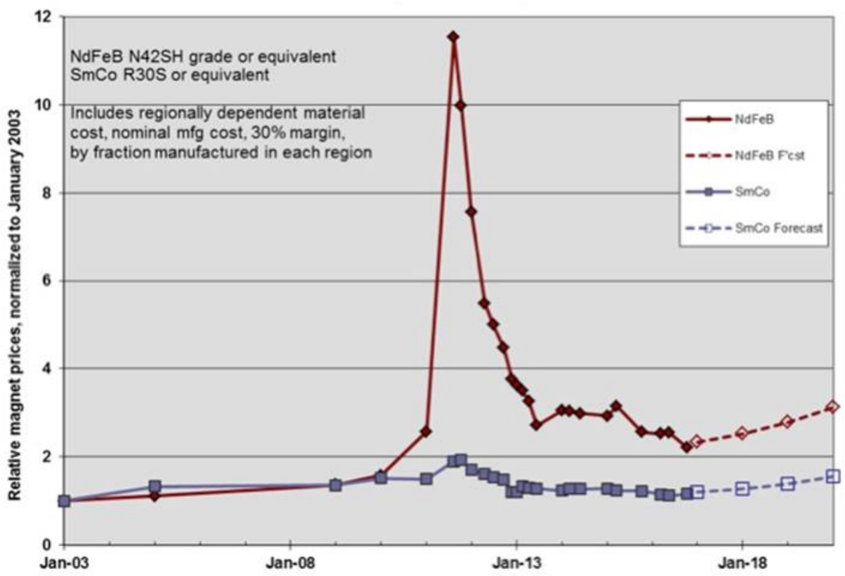
- Baldor, U. Wisconsin, NREL, Ford, GM, GE, UQM, Synthesis Partners (collaborators)
- ORNL, U. Nebraska, Arnold Magnetic Tech. (DREaM subcontractors)
- Project lead: Ames Lab

*2020 VT Targets

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.
- Likely 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.





FY17 DREaM Tasks

2016 Oct	Nov	Dec	2017 Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep

Develop enhanced alnico (non-RE) magnets

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

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

Synthesis of Test Samples:
Improve remamance through texture enhancement while optimizing heat treatments for new alloy compositions

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

Produce a bulk alnico magnet of final size and same shape desired by a motor industry partner

Characterization:
Extend advanced structural characterization.to 3D.
Magnetic and microstructural characterization of modified 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: Well-controlled bulk magnet samples will be fabricated with enhanced grain alignment and energy product (MGOe) and superior Hci compared to commercial alnico 8HE.

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.

FY17 Focus: Produce a bulk anisotropic alnico magnet with Br in excess of 0.7 T and Hci in excess of 2500 Oe. Properties of the magnet will be provided to UQM and ORNL for evaluation in their initial motor designs. (Complete in December 2016).

Key Deliverable: Well-controlled bulk magnet samples will be fabricated with enhanced grain alignment and energy product (MGOe) and superior Hci compared to commercial alnico 8HE. (Complete in March 2017).

Go/No Go Decision Point: Does bulk sub-sized alnico magnet have improved magnetic properties compared to alnico 8HE and/or alnico 9?

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.

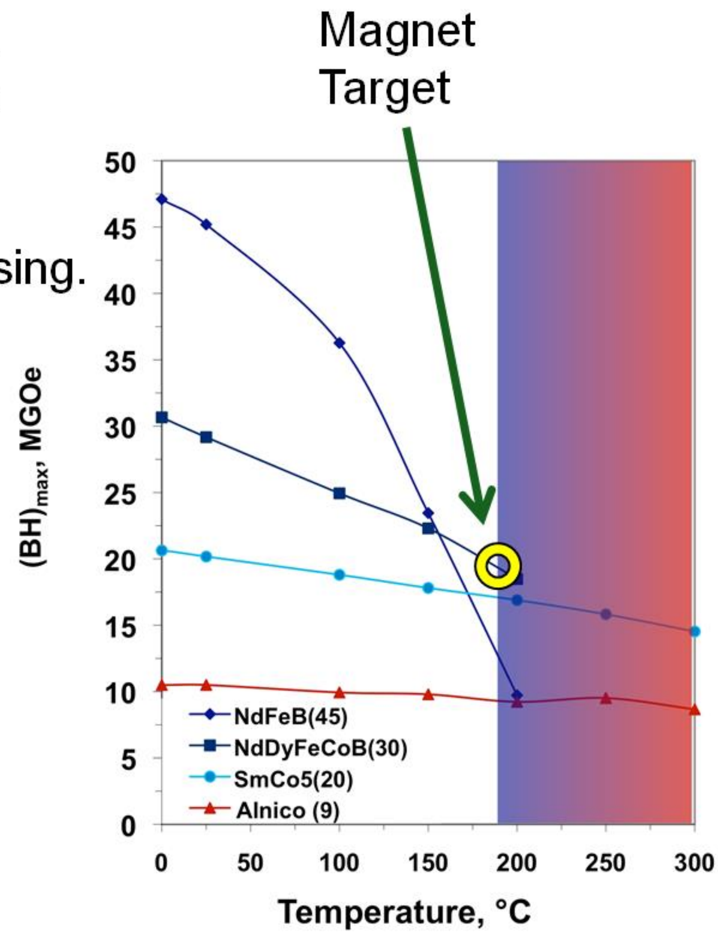
Deliverables: Bulk alnico magnet samples made with low-Co alnico alloy of reduced cost.

DREaM Overall Approach/Strategy

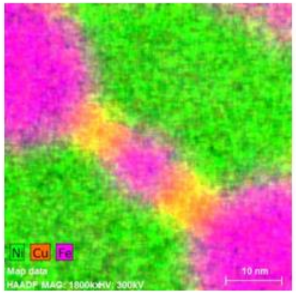
Near-term non-RE Magnets: Best RE-free magnets (alnico) further enhanced (coercivity) by low-Co alloy design and bulk powder processing improvements using detailed and innovative analysis of micro/nano structure-magnetic property relationships, extensive theory results, and critical industry input.

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

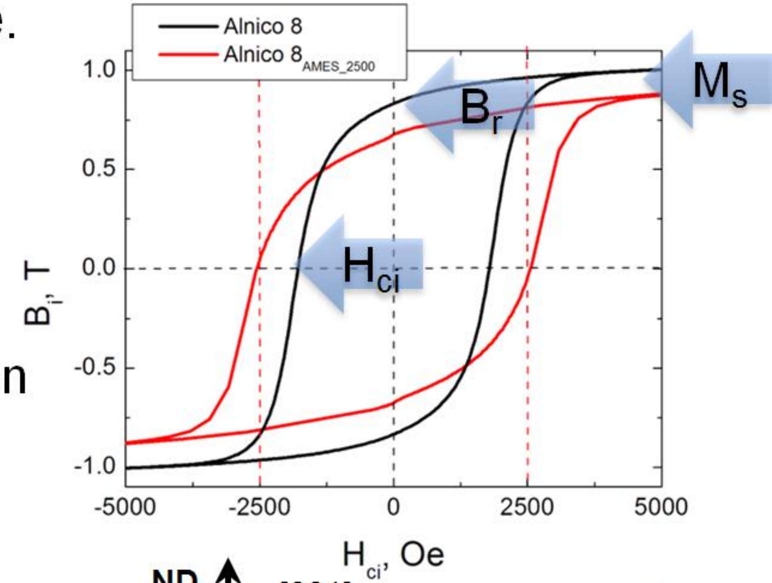
		Alnico 8	Alnico 9
aspect ratio		~ 10:1	> 10:1
fraction bcc phase (f)		0.53	0.53
Fe:Co in bcc phase		0.54	0.60
mole % Fe+Co in bcc		0.84	0.91
~M_s (KG) for bcc based on Fe:Co		23.8	23.9
Fe:Co in intermetallic		0.24	0.27
mole % Fe+Co in bcc		0.36	0.40
B_r (KG)	measured	8.2	10.6
	calculated	10.6	11.5
Hc_i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



Alloy Design Requisites

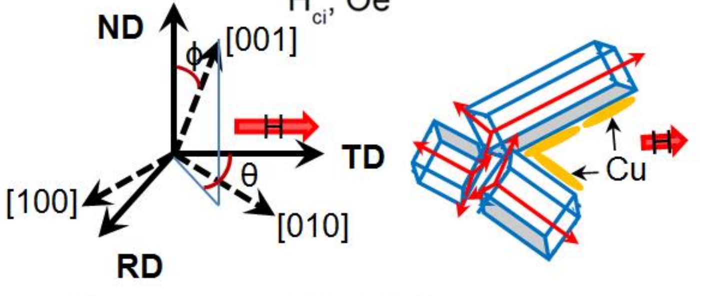


- Maximize saturation magnetization (M_s)
  - Fine tuning of the alloy chemistry to maximize the volume fraction of Fe-Co phase.



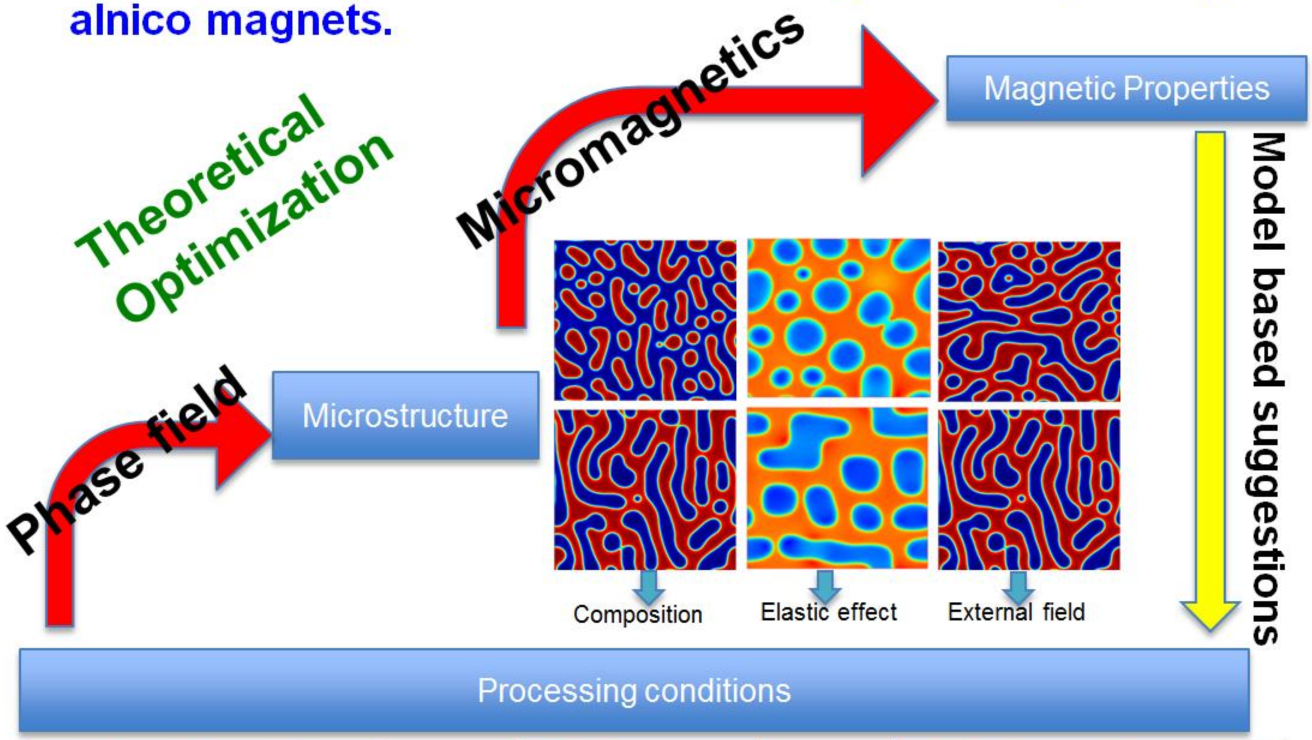
- Maximize coercivity (H_{ci})
  - Spinodal as fine as possible while insuring complete chemical separation

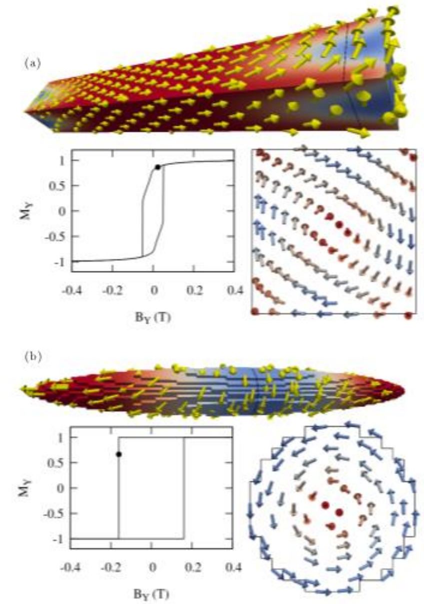
- Maximize Remanence (B_r)
  - Align <100> to the orientation of the field annealing



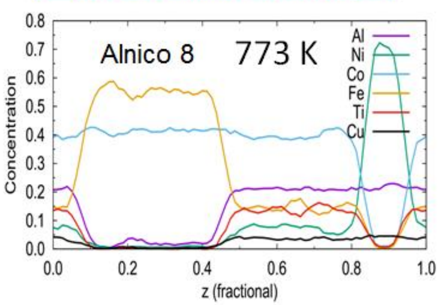
Technical Accomplishments in Theory and Modeling

- 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.

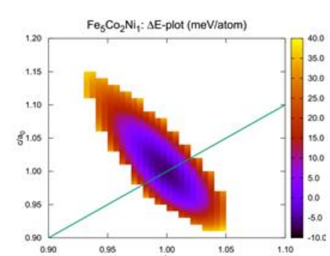




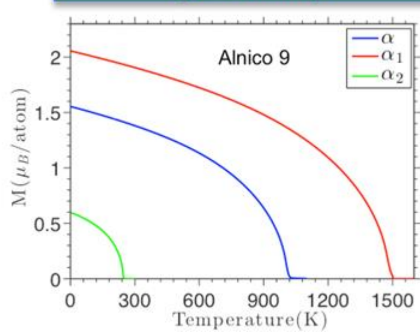
Composition profile (MC & Cluster Expansion)

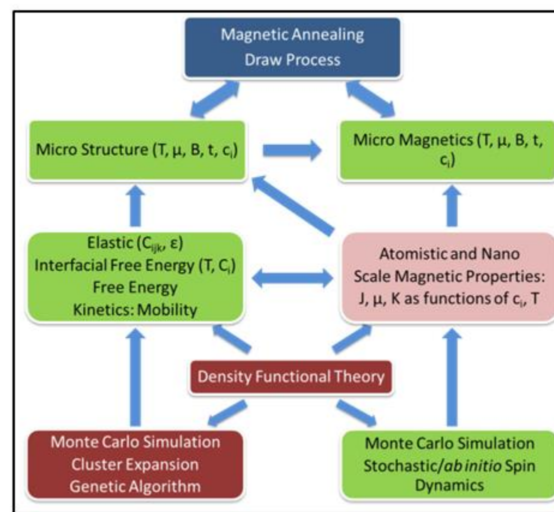


Elastic response (DFT)



Intrinsic magnetic property (DFT & MFT)



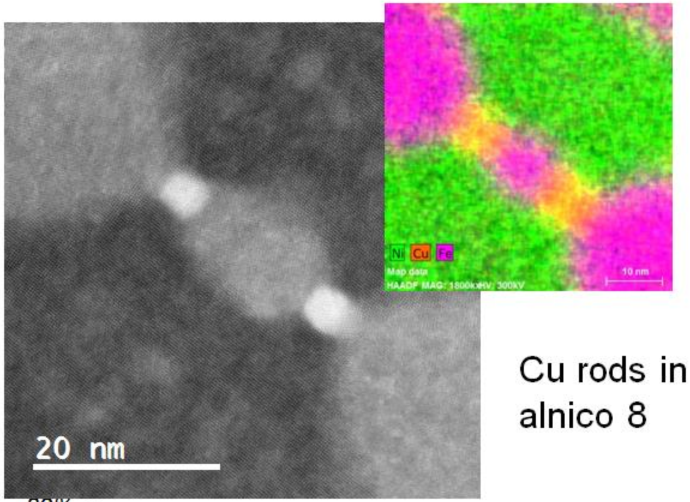


Monte Carlo Simulations Taking Cu Into Account

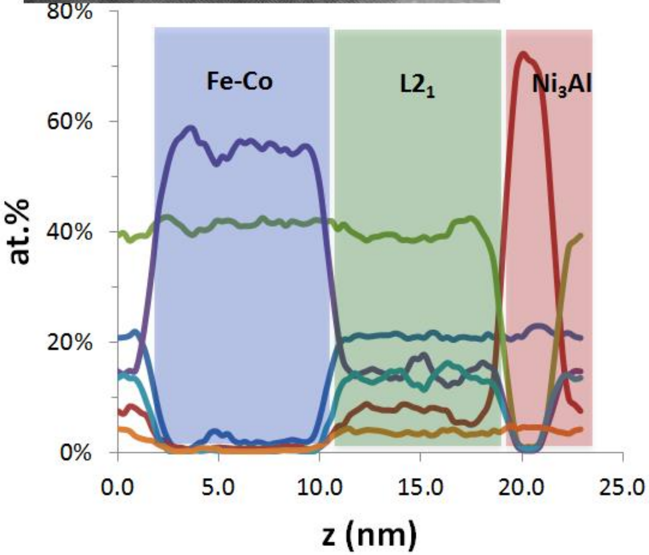
- **Experiment observations:**
  - Cu rich area connect magnetic needles.
  - Cu rich phase forms BCC first, then transforms to FCC and elongates during draw.
- Why does Cu form at specific locations?
- What roles does it play in coercivity?

Cluster expansion terms optimized for Monte Carlo (MC) simulations. Database includes 5500 structures.

Cu plays an critical role in spinodal spacing and isolation of the Fe-Co needles



Cu rods in alnico 8

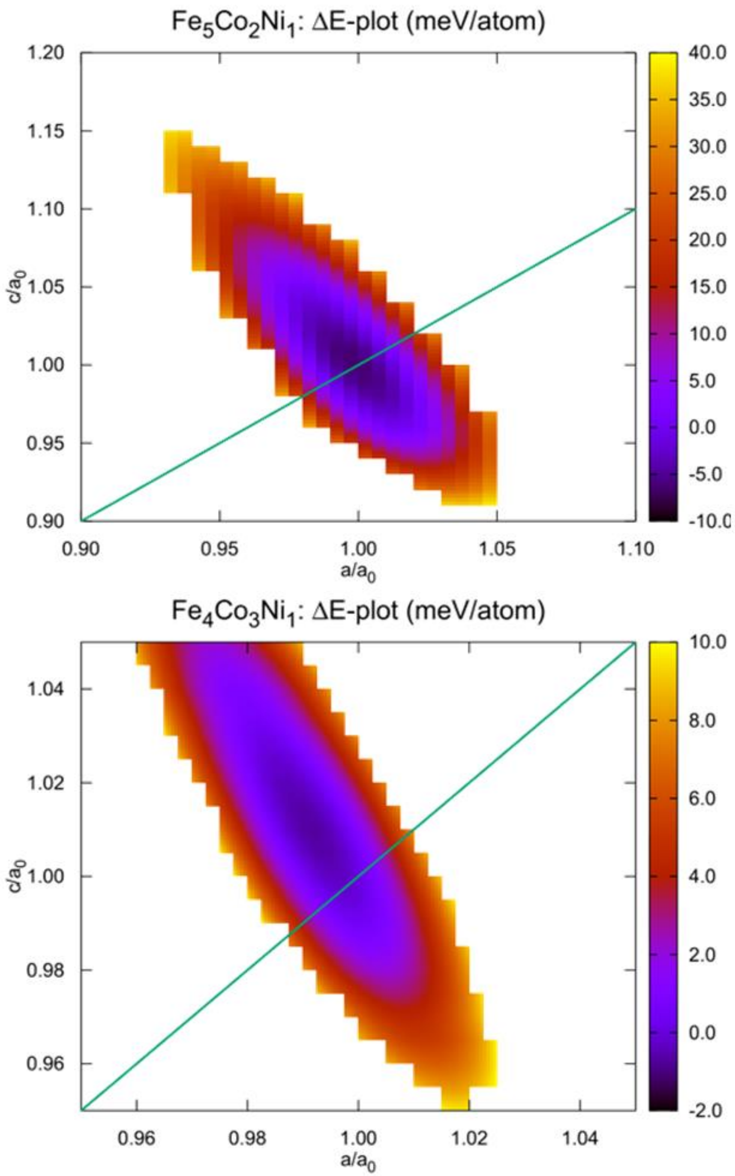


$Al_{14.0}Ni_{11.7}Co_{35.9}Fe_{28.7}Ti_{7.20}Cu_{2.50}$
supercell 6 x 6 x 80

First-principles simulations

Induce tetragonal distortion to enhance coercivity?

Ni induces distortion but induced anisotropy is small, so likely increase in coercivity is insignificant.

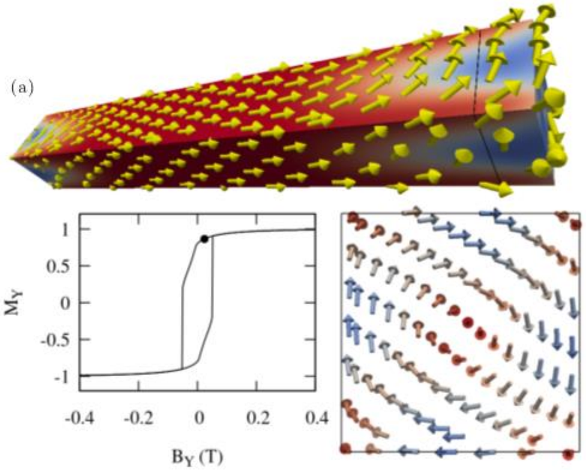


Simple Ni addition for anisotropy not worth it.

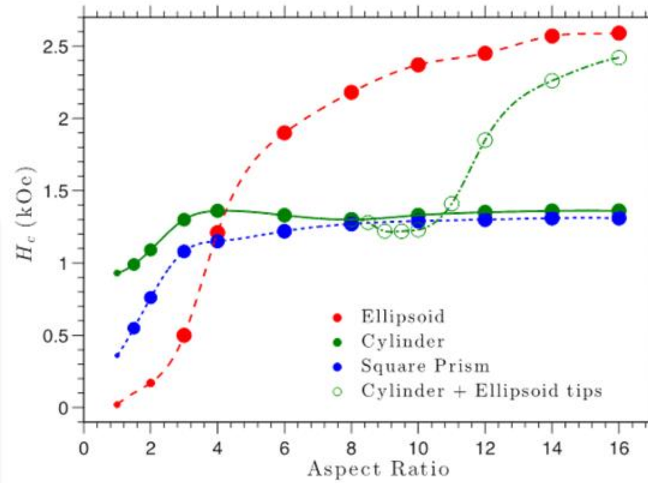
Theory saved us time and effort!

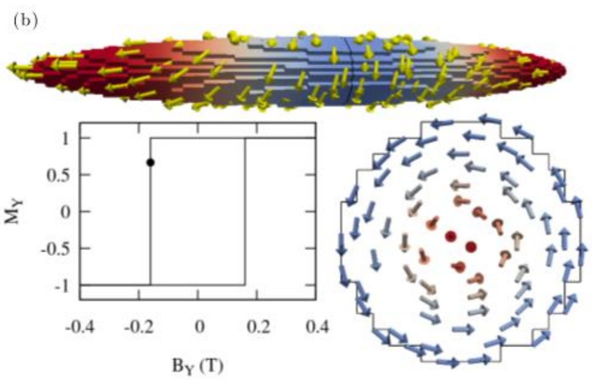
Micromagnetic Simulations

Conventional mechanism appear to be wrong!

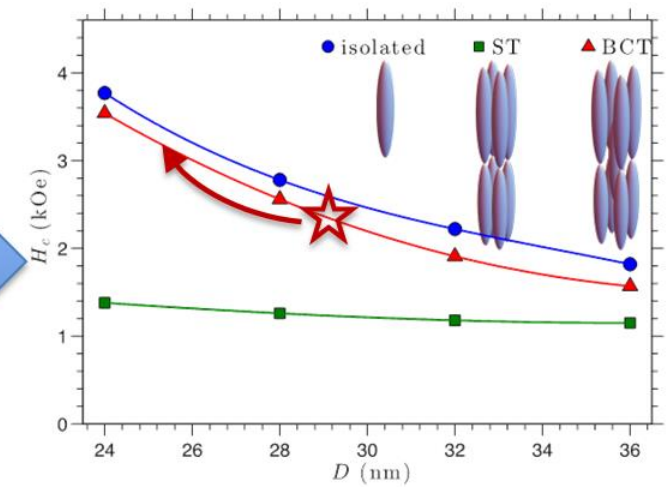


Curling of the spins makes the reversal highly dependent on shape.





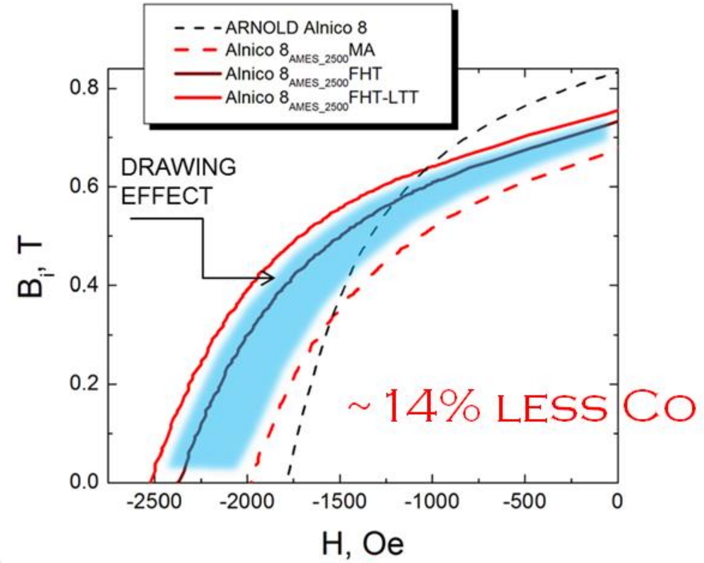
Coercivity highly dependent on size, shape and packing

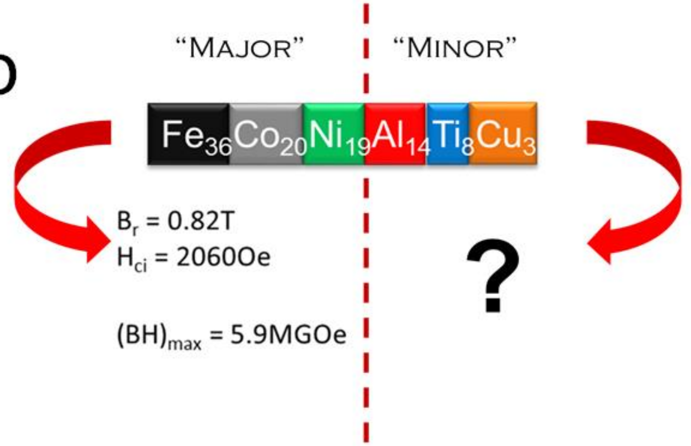


Size, shape and packing can be controlled by chemistry and processing!

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

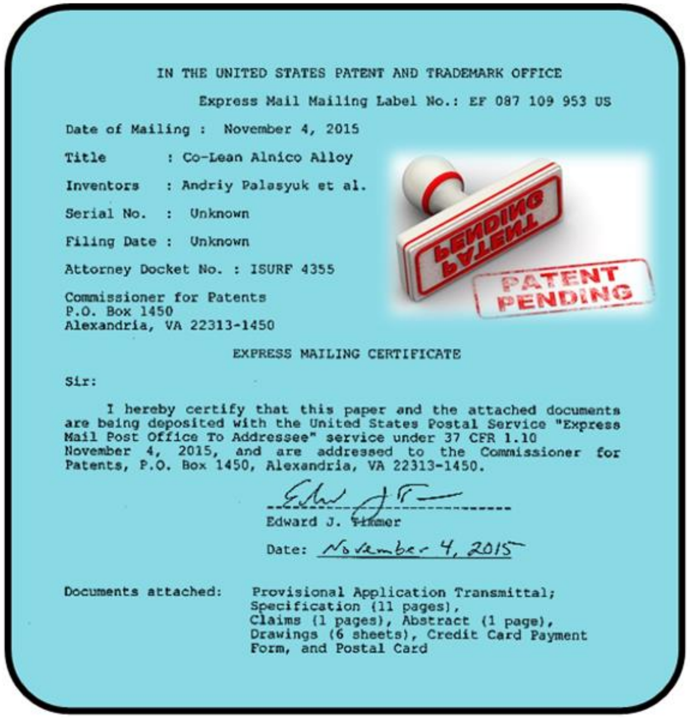




Co-lean alnico

Co high cost and price variability

- Co traditionally added to increase coercivity and high T stability.
- New knowledge of the chemistry and phase relationships enables design of lower Co content without losing Hci.
- Chemical substitution is limited
  - Further improvements need to optimize minor elements
  - Each new chemistry requires processing optimization



IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Express Mail Mailing Label No.: EF 087 109 953 US

Date of Mailing : November 4, 2015

Title : Co-Lean Alnico Alloy

Inventors : Andriy Palasyuk et al.

Serial No. : Unknown

Filing Date : Unknown

Attorney Docket No. : ISURF 4355

Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

EXPRESS MAILING CERTIFICATE

Sir:

I hereby certify that this paper and the attached documents are being deposited with the United States Postal Service "Express Mail Post Office To Addressee" service under 37 CFR 1.10 November 4, 2015, and are addressed to the Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450.

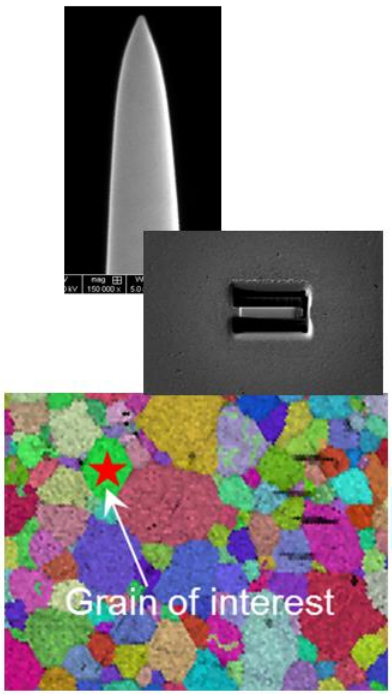
Edward J. Timmer

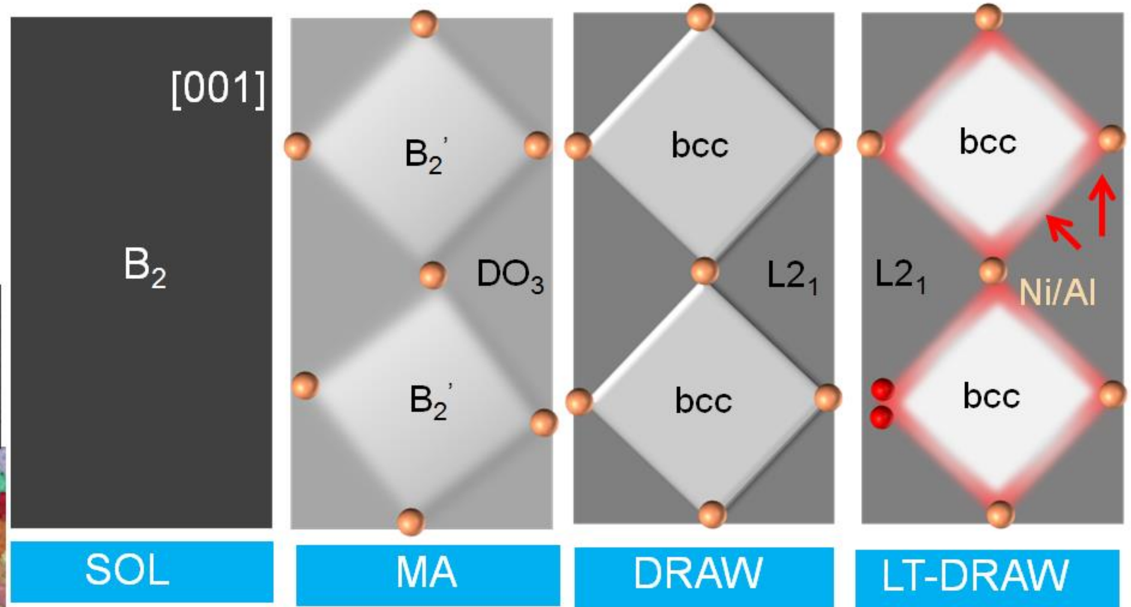
Date: November 4, 2015

Documents attached: Provisional Application Transmittal; Specification (11 pages), Claims (1 pages), Abstract (1 page), Drawings (6 sheets), Credit Card Payment Form, and Postal Card

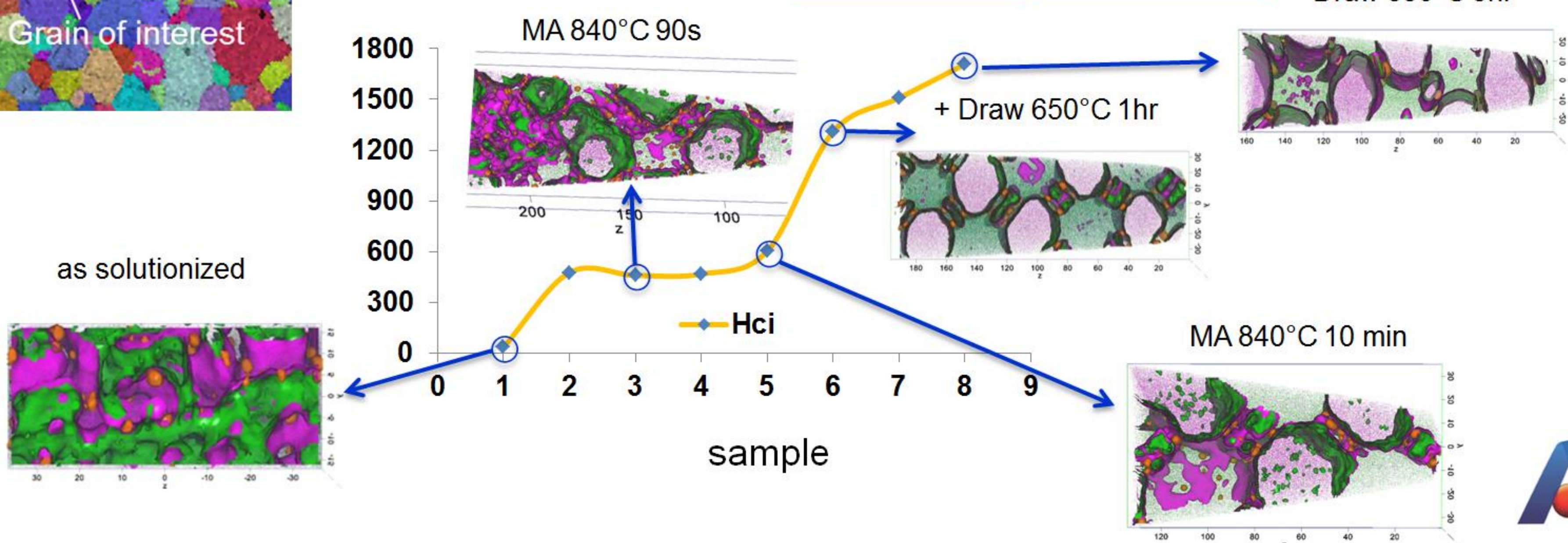
Provisional Patent Application
Co – lean alnico; ISURF 4355

Optimized Processing and Chemistry to Enhance Coercivity

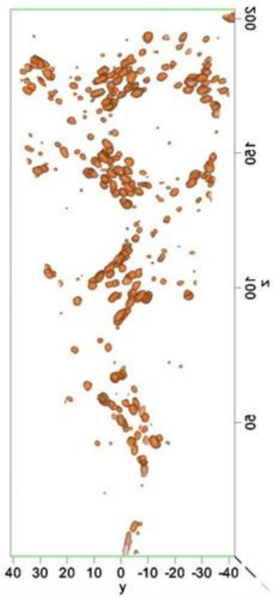


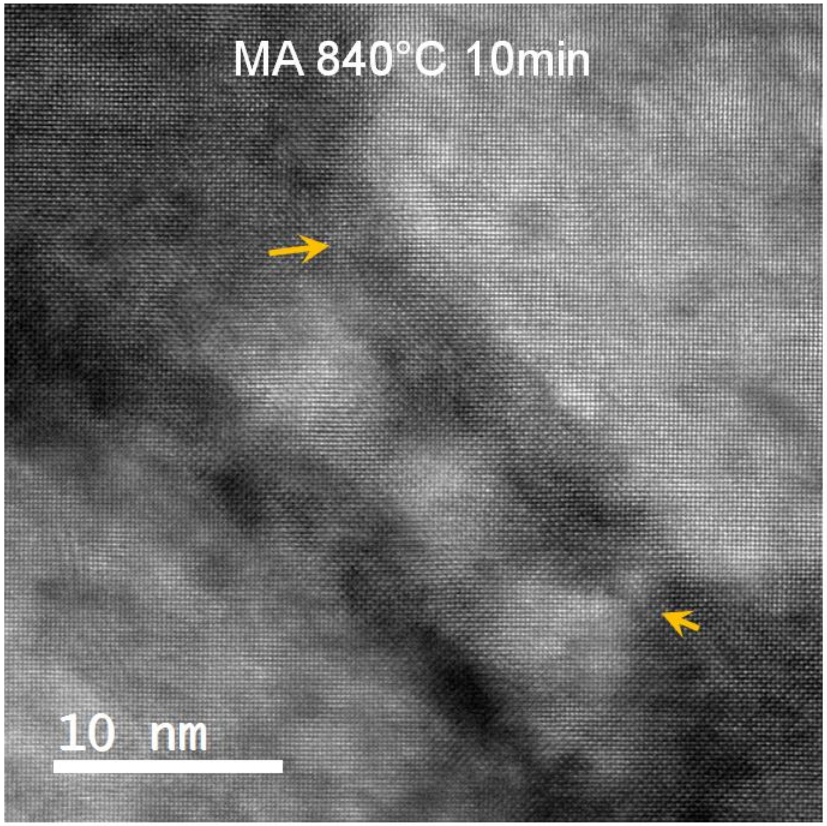


Series of samples alnico 8 were examined using 3DAP and TEM at critical points of the processing

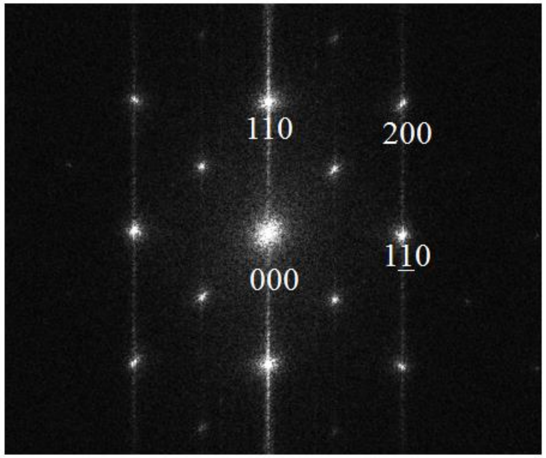


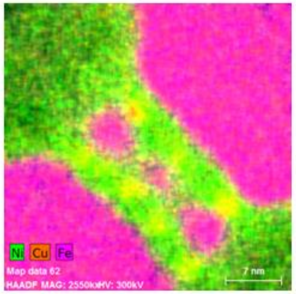
Coercivity and Microstructure

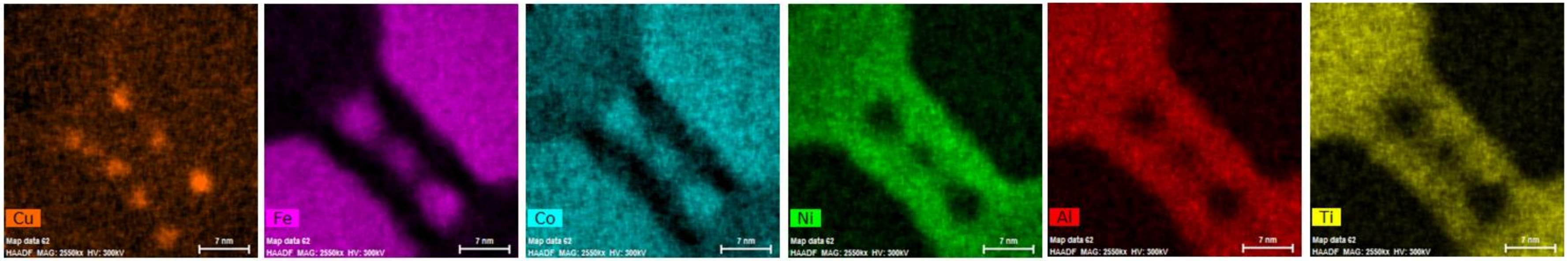




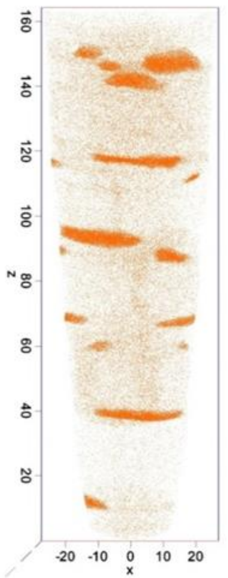
After magnetic anneal Cu-enriched clusters are dispersed in the matrix with similar lattice as the matrix.

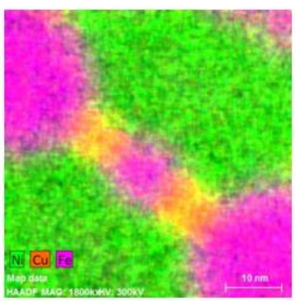


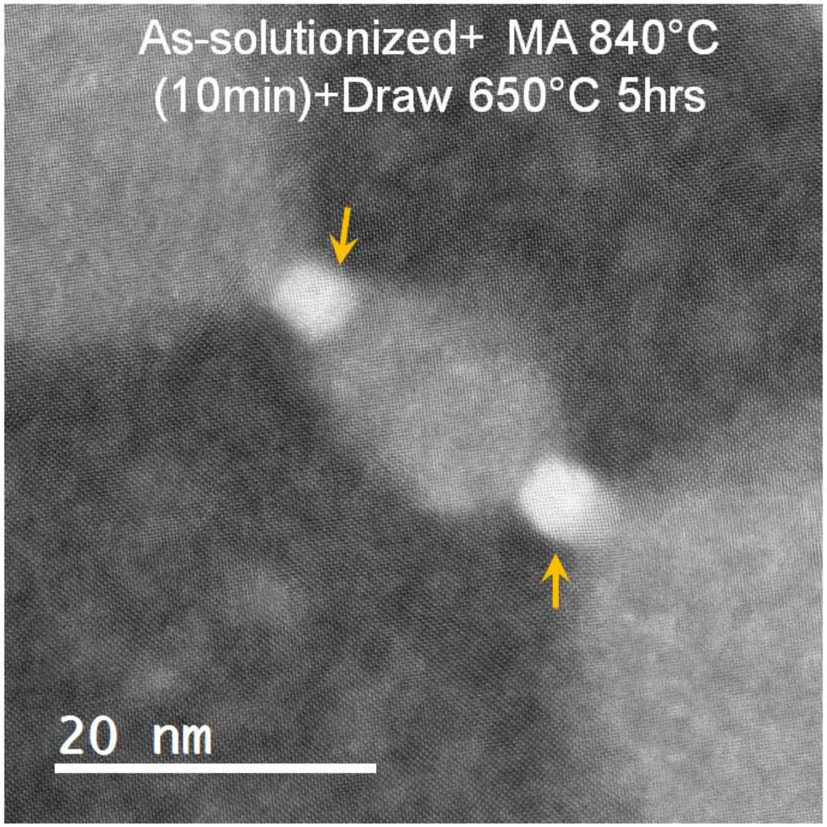




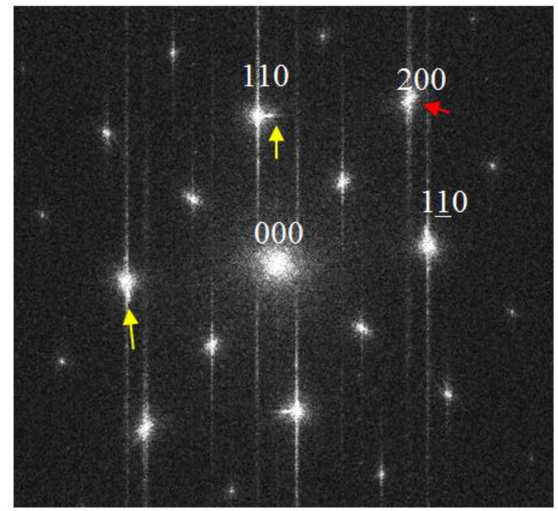
Coercivity and Microstructure

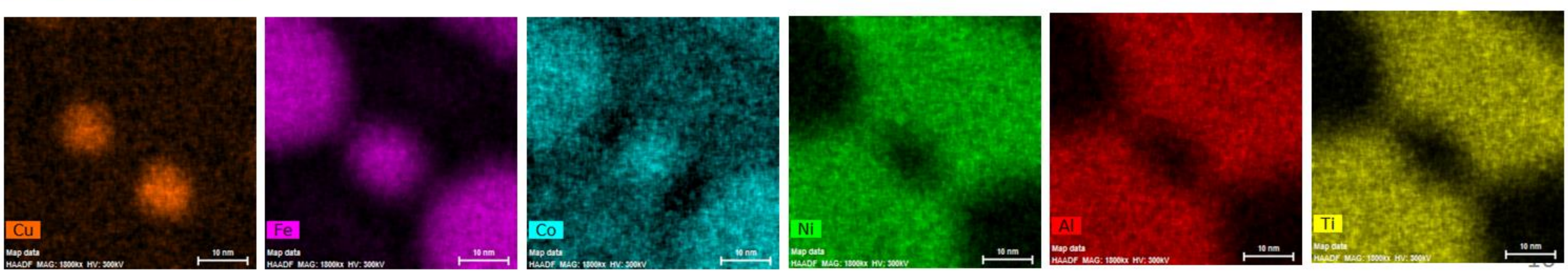




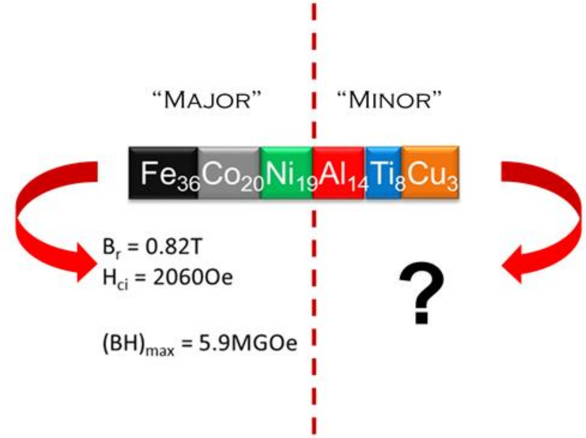


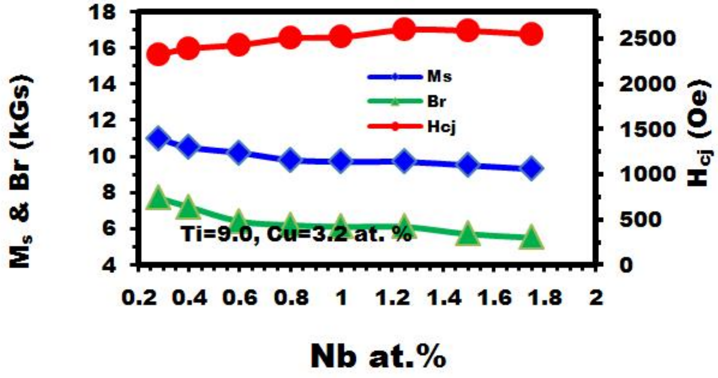
After full heat treatment Cu clusters coalesce with slightly distorted structure along the Fe-Co rods and matrix.

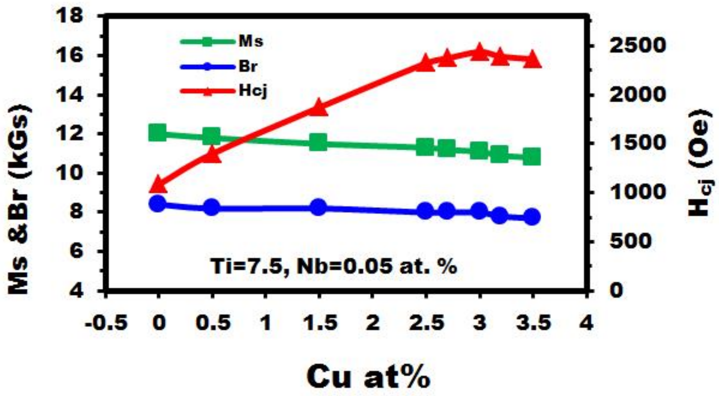


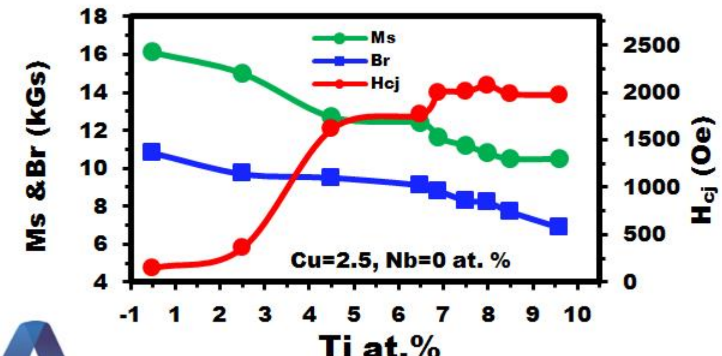


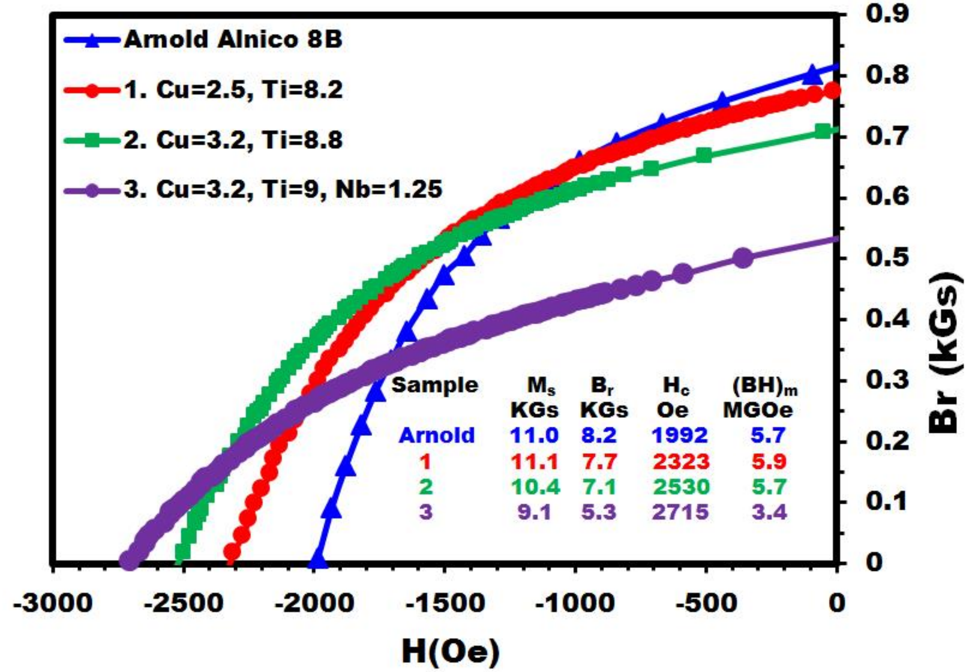
Minor Element Optimization







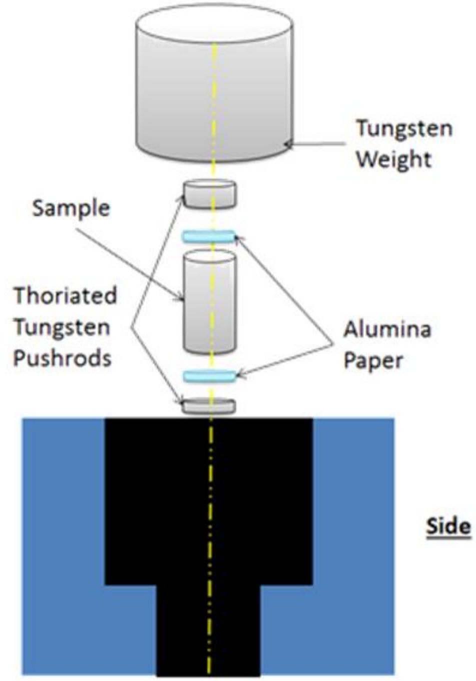




After optimization of the major elements, control of minor elements is needed.

Technical Accomplishments in Texture Alignment

Sample	Stress (kPa)	Br (kG)	Hci (Oe)	BHMax (MGOe)	Remanence Ratio (Br/Ms)
200g load	277	9.34	1638	5.59	0.79
1. 8h sintered	-	10.05	1688	6.5	0.85
2. 8h sintered	-	9.72	1735	6.4	0.83
AMT cast alnico 8HE	-	9.3	1550	6.0	0.85*
AMT sintered alnico 8H	-	6.7	2020	4.5	0.72*
AMT cast-DS alnico 9	-	10.6	1500	9.0	0.90*



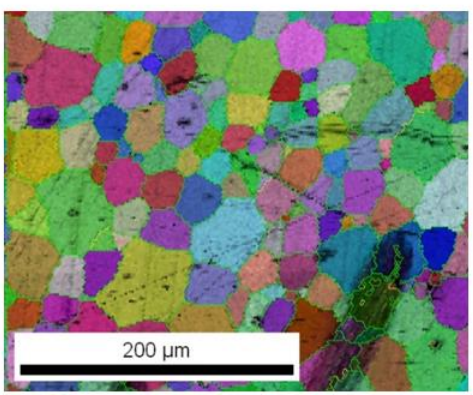
Texture depending on mechanism:

High stress: [111] grain rotation, poor

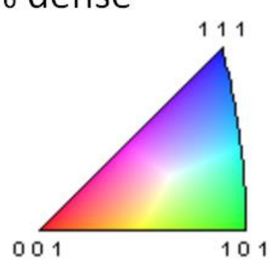
Low stress: [115] GB biasing, 18° off-ideal

Mid stress: [115], rotate to [001], ideal

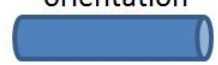
Completed mechanism to meet Q2 milestone



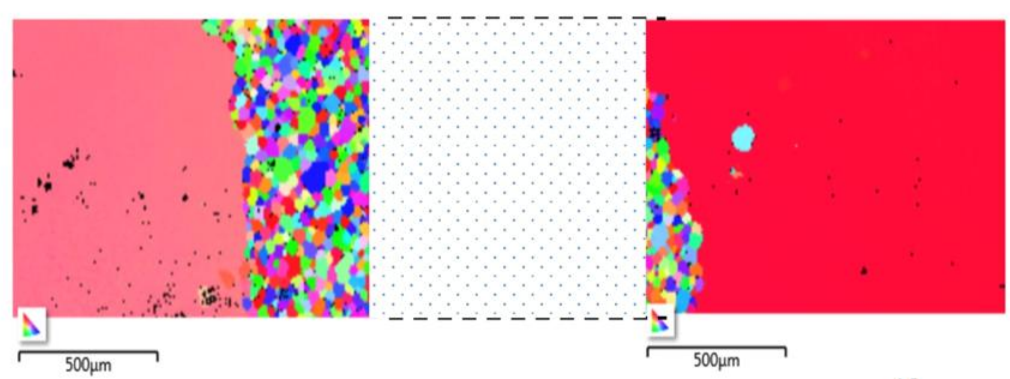
Initial: 4h sintered, equiaxed, small grain (30-40µm) >99% dense



Sample orientation



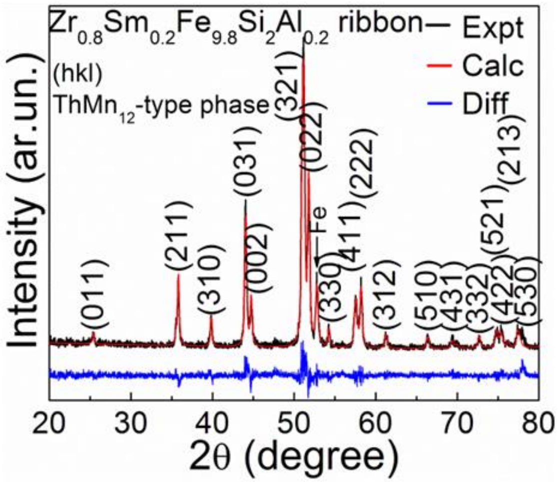
Large grains near <001> on ends of cylinder magnet, 50 vol.% equi-axed grains in middle. Longer sintering to complete---re-measure.



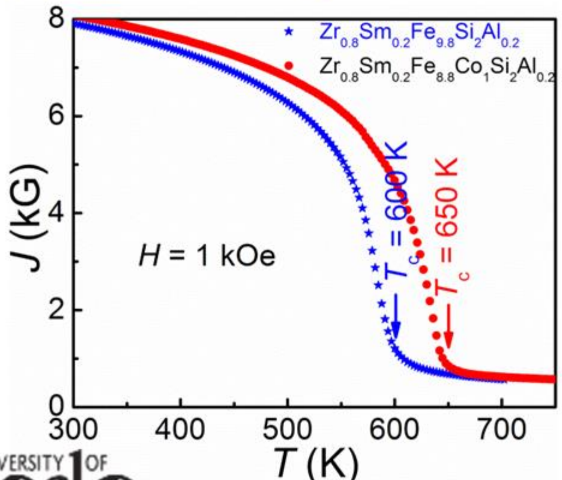
Patent Pending (Utility Patent filed March 2017): Solid State Grain Alignment of Heat Treatable Permanent Magnets in Near-Final Shape

Technical Accomplishments to Enhance Anisotropy in alnico 8

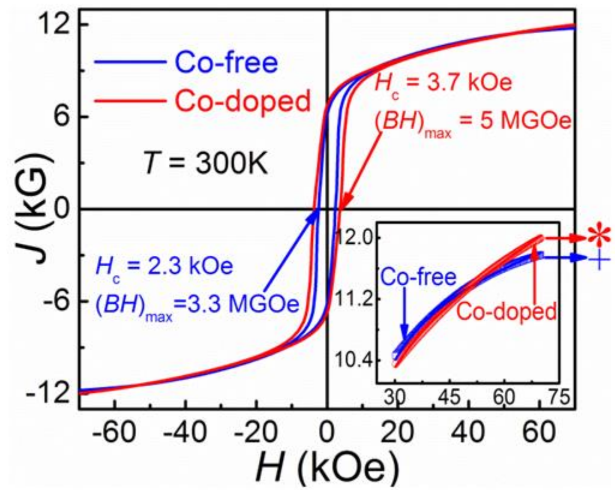
The ribbons mainly consist of the 1:12 phase.



The $M(T)$ result well agrees with XRD data.



Co addition increase K, thus H_c.



+ J_s = 11.0 kG, K = 35.3 Mergs/cm^3

* J_s = 11.4 kG, K = 45.9 Mergs/cm^3

Summary

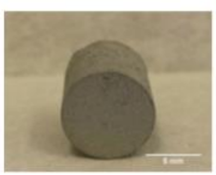
- **High-anisotropy tetragonal compound has been fabricated.**
- **Co addition has been found to increase J_s, T_c, and K, thus enhancing H_c and $(BH)_{max}$.**
- **This high-K phase may be introduced in alnico magnets and used to enhance their H_c.**

University of Nebraska Lincoln

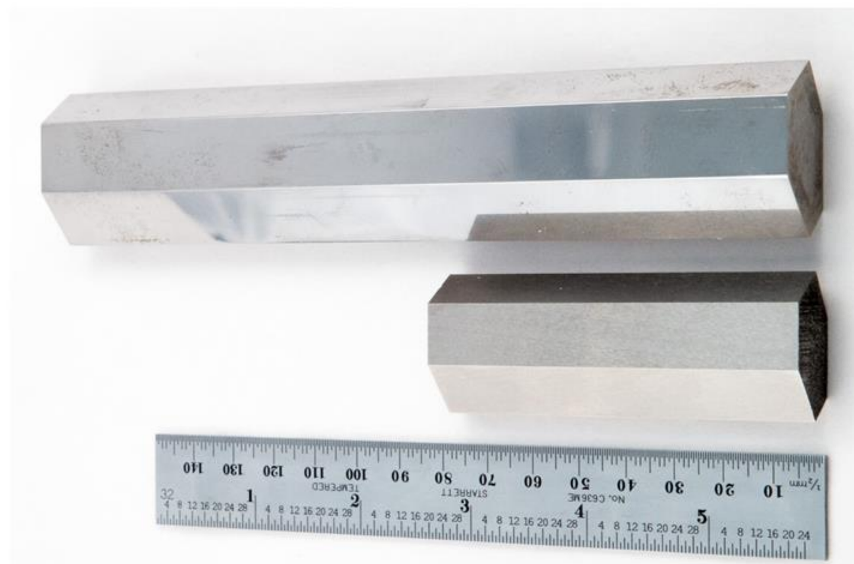
Technical Accomplishments
Full Size Complex Shaped Magnets

- Scale up of powder processing to > 98% dense magnets with complex shapes
- Achieved **near-final shape** that requires inexpensive surface grinding to the final dimensions, minimizes material removal, and boosts cost effectiveness

10 mm



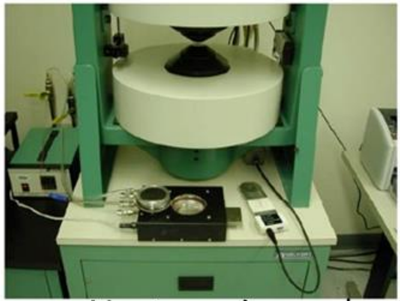
Cylindrical shape (9 mm × 10 mm)



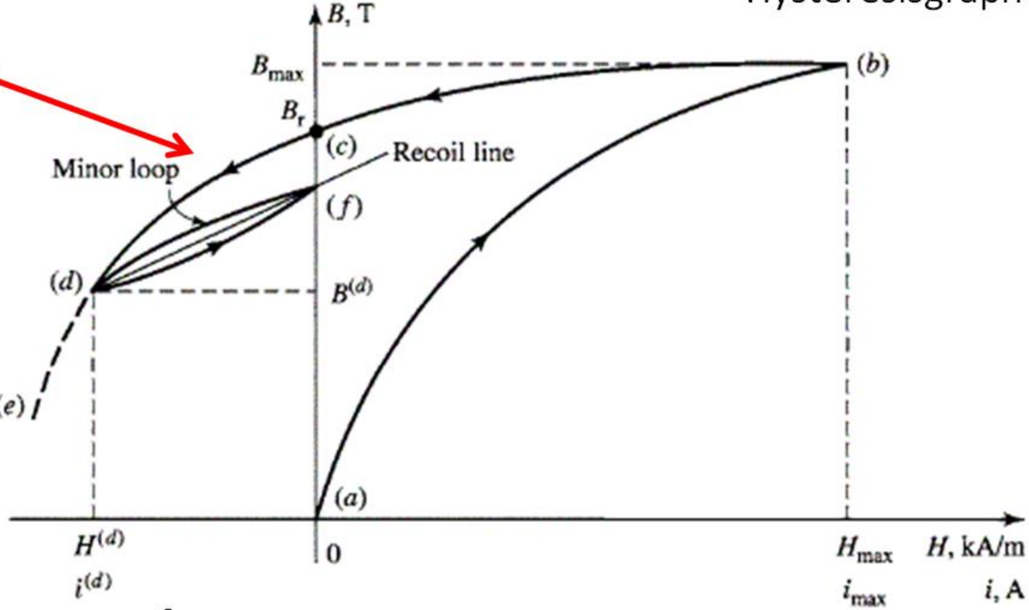
Near-final shape (14 mm × 28 mm × 66 mm)

Technical Accomplishments in Electrical and Magnetic Measurements

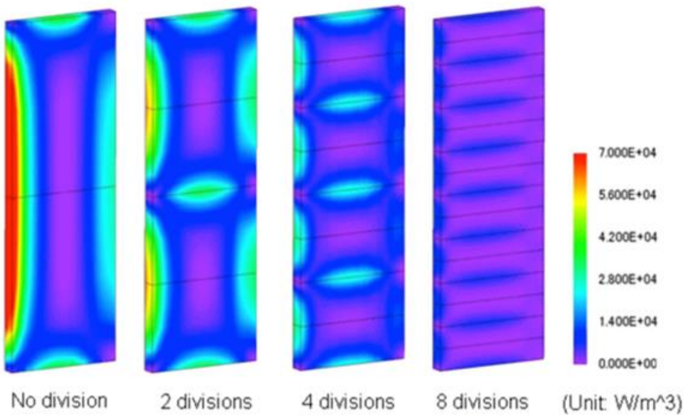
- B-H hysteresigraph testing
  - Permeability
  - 4-quadrant B-H testing
  - Recoil testing – to determine magnetic field at which B_r is reduced permanently
- Resistivity and Eddy Current loss analysis
  - Important in considering the use of magnet segments in motor or generator designs to minimize eddy current losses.



Hysteresisgraph



Eddy current loss in magnets for various number of segments



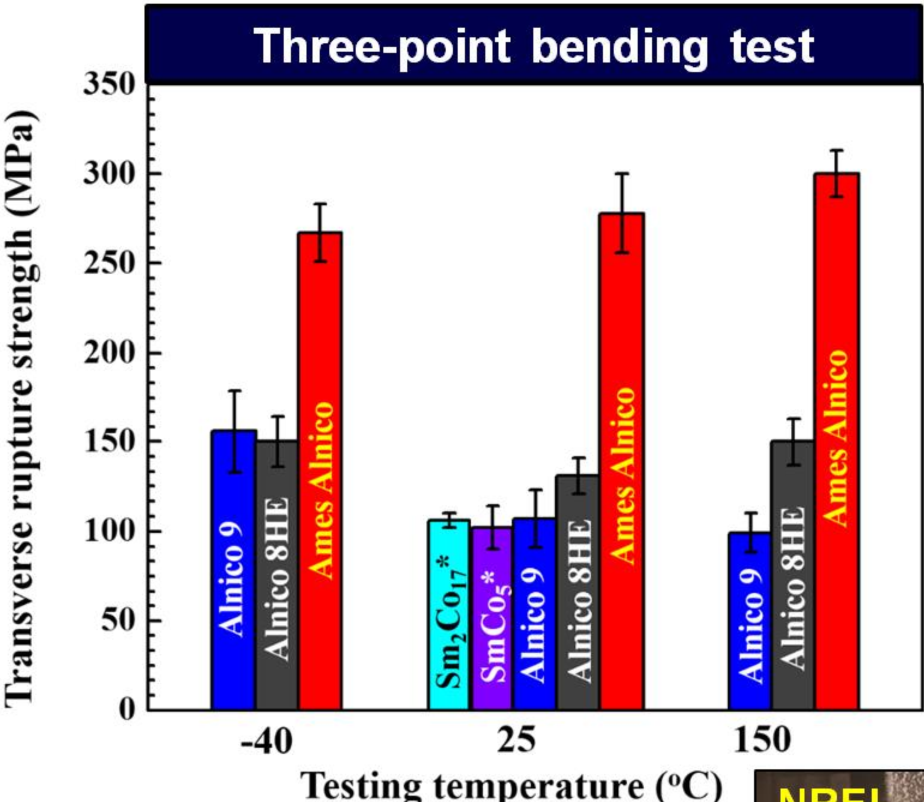
Source: https://www.jmag-international.com/catalog/22_IPMMotor_MagnetLoss.html

Classic Eddy Current Loss

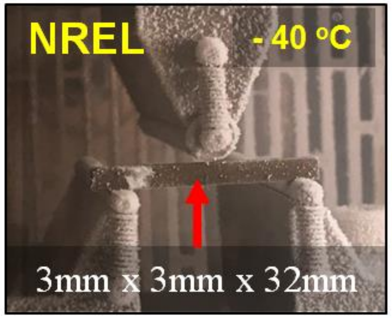
$$P_e = (\pi f d B)^2 / 6 \rho \rho_e$$

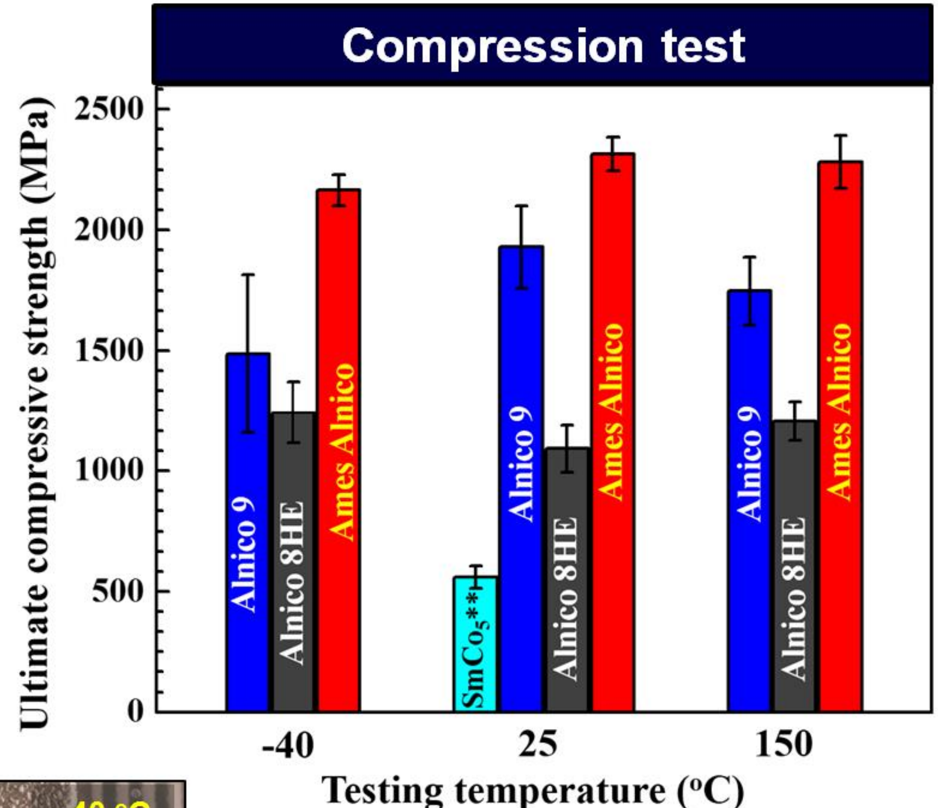
f: frequency
d: sheet thickness
B: flux density
ρ: density
ρ_e: specific elec. resistivity

Technical Accomplishments in Mechanical & Thermal Properties



Enhanced strength to improve assembly reliability and permit high rpm.





Achieved with minimal change in thermal conductivity!
See EDT 075

Oak Ridge National Laboratory
NREL National Renewable Energy Laboratory

Response to Previous Year Reviewers' comments

The reviewer stated that the program identified the following major challenges: cost and size reduction of traction motor (**using non-rare earth (NRE) materials**, new materials for laminations…..

The reviewer also identified the development and demonstration of advanced motor designs that **use less RE elements as another notable success**. The reviewer suggested revisiting the focus on RE reduction as a program goal, pointing out that the **RE supply crisis has abated**, due in no small part to programs such as this one that have produced system- and component-level substitutes. The reviewer stated that it might be appropriate to expand the focus to include more critical elements beyond REs …

While the RE shock has abated, this is more of a reflection of the oversupply of commodities. Market structures haven't changed, China still dominates with >90% production and long term demand remains strong. The next crisis is not "if," but "when."

The reviewer suggested that the program area may wish to evaluate the risk posed by other critical materials in the supply chain for EDT systems and component technology beyond RE ones. The reviewer stated that **coordination with the Critical Materials Institute may identify future supply chain risks** that may be avoided if prudent investments are made in substitute technologies

Ames is uniquely placed here and PI are involved in CMI and would be willing to facilitate this.

Ames Lab Partners/Collaborators for FY2016-FY2017

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

DREaM Team:

K.M. Ho and C.Z. Wang: AL

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

M. Eisenbach and M. Stocks: ORNL

Aaron Williams: 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): Supply of permanent magnet data, DREaM project adviser.
- NREL (Sreekant Narumanchi): Mechanical and thermal properties, DREaM project (collaborator).
- 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) and TCF project (partner).
- Carpenter Powder Products (Jim Scanlon): Pre-alloyed powder production, TCF project (partner).
- Ford Motor Co. (Franco Leonardi): Motor manufacture and test advice, TCF project (partner).

Remaining Challenges and Barriers

- Coercivity levels are nearing optimal for the lower Co alloys. Increase in remanance and energy density will require ability to improve grain alignment while reducing nano-structure.

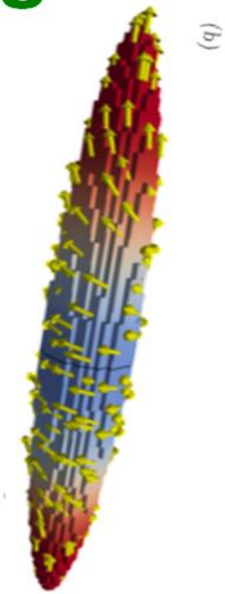
- Significant understanding of the role of magnetic processing of alnico microstructure and nano-structure for enhancing magnetic properties has been achieved but a clear mechanism explaining the longer, lower temperature anneal and nearly a 2x in coercivty remains elusive.

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

- Need to make progress toward control of the magnetic anneal process to reduce Fe-Co rods diameters to < 25 nm for maximum coercivity, as predicted by micro-magnetic modeling.

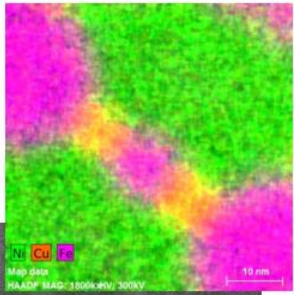
proposed future work is subject to change based on funding levels

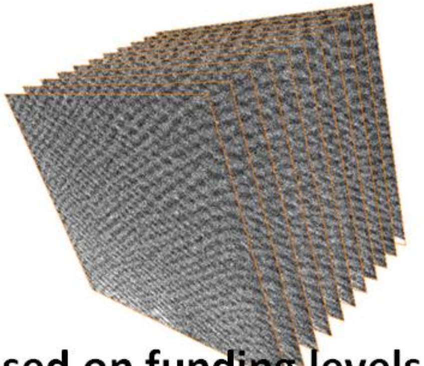
Remaining FY17 DREaM Tasks

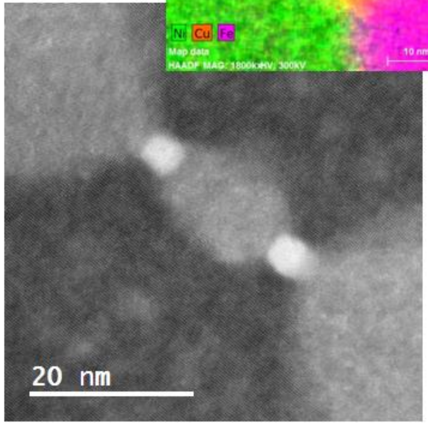


Develop Focused Theory & Simulation: The theory efforts will continue to establish a clear set of kinetic models to predict evolution of the various competing phases, especially Cu. Emphasis is shifting to micro-magnetic modeling, which has given clear microstructural targets.

Synthesize Test Samples: Continue to improve the texture. This will be a challenge with the complex geometry of UQM's design. Adding Halbach array for magnetic field alignment in addition to thermal/uni-axial stress approaches.







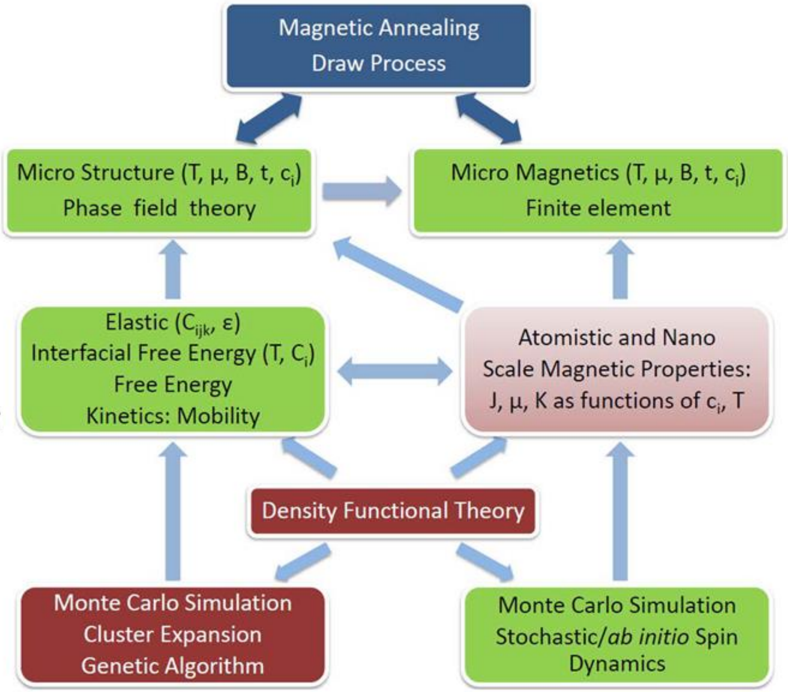
Perform Characterization: Extend the high fidelity characterization to 3D using serial sectioning. Need realistic microstructures for validation of the micro-magnetic modeling.

proposed future work is subject to change based on funding levels

Future (proposed) FY18 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: Verify with experimental results and use for calculating magnetic properties and driving forces to extend phase field and micro-magnetic microstructure calculations using experimentally derived 3D models.



Perform Characterization: Expand detailed characterization to high fidelity 3D images. Continue NREL collaboration to add magnet mechanical property data and ORNL studies to include temperature dependent magnetic properties and FEM for motor design.

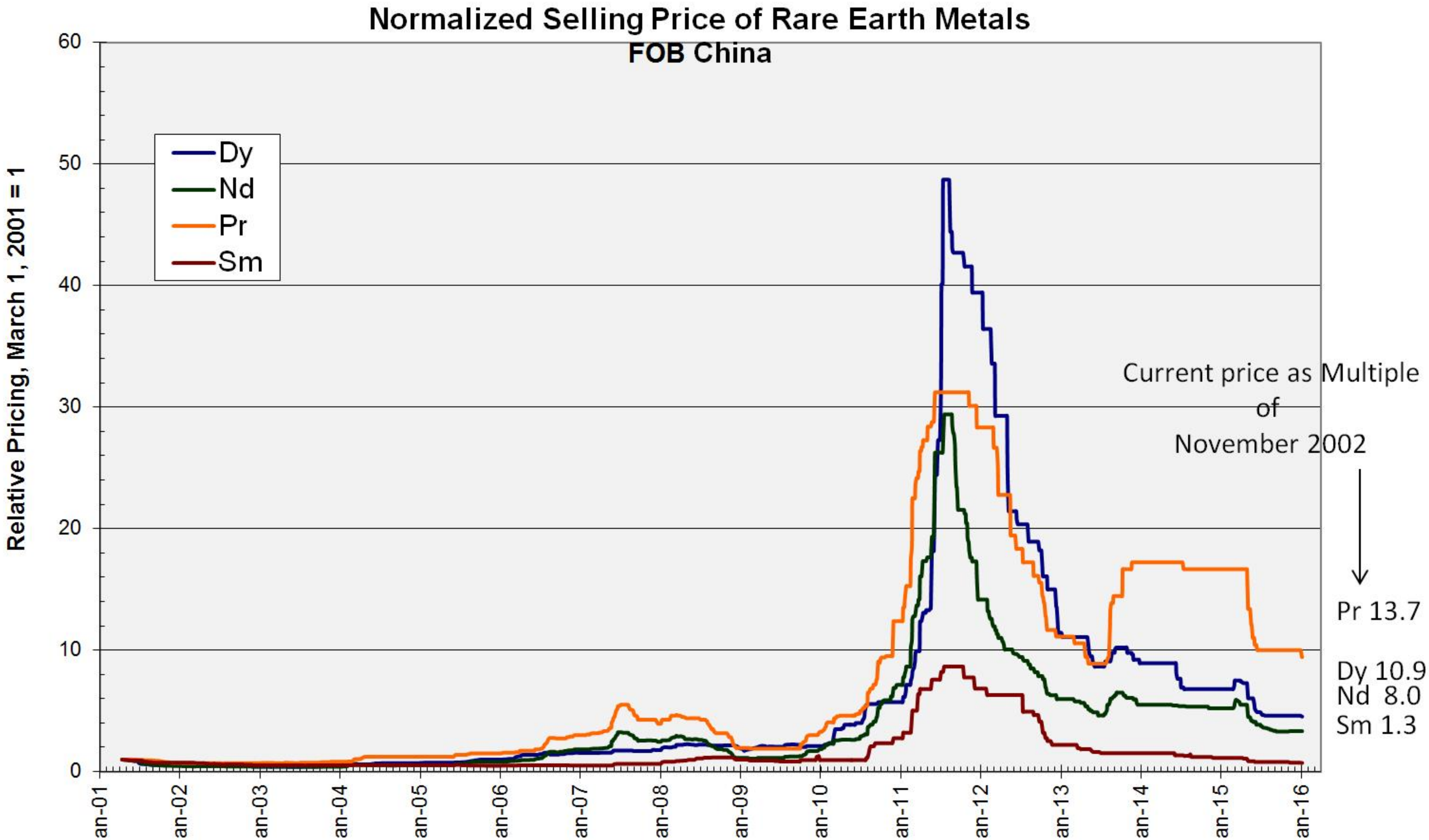
Synthesize Test Samples: Optimize bulk samples using magnetic and thermal processing parameters for pre-alloyed powder (alnico 8, refined alnico "Co-lean"). Refine methods to gain control over texturing effects in sintered bulk magnets to further improve magnetic properties. Analyze and report results of high magnetic field experiments on nano-structure and magnetic properties. [SMART milestone, complete September 30, 2017]

Summary

- **Coercivity > 2700 Oe (alnico 8H ~ 2170 Oe), but need microstructural alignment for maximum energy product and traction motor application.**
- Co decreased while maintaining/enhancing coercivity.
  - New pathways show even more promise.
- Bulk sintering and grain alignment demonstrated.
  - Patent filed
- Full scale motor magnets fabricated.
- Modeling providing useful guidance on alloying and processing routes.

Technical Back-Up Slides

Rare earth metal prices (normalized)



ARNOLD MAGNETIC TECHNOLOGIES

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
  - 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:

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

where:

TRS = transverse rupture strength (MPa)

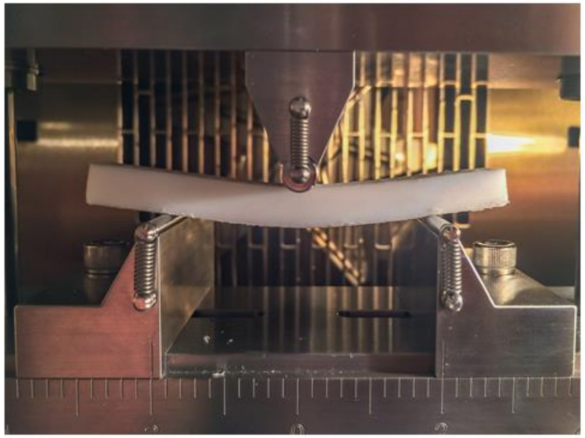
P = force required to rupture specimen (N)

L = Distance between supporting rods (25.4 mm)

w = specimen width (mm)

t = specimen thickness (mm)

Compression Test Fixture



Transverse Rupture Test Fixture

NREL
NATIONAL RENEWABLE ENERGY LABORATORY