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

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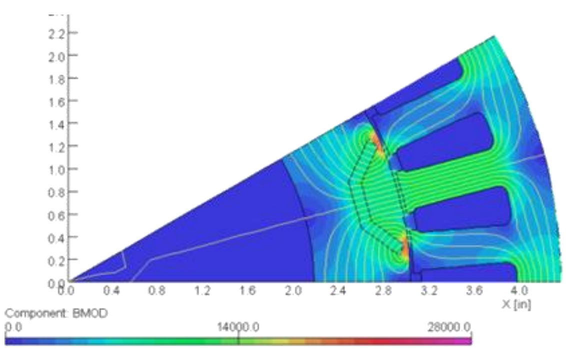


June 19, 2018

Project ID # ELT015

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

Overview

Timeline

- Start – October 2014
- Finish - September 2018

85% Complete

Budget

- Total funding - DOE share 100%
- FY 17 Funding - $1400K
- FY 18 (plan) Funding - $700K

Barriers & Targets*

- High energy density permanent magnets (PM) needed for compact, and power density >50 kW/L).
- Reduced cost (<$3.3/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, Carpenter, U. Wisconsin, NREL, Ford, GM, UQM, (collaborators)
- ORNL, U. Nebraska, Arnold Magnetic Tech. (DREaM subcontractors)
- Project lead: Ames Lab

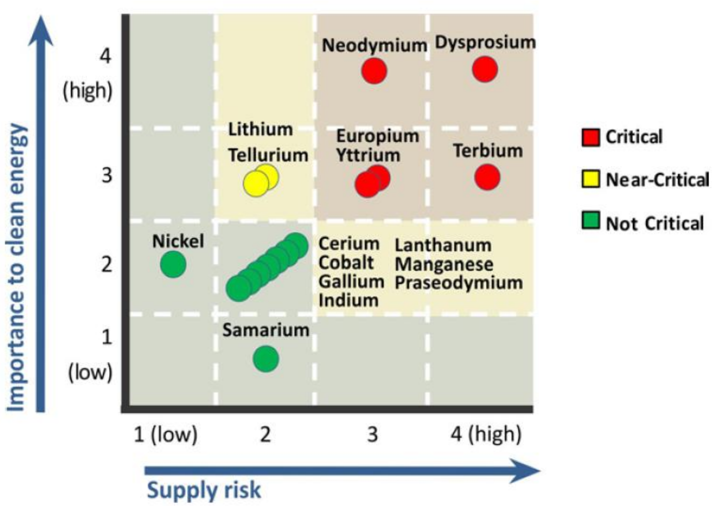
*2025 VT Targets

Project Relevance/Objectives

- To meet 2025 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.



	Total Market, millions		% EV (inc. hybrid)		No. EV (inc. hybrid)		Magnets Req'd, tons	
Year	**USA**	**Global**	**USA**	**Global**	**USA**	**Global**	**USA**	**Global**
2015	17.4	88.0	2.9%	3.5%	0.5	3.1	631	3,850
2020	17.2	103.0	9.7%	14.0%	1.7	14.4	2,086	18,025
2025	17.1	113.0	20.1%	35.0%	3.4	39.6	4,296	49,438
2030	17.0	119.0	30.0%	50.0%	5.1	59.5	6,375	74,375
2040	17.0	125.0	50.0%	80.0%	8.5	100.0	10,625	125,000

Vehicle quantities shown in millions
Average kg NdFeB magnets per traction drive system = 1.25
Extreme case in 2040:
All cars are EV = 125,000,000 vehicles
1.25 kg per vehicle traction drive = 156,250,000 kg = 156,250 tons of magnets
156,250 tons of NdFeB magnets requires 416,000 tons of REO

FY18 DREaM Tasks

2017 Oct	Nov	Dec	2018 Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep

Develop enhanced alnico (non-RE) magnets

Focused Theory and Simulation:

Develop micro-magnetic for simulation of effects of morphological 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 remamence 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 alnico 8 alloy system samples to verify effects on nano-scale and micron-scale microstructure.
Temperature and frequency dependent measurements will be performed in collaboration with ORNL involving magnetic properties and other parameters of permanent magnets
Thermal and mechanical properties of baseline commercial samples will be analyzed in collaboration with NREL.

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.

FY18 Focus: Produce a bulk anisotropic alnico magnet with Br in excess of 0.8 T and Hci in excess of 2500 Oe. Properties of the magnet will be provided to ORNL for evaluation in their initial motor designs. (in progress)

Key Deliverable: Well-controlled bulk magnet samples will be fabricated with enhanced grain alignment and energy product (MGOe) and with mechanical properties, all exceeding commercial alnico (grades 8 and 9). (in progress)

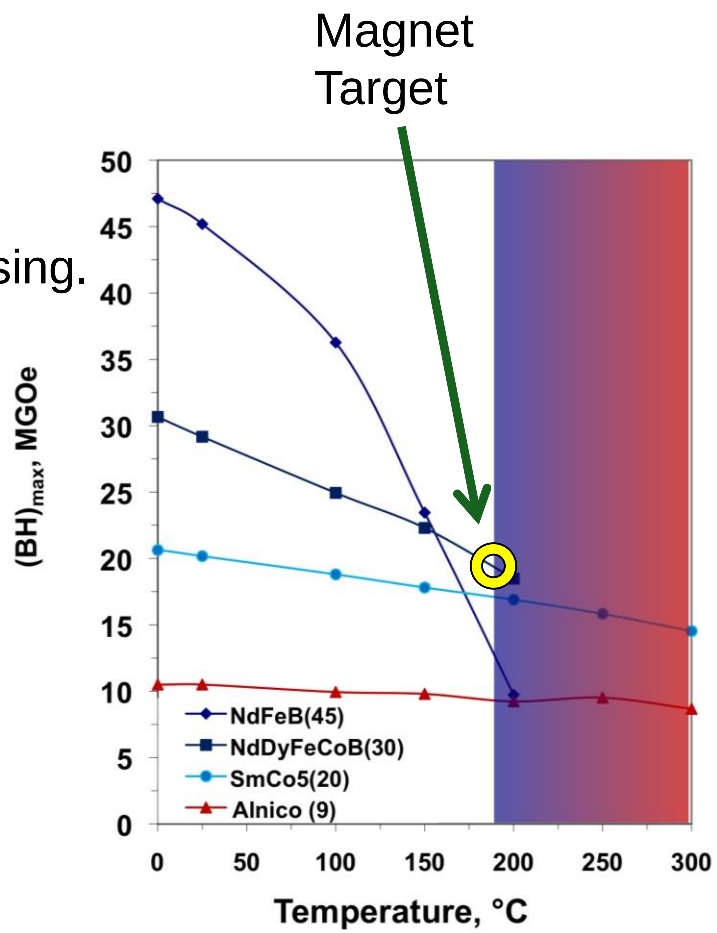
Go/No Go Decision Point: Does bulk sub-sized alnico magnet have improved magnetic properties compared to alnico 8HE and/or alnico 9?

DREaM Overall Approach/Strategy

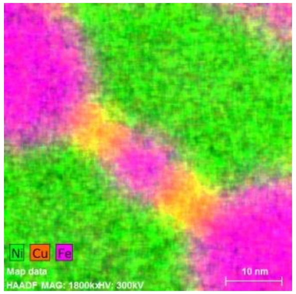
Near-term non-RE Magnets: Best RE-free magnets (alnico) further enhanced (coercivity) by low-Co alloy design and bulk powder processing improvements using detailed and innovative analysis of micro/nano structure and magnetic property relationships, focused theory results, and critical industry input.

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.

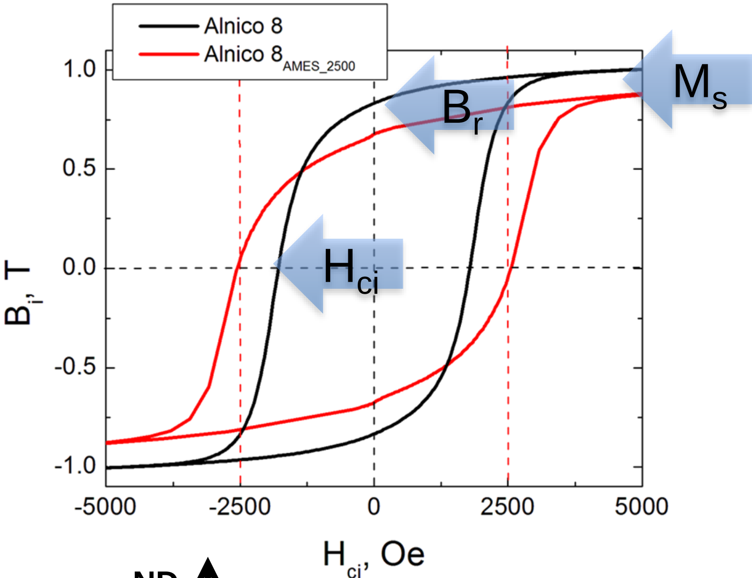
		Alnico 8	Alnico 9
aspect ratio		~ 10:1	> 10:1
fraction bcc phase (f)		0.53	0.53
Fe:Co in bcc phase		0.54	0.60
mole % Fe+Co in bcc		0.84	0.91
~M_s (KG) for bcc based on Fe:Co		23.8	23.9
Fe:Co in intermetallic		0.24	0.27
mole % Fe+Co in bcc		0.36	0.40
B_r (KG)	measured	8.2	10.6
	calculated	10.6	11.5
Hc_i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



Alloy Design Requisites



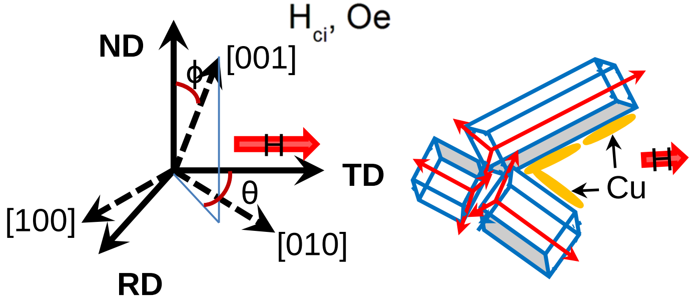
- Maximize saturation magnetization (M_s)
  - Fine tuning of the alloy chemistry to maximize the volume fraction of Fe-Co phase.
- Maximize coercivity (H_{ci})
  - Spinodal as fine as possible while insuring complete phase separation
- Maximize Remanence (B_r)
  - Align <100> to the orientation of the field annealing



Major Challenges

↑ Fe:Co without ↓ M_s and ↓ H_{ci}

Cost effective texturing process

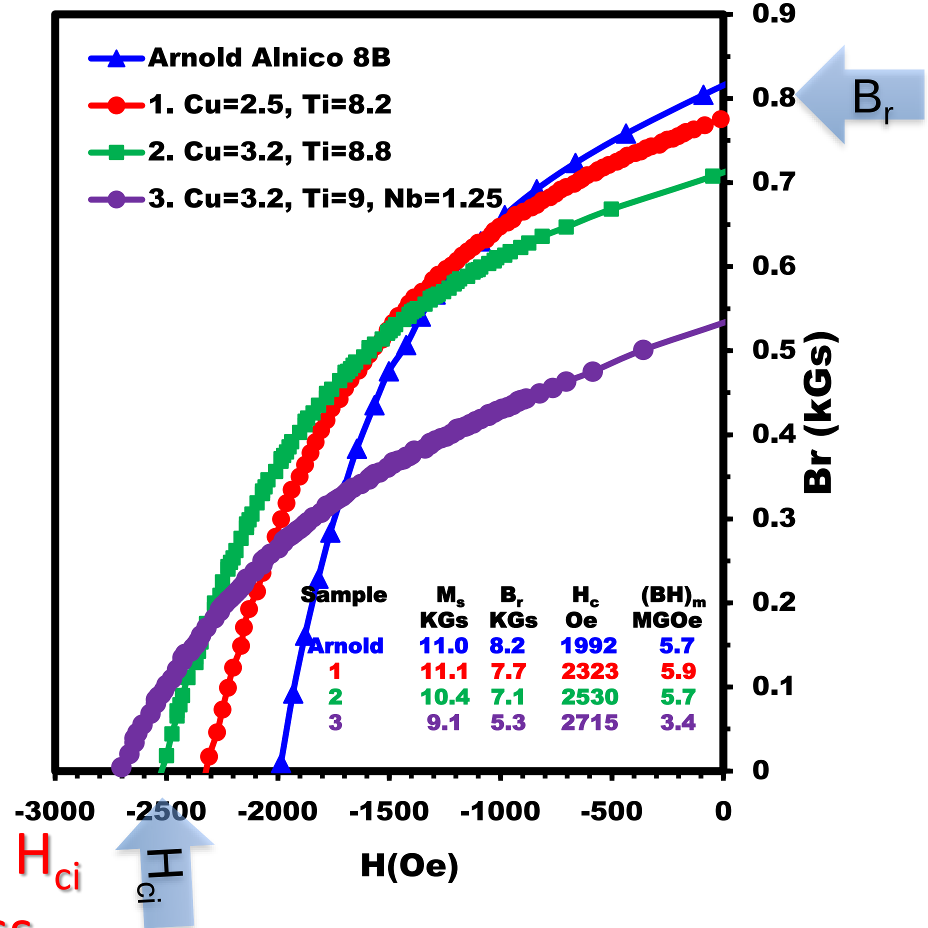


$H_{// <100>} \sim \cos(\theta)\sin(\phi)$

Zhou, L., W. Tang, L.Q. Ke, W. Guo, J.D. Poplawsky, I.E. Anderson, and M.J. Kramer, *Microstructural and magnetic property evolution with different heat-treatment conditions in an alnico alloy. Acta Materialia, 2017.* ***133: p. 73-80.***

Alloy Design Requisites

- Maximize saturation magnetization (M_s)
  - Higher Fe+Co
- Maximize coercivity (H_{ci})
  - Increased Cu, Ti, (Nb)
- Maximize Remanence (B_r)
  - Align <100> to the orientation of the field annealing



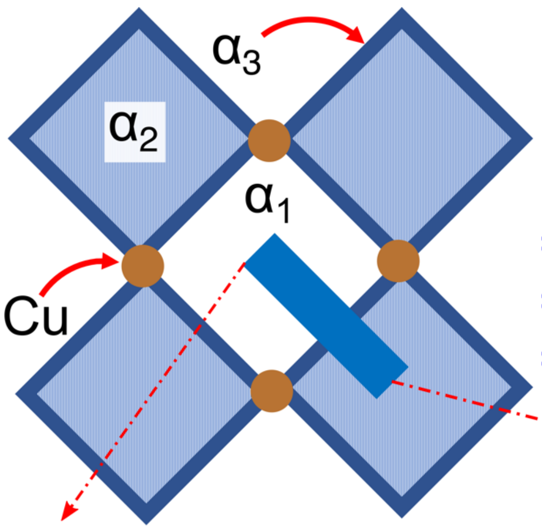
Major Challenges

↑ Fe:Co without ↓ M_s and ↓ H_{ci}

Cost effective texturing process

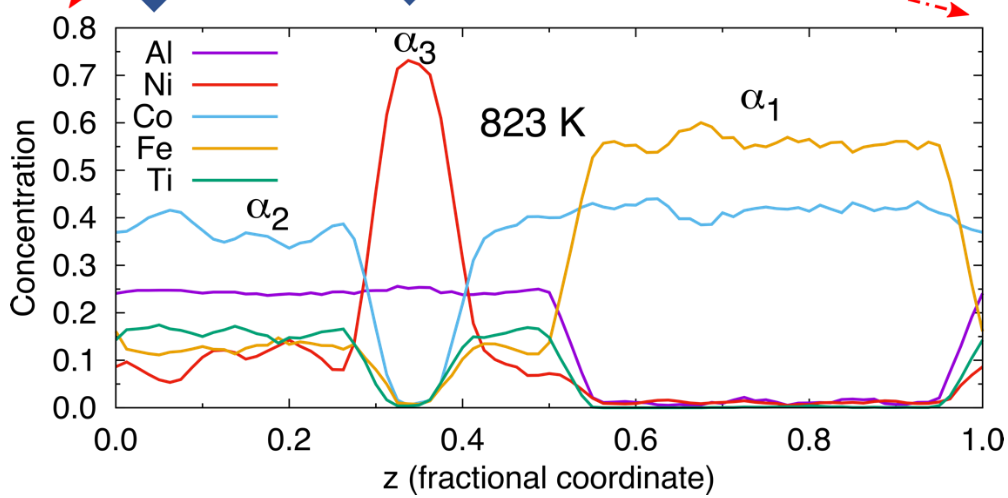
Kassen, A.G., E.M.H. White, L.F. Hu, W. Tang, L. Zhou, M.J. Kramer, and I.E. Anderson, *Novel mechanisms for solid-state processing and grain growth with microstructure alignment in alnico-8 based permanent magnets. Aip Advances, 2018.* ***8(5).***

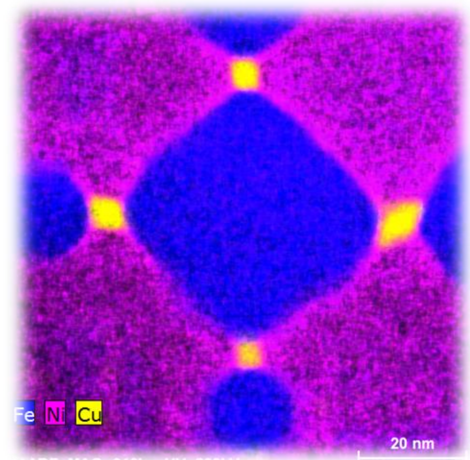
Technical Accomplishments in Theory and Modeling



Alnico 8/9

Low T annealing
=> α_3 with ~ 0.0 μ_B
=> more isolating α_1
=> increasing Hci

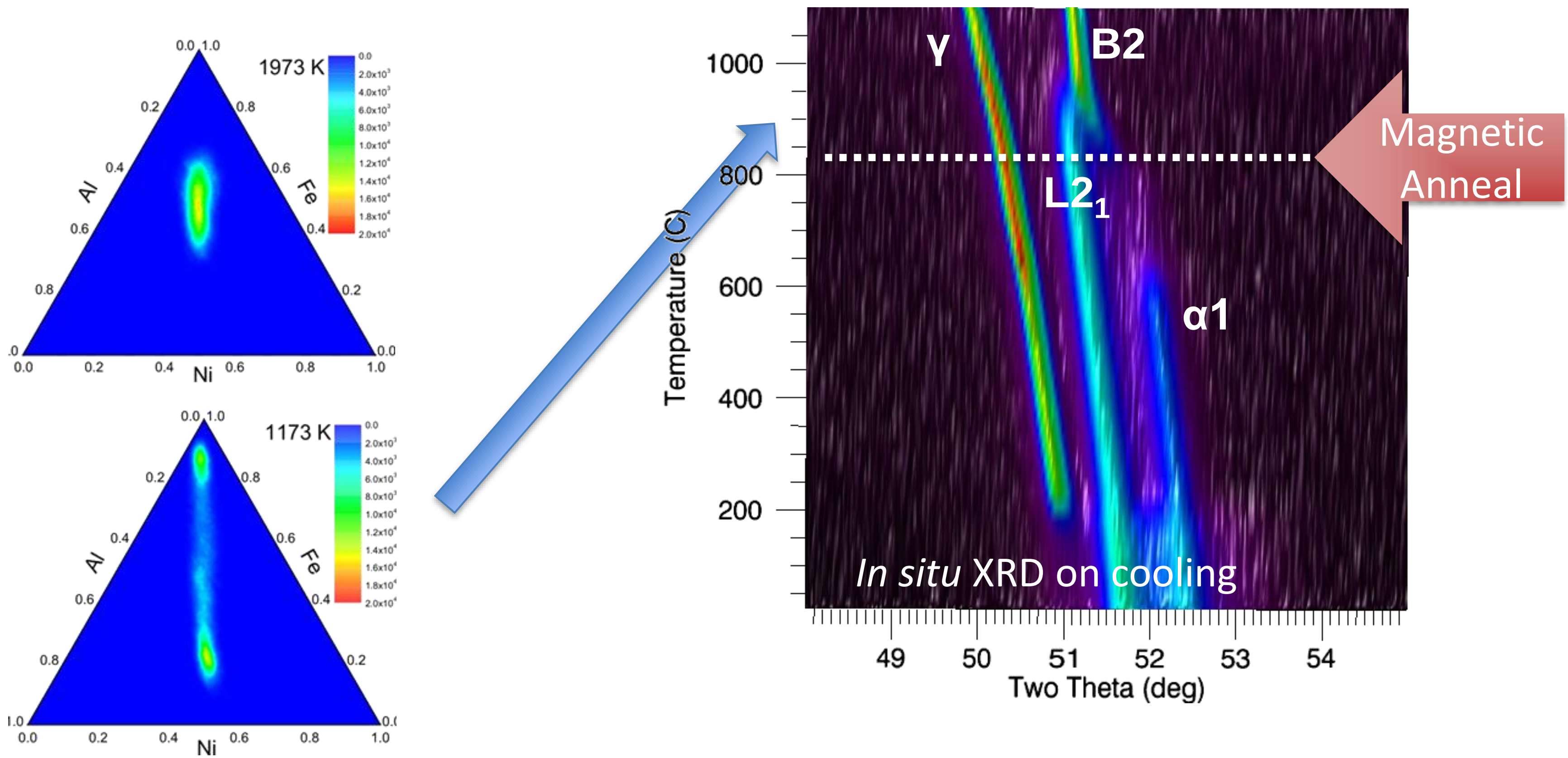




Cluster expansion and Monte Carlo simulations guiding annealing and agreed with microstructure analysis

Nguyen, M.C., L. Zhou, W. Tang, M.J. Kramer, I.E. Anderson, C.Z. Wang, and K.M. Ho, *Cluster-Expansion Model for Complex Quinary Alloys: Application to Alnico Permanent Magnets. Physical Review Applied, 2017.* ***8(5).***

Monte-Carlo Simulations and In Situ XRD of Phase Evolution



The $L2_1$ is forming at a T much higher than originally estimated, but consistent with the Monte-Carlo modeling!

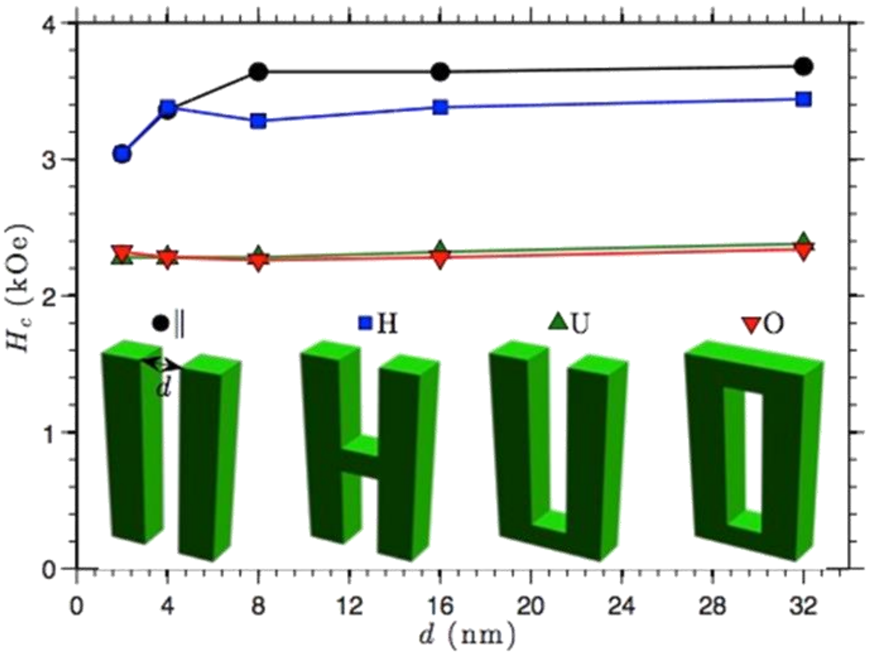
Experiment observations:

– $L2_1$ forms ~950°C well above the magnetic annealing temperature
– α1 (ordered Fe-Co) forms slowly
– γ phase (unwanted) is unstable below ~200°C

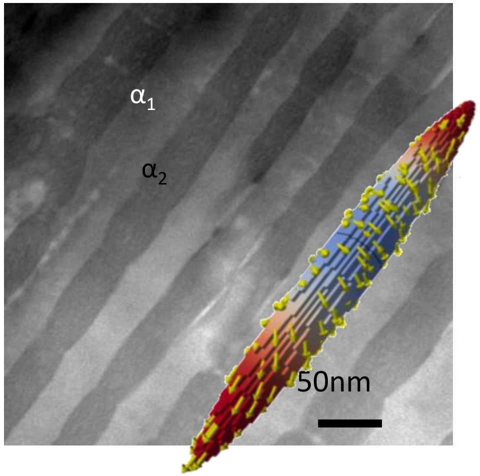
Micromagnetic Simulations

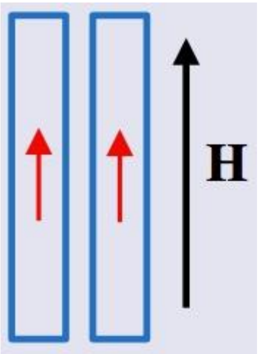
Interacting Rods

Affect of spacing (d) between Rods

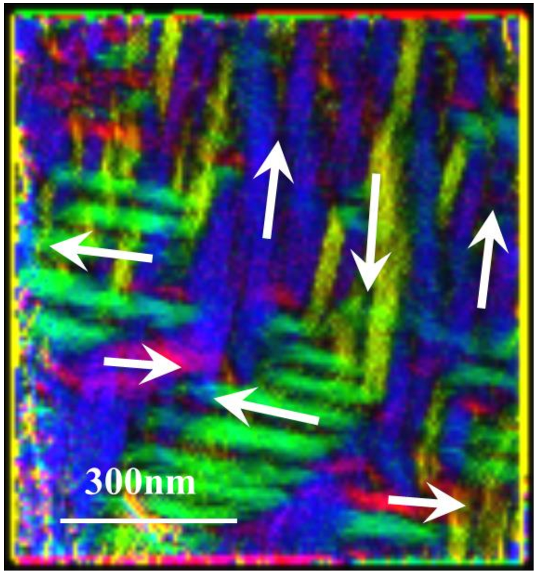


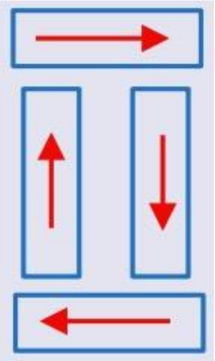
Rods connecting at their ends promote easy spin rotation and decrease H_{ci}.





Elongation with external field.

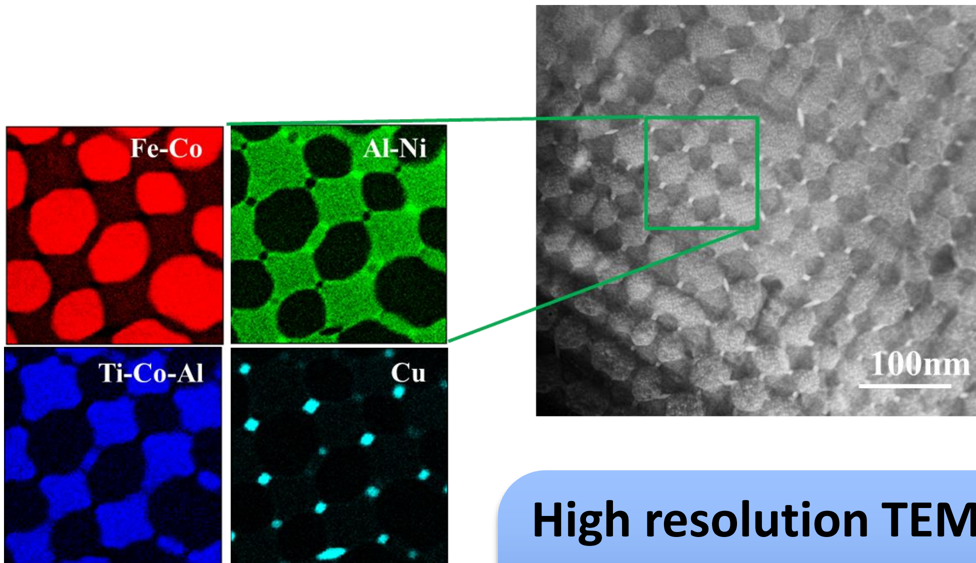


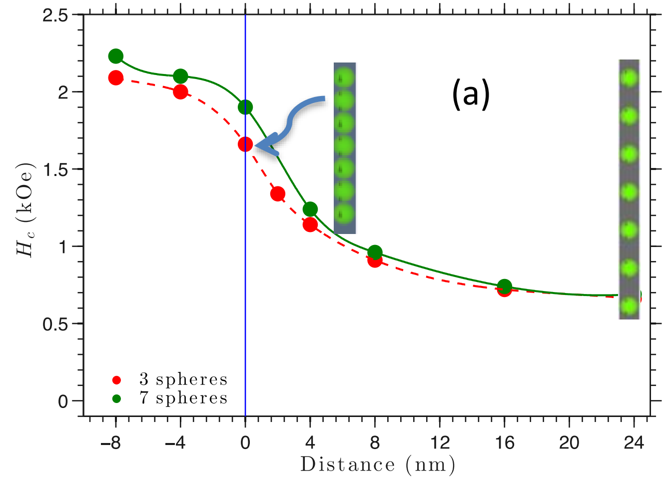


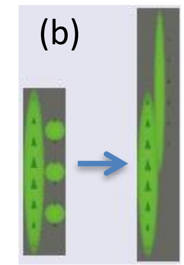
Elongation without external field.

Ke, L.Q., R. Skomski, T.D. Hoffmann, L. Zhou, W. Tang, D.D. Johnson, M.J. Kramer, I.E. Anderson, and C.Z. Wang, Simulation of alnico coercivity. Applied Physics Letters, 2017. 111(2).

Micro-magnetic Simulations







High resolution TEM observations of α_1 precipitates and small α_1 rods in α_2 phase or between two α_1 facets:

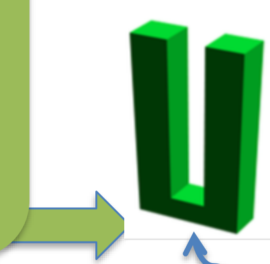
(a) A chain of small α_1 spheres

(b) Small rods or particles

Site ordering vs. T_C of α_2 phase in alnico 8

Ordering	T_C (K)
$L2_1$	209
DO_3	285
BCC	445

Cu rods become larger and longer during draw and can aid in shorting "bad connection" significantly increase H_C.

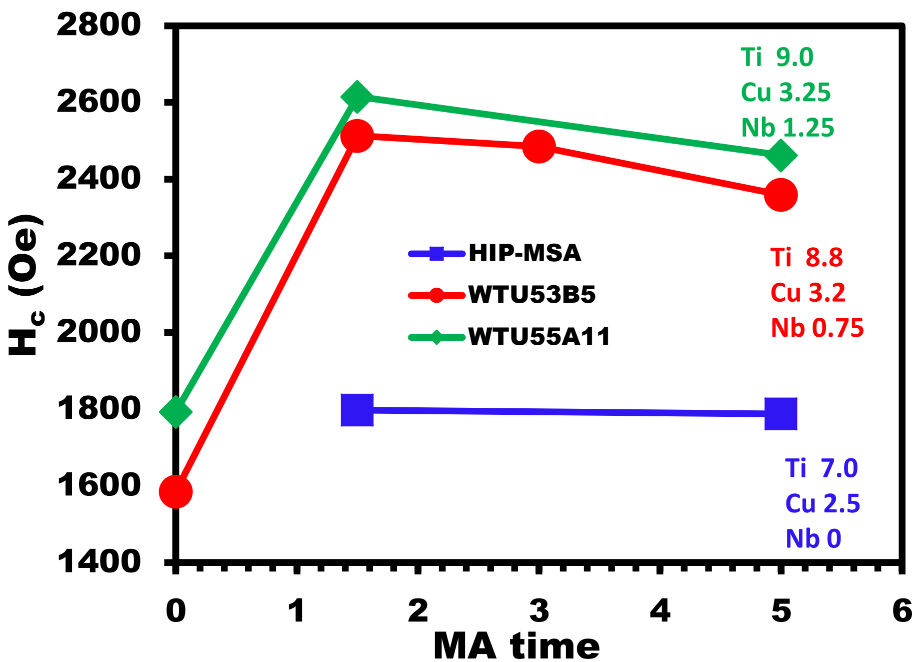


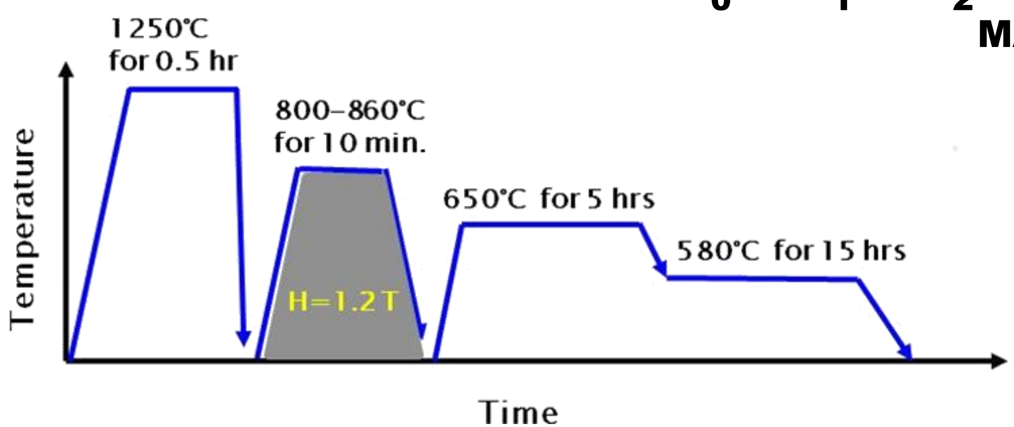
Bad connection

Site ordering during draw lowers energy and T_C of the matrix phases.

Technical Accomplishments in Synthesis of Bulk Magnetic Samples

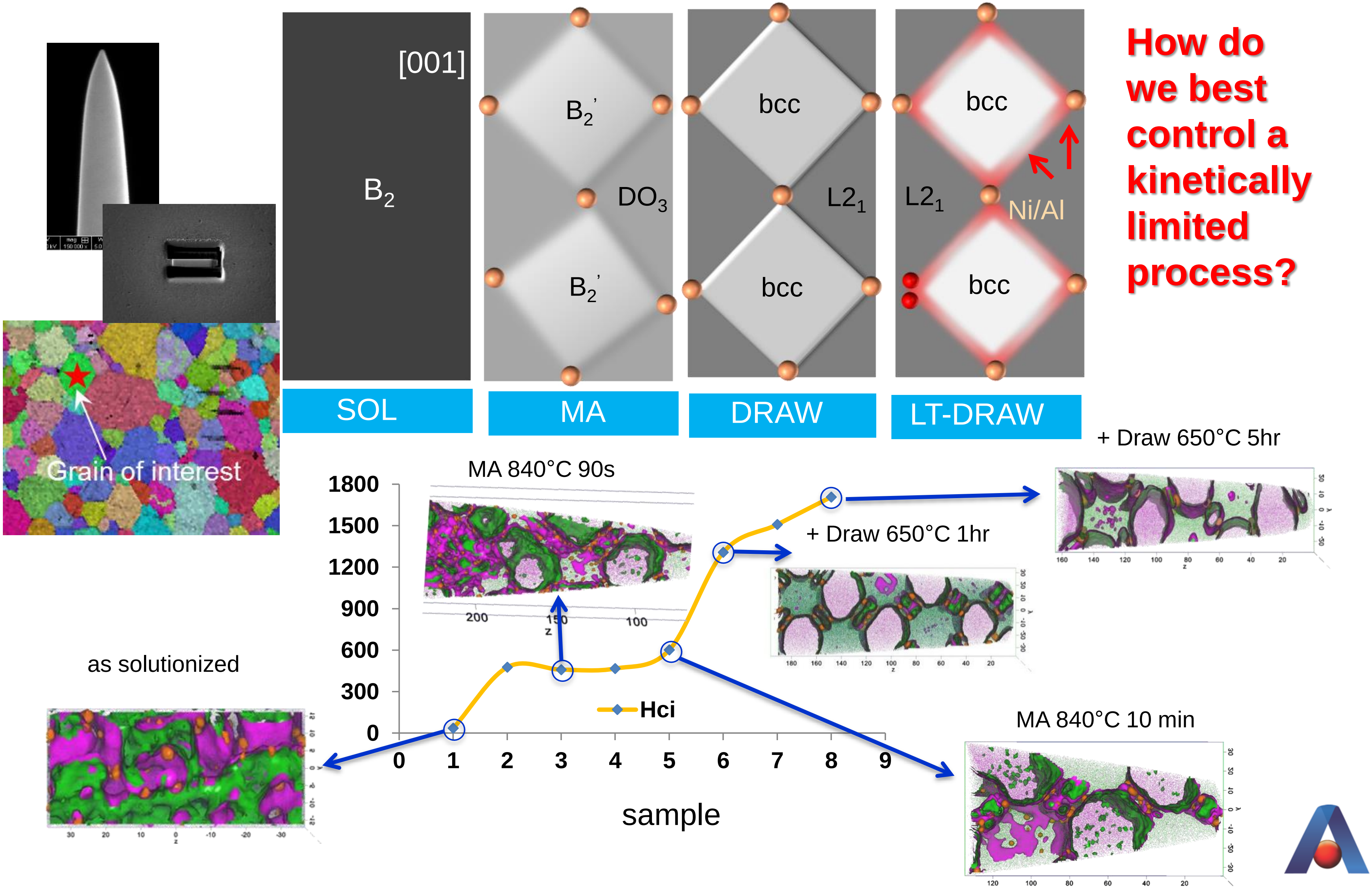
- Optimize processing and chemistry on cast samples to enhance coercivity
  - Magnetic and thermal anneals
- Sintering under uni-axial stress and compression molding with magnetic field-on: optimize to produce grain-aligned alnico by powder processing.





Typical heat treatment profiles for sintered magnets after grain alignment.

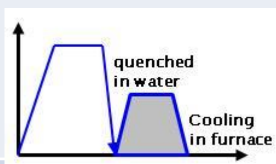
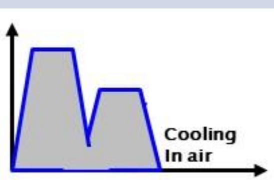
Optimized Processing and Chemistry to Enhance Coercivity



How do we best control a kinetically limited process?

Magnetic Field Anneal Optimization of Coercivity

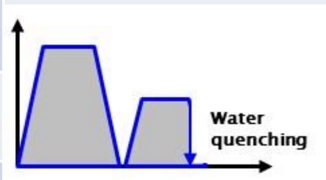
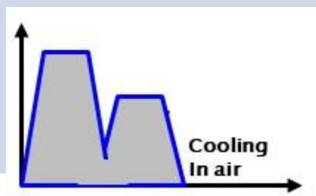
Solutionizing with vs. without a magnetic field

Sample ID	HT Profile	830C	MA only			FHT		
Ti=8.8, Nb=0.75 Cu=3.24		t, (min.)	Ms (kGS)	Br (kGS)	Hc (Oe)	Ms (kGS)	Br (kGS)	Hc (Oe)
WTU53B5a-4		1.5	10.5	6.4	1605	10.6	6.7	2366
WTU53B5a-1		3	10.4	6.4	1667	10.6	6.9	2425
WTU53B5-1		8	10.5	6.3	2018	10.4	6.5	2428
WTU53B5a-3		0	10.4	6.2	791	10.5	6.3	1585
WTU53B5a-5		1.5	10.5	6.6	1703	10.6	7.0	2513
WTU53B5a-2		3	10.4	6.5	1754	10.5	6.9	2485
WTU53B5-4		5	10.6	6.8	1839	10.7	7.3	2411

The shorter magnetic anneal time minimizes growth of the rod diameters and increases coercivity.

Magnetic Field Anneal Optimization of Coercivity

Effect of cooling rate after magnetic annealing

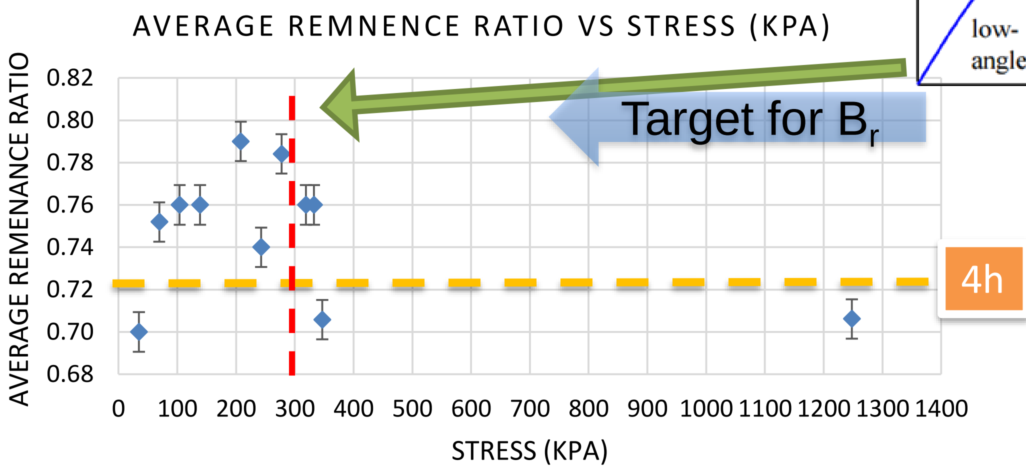
Sample ID	HT Profile	830C	MA only			FHT		
Ti=8.8, Nb=0.75 Cu=3.24		t, (min.)	Ms (kGS)	Br (kGS)	Hc (Oe)	Ms (kGS)	Br (kGS)	Hc (Oe)
WTU53B5b-4		0.5	10.1	5.96	1035	10.2	5.9	1800
WTU53B5b-5		1.0	10.3	6.16	1100	10.35	6.2	2161
WTU53B5b-6		1.5	10.1	5.98	1196	10.3	6.3	2280
WTU53B5a-5		1.5	10.5	6.6	1703	10.6	7.0	2513
WTU53B5a-2		3	10.4	6.5	1754	10.5	6.9	2485
WTU53B5-4		5	10.6	6.8	1839	10.7	7.3	2411

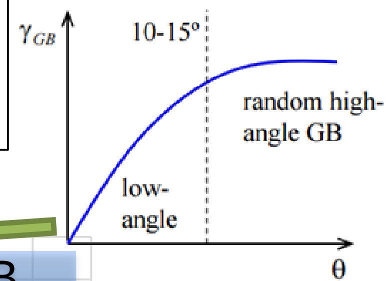
The slower quench (air cool) prolongs diffusion & boosts coercivity.
Positive impact on processing of larger samples!

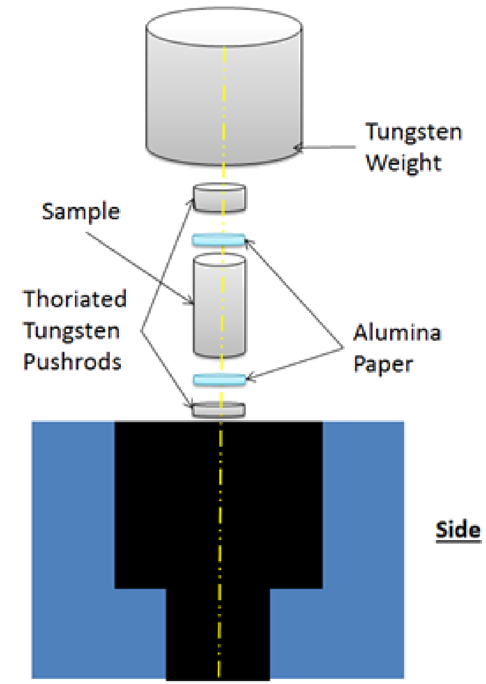
Coercivity target is meet, need to improve texture to meet remanence target of 0.8

Technical Accomplishments in Texture Alignment

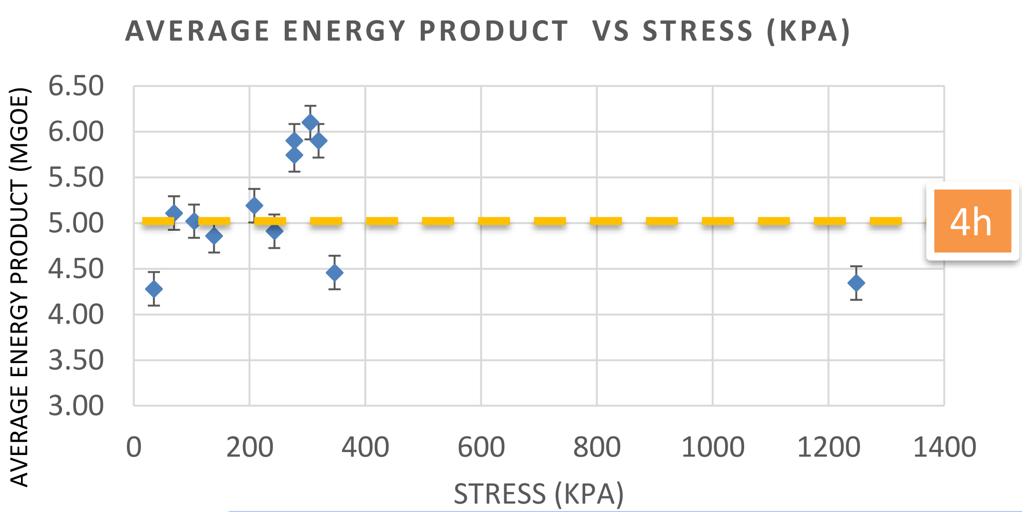
Uni-axial stress applied in secondary sintering by dead-weight loading (DWL) to apply bias for abnormal grain growth (AGG).







DWL fixture for 3mm X 10mm cylinder.



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

Texturing is maximized @ uni-axial stress ≈ 300 kPa during sintering

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

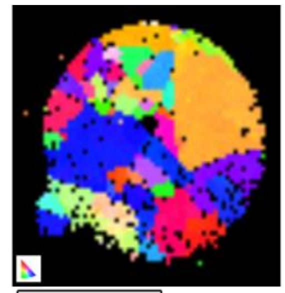
Technical Accomplishments in Texture Alignment

-20µm powder, tilting Halbach PM array
+ Finer powder, AGG already occurred before DWL
* Estimated, 1h sintered vs 2h sinter before DWL

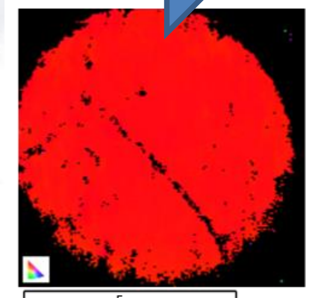
Angle (Deg)	Stress (kPa)	Br (kG)	Hci (Oe)	BHMax (MGOe)	Remanence Ratio (Br/Ms)
90	104	7.27	1,459	3.1	0.63
54	277	9.3	1,637	6.0	0.78
54[1]	277	9.1	1,794	6.0	0.75
54	277	9.3	1,731	6.0	0.78
45	277	9.8	1,594	5.97	0.77
36[1]	277	9.1	1,781	5.95	0.76
36[1]	277	9.3	1,781	6.3	0.78
0	277	8.8	1,697	5.2	0.70
DEAD-WEIGHT ONLY+	*277*	*8.6*	*1,680*	*5.2*	*0.70*
ALNICO 8HC	*-*	*6.7*	*2,020*	*4.5*	**0.70*

GA-1-194
Alloy powder

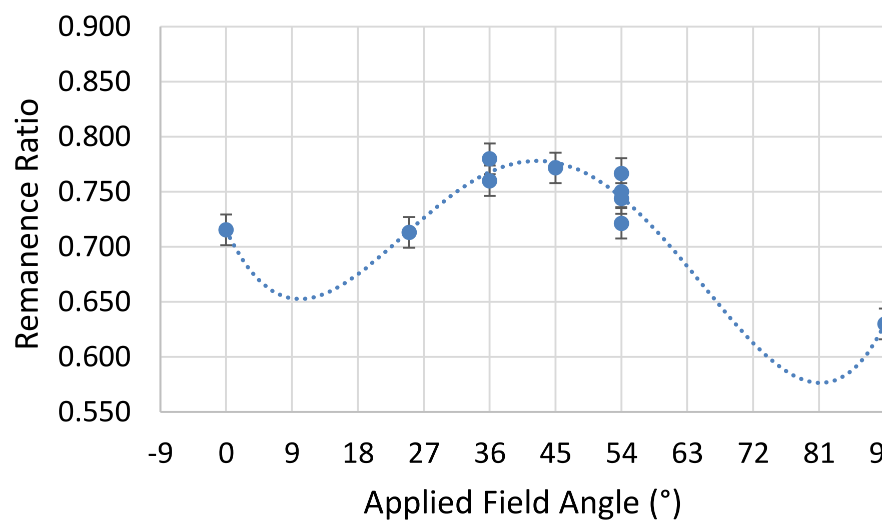
Decreasing Size



38µm



8µm



Remanence can be further increased using appropriate magnetic alignment during compression molding.

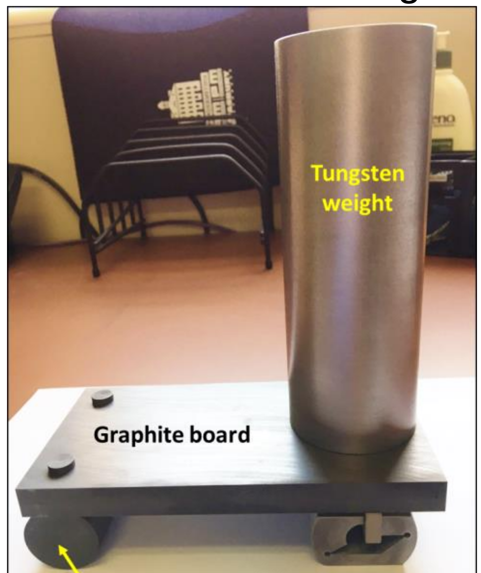
Technical Accomplishments:
Full Size Complex Shaped Magnets

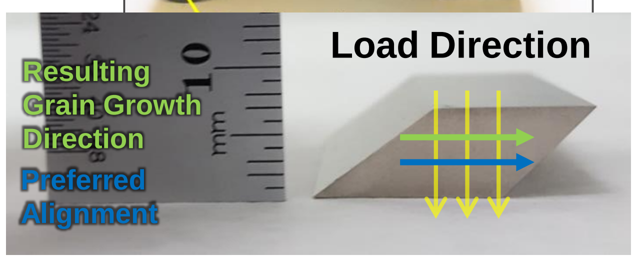
Scaled Up

Current Capability:
Tested on near-final shape of half-scale magnets:
33mm height, 144mm^2

Objective: Dead weight loads to preferentially grow grains along the parallel edges

DWL of half-scale magnet.

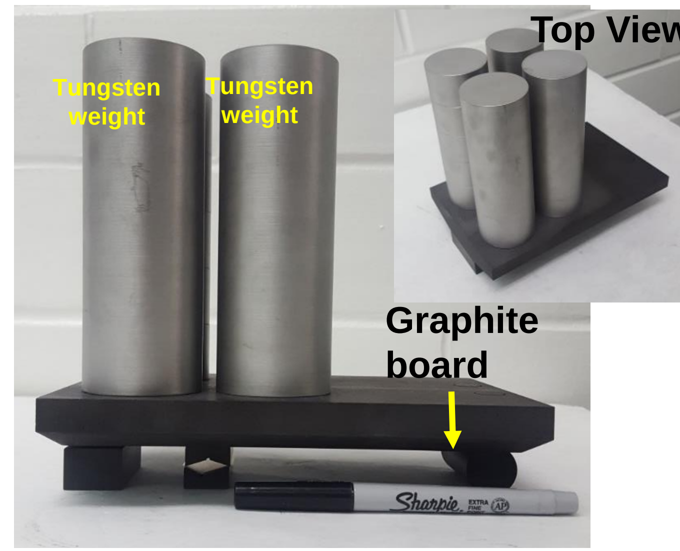


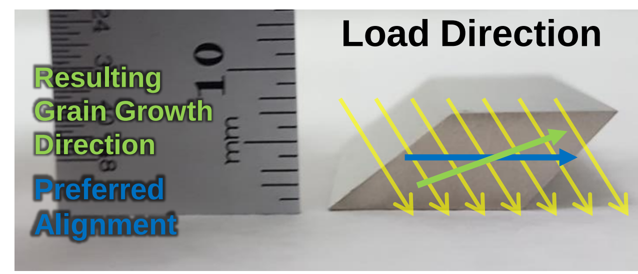


Localized Dead Weight Loading

- Load **only influences limited volume** of the magnet.
- Load is in **correct orientation** to promote preferred growth alignment.

DWL for AGG of full-scale magnet.

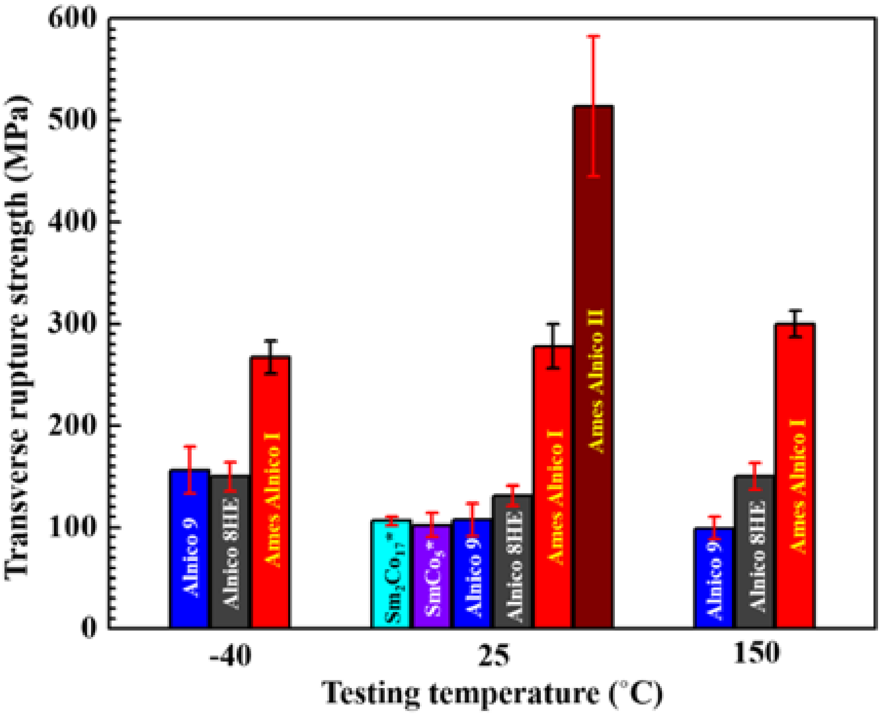


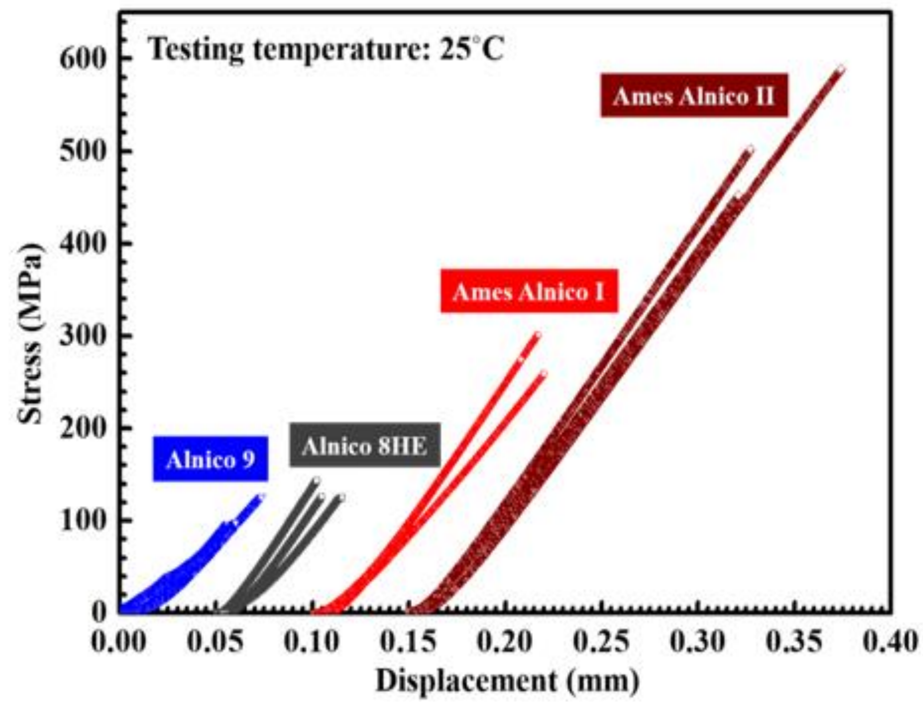


Uniform Dead Weight Loading

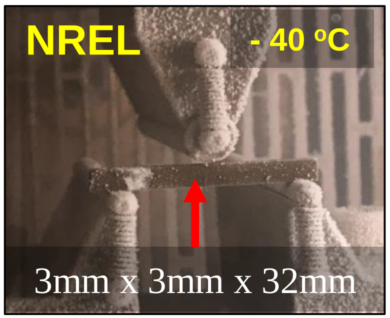
- Load is **uniformly distributed** across the majority of the magnet
- Yields **non-optimal grain growth alignment** in the preferred direction.

Technical Accomplishments in Mechanical & Thermal Properties





Sintered magnets show enhanced strength to improve assembly reliability and permit high rpm.



Alnico II by secondary sintering with DWL: higher density.

Achieved with minimal change in thermal conductivity!
See ELT 075

Response to Previous Year Reviewers' Comments

The reviewer remarked that the project is making great strides to understand at a material level what is happening with the magnetic materials. The formation process, and certain processes that cause variation, will help manufacturers make higher quality magnets.

The reviewer also remarked that, "The project **completed bulk magnets in March, but did not present magnetic properties** yet. This reviewer noted that **some sort of physical testing is needed**, for a go/no go decision, before moving on to the next iteration."

> *Bulk magnets of half-size and full-size of an industry design have been fully sintered and tested with NREL, showing bend strength 2-3 times of alnico 9 and 8H cast magnets. Scale-up not completed of new methods for stress-aligned grain growth and particulate alignment during molding to permit meaningful magnet property testing.*

The reviewer suggested that the group **start making progress towards building a prototype by involving OEM Tier 1 suppliers**. Another reviewer remarked it would be **desirable if test samples are used for electric motor fabrication**.

> *Agreements developing for collaboration with ORNL on alnico-specific motor design and fabrication to enable new full-scale magnet design to be established and processing of full-scale aligned test magnets to be determined. If new motor is finalized and built, cooperation with OEM for performance testing has been offered in related TCF project.*

Ames Lab Partners/Collaborators for FY2017-FY2018

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.
- 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).
- ORNL (Burak Ozpineci, Jason Pries): Motor design and fabrication, TCF project (collaborator).

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.

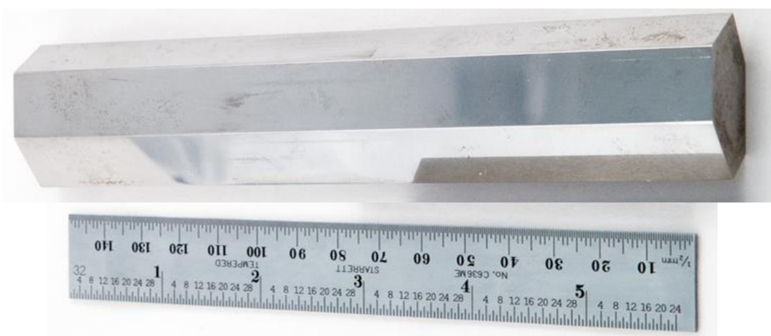
- Need to make progress toward control of the magnetic anneal process to reduce Fe-Co rods diameters to < 20 nm for maximum coercivity, as predicted by micro-magnetic modeling.

proposed future work is subject to change based on funding levels

Remaining FY18 DREaM Tasks

Develop Focused Theory & Simulation: The theory is shifting to focus on micro-magnetic modeling, which has given clear microstructural targets.

Synthesize Test Samples: Continue to improve the texture in aligned alnico. This will be a challenge with the complex geometry of full-scale magnet design. Adding Halbach array for magnetic alignment during compression molding to improve grain texture effect from secondary sintering under uni-axial stress.



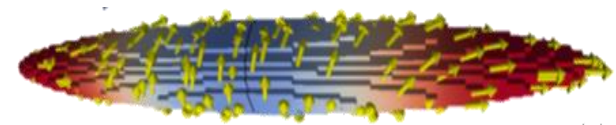
Halbach PM array.

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

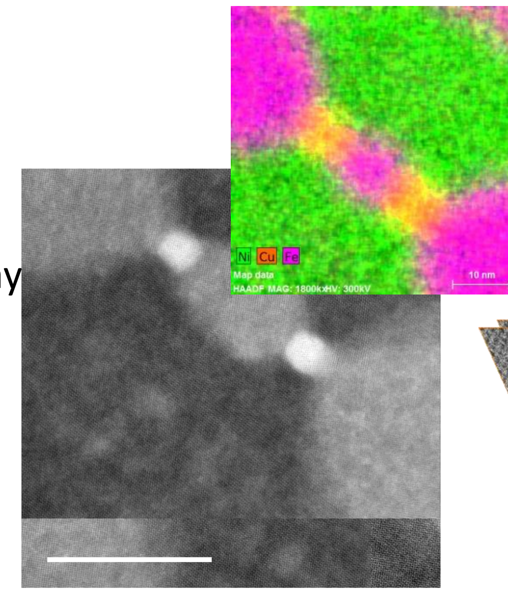
proposed future work is subject to change based on funding levels

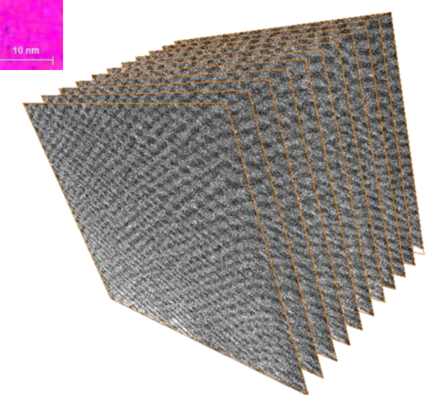
Future (possible extension) FY19 DREaM Research Tasks

Promote 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 micro-magnetic microstructure calculations using experimentally derived 3D models.





Perform Characterization: Expand detailed characterization to high fidelity 3D images. Perform extensive in situ XRD investigation at high energy X-ray line (e.g., APS) to explore modified parameters for magnetic annealing and draw cycles. Continue NREL collaboration to add magnet mechanical and thermal property data and add ORNL studies to include temperature and frequency dependent magnetic properties and FEM for motor design.

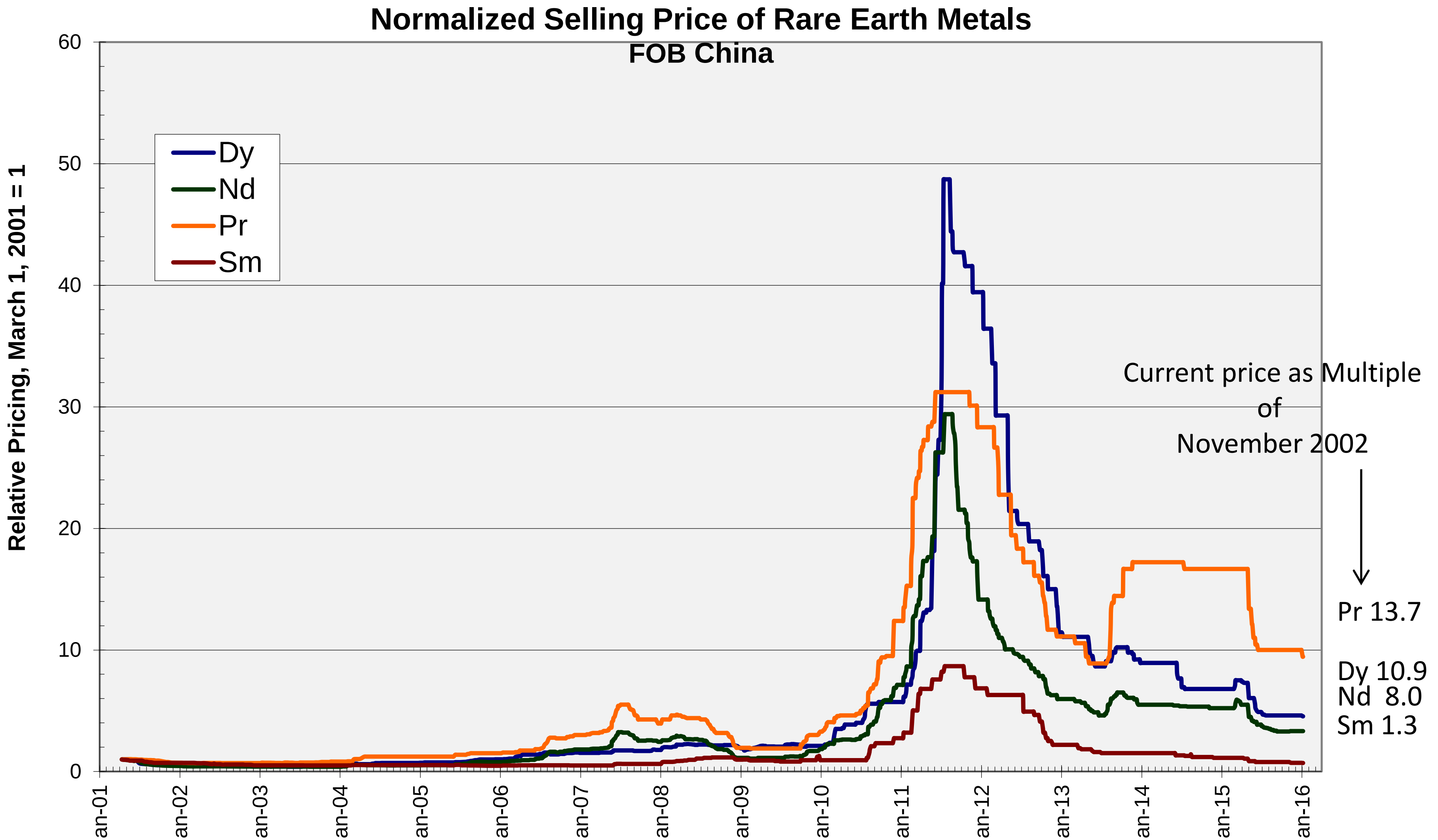
Synthesize Test Samples: Optimize bulk samples using magnetic and thermal processing parameters for pre-alloyed powder (including micro-alloyed alnico 8 and refined low-Co alnico). Improve methods to gain control over texturing effects in sintered bulk magnets to further improve magnetic properties. Gather, analyze, and report results of high magnetic field experiments on nano-structure and magnetic properties.

Summary

- **Coercivity > 2700 Oe (alnico 8H ~ 2170 Oe), but need improved microstructural alignment for maximum energy product and traction motor application (B_r > 0.8).**
- Co decreased while maintaining/enhancing coercivity.
  - New pathways show even more promise.
- Bulk sintering and grain alignment demonstrated (**B_r ~ 0.79**).
  - 2 US patents filed on grain alignment methods
- **Full scale motor magnets fabricated with high strength**.
- Modeling providing useful guidance on alloying and processing routes.

Technical Back-Up Slides

Rare earth metal prices (normalized)



ARNOLD MAGNETIC TECHNOLOGIES

Magnet Requirements for EVs

Year	Total Market, millions		% EV (inc. hybrid)		No. EV (inc. hybrid)		Magnets Req'd, tons	
	USA	**Global**	**USA**	**Global**	**USA**	**Global**	**USA**	**Global**
2015	17.4	88.0	2.9%	3.5%	0.5	3.1	631	3,850
2020	17.2	103.0	9.7%	14.0%	1.7	14.4	2,086	18,025
2025	17.1	113.0	20.1%	35.0%	3.4	39.6	4,296	49,438
2030	17.0	119.0	30.0%	50.0%	5.1	59.5	6,375	74,375
2040	17.0	125.0	50.0%	80.0%	8.5	100.0	10,625	125,000

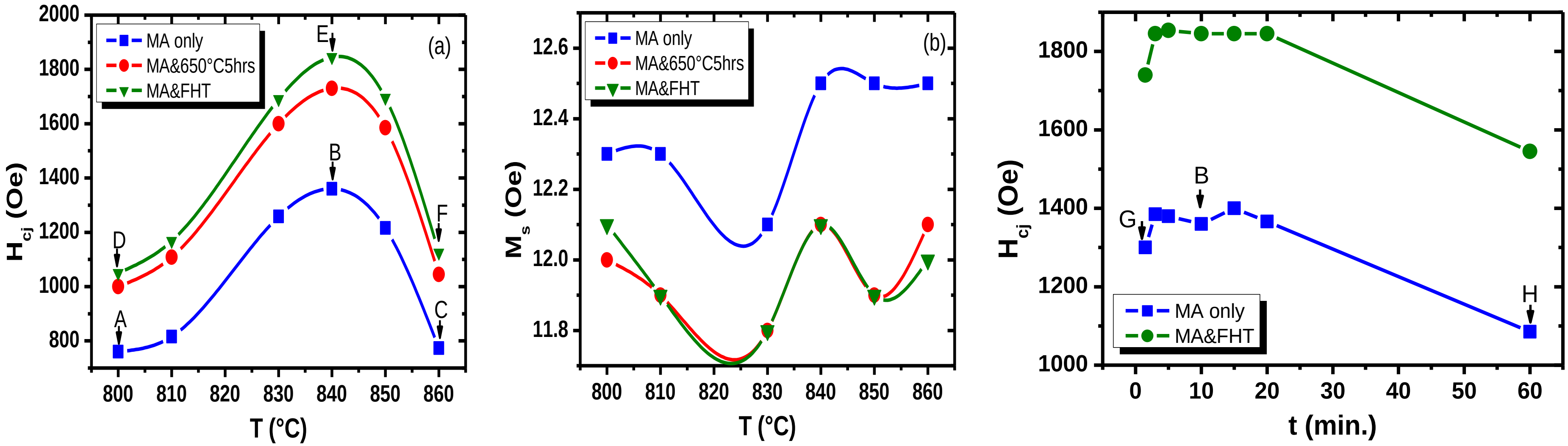
Vehicle quantities shown in millions
Average kg NdFeB magnets per traction drive system = 1.25
Extreme case in 2040:

All cars are EV = 125,000,000 vehicles
1.25 kg per vehicle traction drive = 156,250,000 kg = 156,250 tons of magnets
156,250 tons of NdFeB magnets requires 416,000 tons of REO

REO production * 37.8% = NdFeB magnet output
NdFeB magnets / 37.8% = REO required

While RE crisis has abated somewhat the future supply chain is in more jeopardy than it was in 2012.

Optimizing the Spinodal Processing in Alnico Permanent Magnets



- Thermal-magnetic annealing (MA) and subsequent heat treatments (FHT is 650°C 5hrs + 580°C 15 hrs) are crucial in tuning alnico's magnetic properties.[4]
- Magnetic properties of alnico are sensitive to the time and temperature of the magnetic field annealing step.[2]
- The draw significantly affects intrinsic coercivity (H_{ci}), which is not sufficiently explained by compositional variations.[2]

1. L. Zhou *et al.*, *Acta Mater.* **133**, 73-80 (2017).
2. L. Zhou *et al.*, *Metallurgical and Materials Transactions E* **1**, 27-35 (2014).

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)

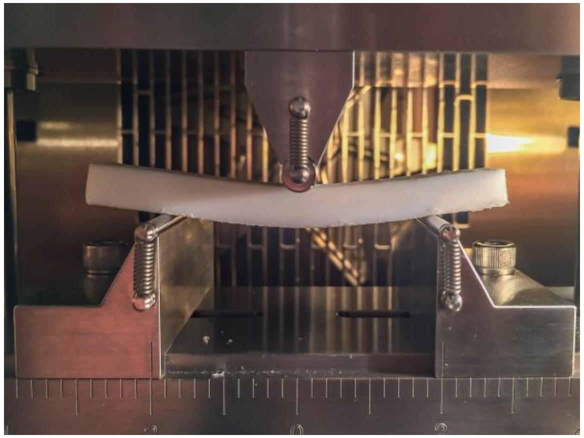
P = force required to rupture specimen (N)

L = Distance between supporting rods (25.4 mm)

w = specimen width (mm)

t = specimen thickness (mm)

Compression Test Fixture



Transverse Rupture Test Fixture