Development of Sustainable High Performance Magnetic Materials for Exceptional Power Density Electric Drive Motors

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Ames Laboratory

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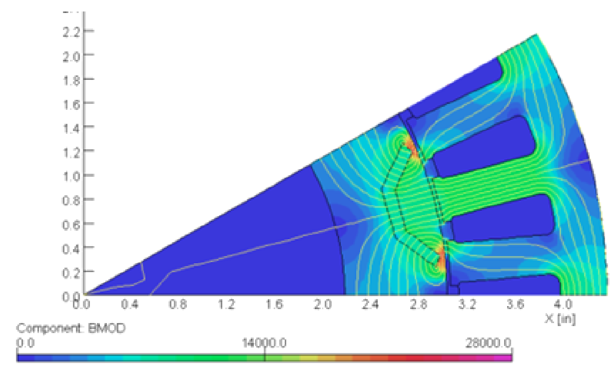

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Overview

Timeline

- Start: October 1, 2019
- End: September 30, 2022
- Percent complete: 10%

Budget

- Total project funding
  - $1,350 K (Federal)
  - $0 K (Cost share)
- Funding for FY 2019: $450K

Barriers and targets

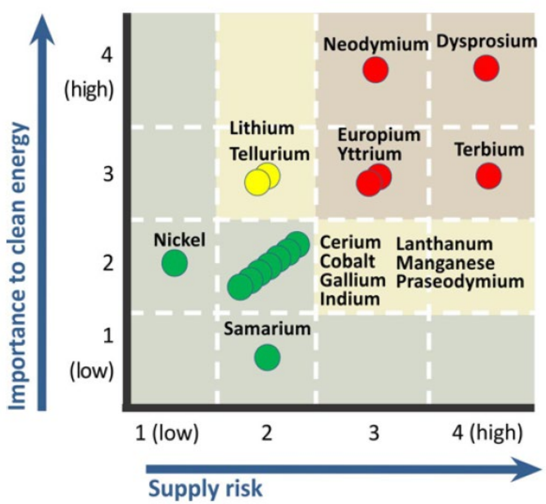
- Barriers addressed
  - Permanent magnet (PM) cost and heavy rare-earth (HRE) element scarcity and price volatility
  - Non-rare earth PM electric motor has low power density
- Targets
  - Exceptional drive motor power density (33 kW/l at $6/kW with 8x reduction in volume)

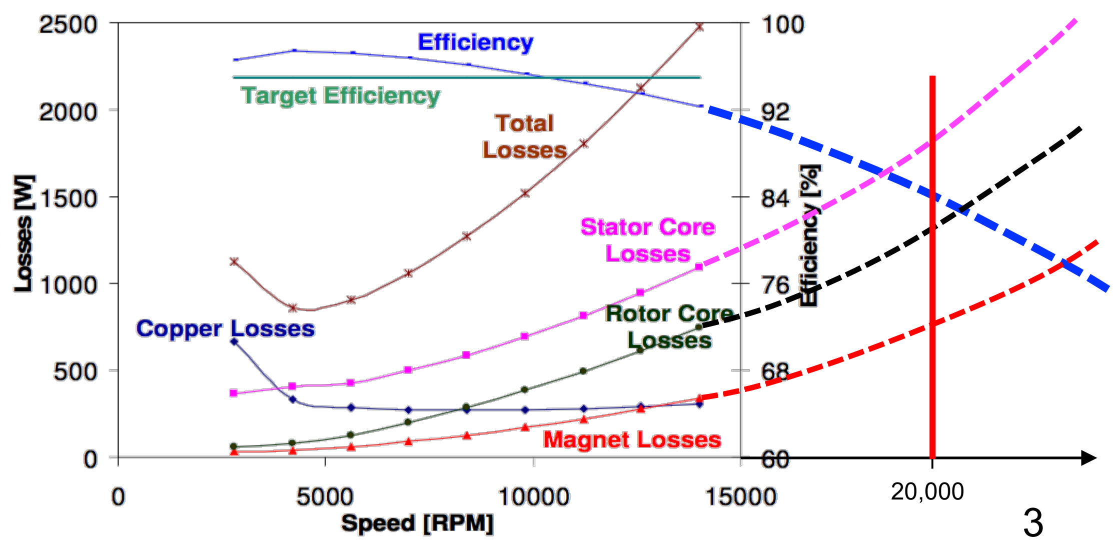
Partners

- Oak Ridge National Laboratory
- National Renewable Energy Laboratory
- Sandia National Laboratory

Relevance

- Objective
  - Develop permanent magnetic (PM) materials and processes that conserve scarce rare earth (HRE) metals, but have suitable performance for electric motors with exceptionally high power density.
- Impact
  - Reduces IPM rotor magnet eddy current losses at increased frequency/RPM
  - Improve interior permanent magnet (IPM) motor power density
  - Maintain drive system cost-effectiveness and high efficiency





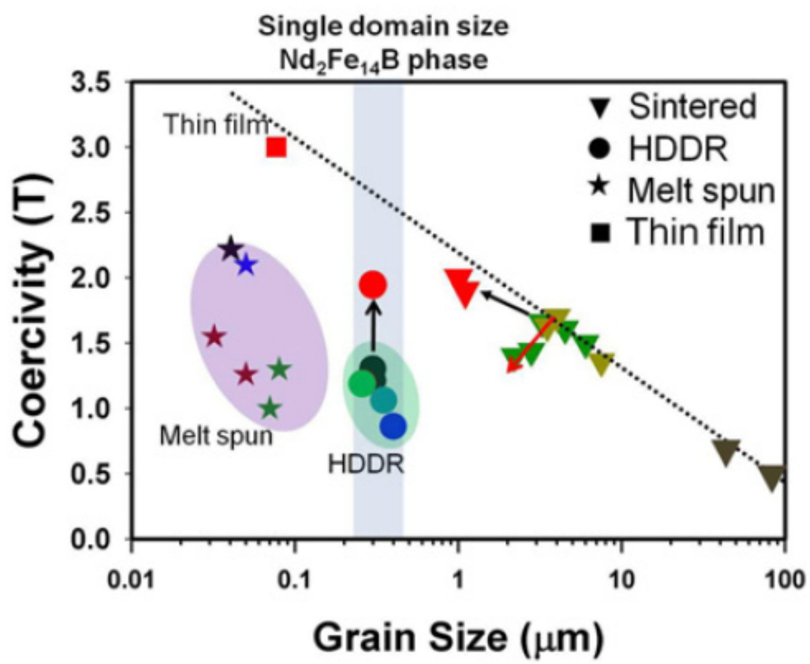
Milestones

Tasks #	Description	2019				
1	Develop fine-grain RE permanent magnet with high coercivity at high temperature	1	2	3	4	Status
Yr1-Q1	Establish theoretical framework for fine-grain approach.	■				75%
Yr1-Q2	Identify processing challenges and solutions for producing fine-grain, high coercivity magnets.		■			90%
Yr1-Q3	Down select and evaluate processes for fine grain magnet production by powder-based approach.			■		
Yr1-Q4	Validate and initial testing of magnets identified through micro-magnetic modeling of bulk RE permanent magnets with heterogeneous and homogenous microstructures.				■	
2	Develop graded HRE-free magnet with high performance at high temperature	1	2	3	4	
Yr1-Q1	Establish theoretical framework for graded-magnet approach	■				60%
Yr1-Q2	Assess technology of graded magnets (alternative approaches for graded magnet processing) and scale-up feasibility.		■			50%
Yr1-Q3	Develop methods for achieving spatially varying composition architectures to maximize coercively where needed.			■		
Yr1-Q4	Validate and initial testing of architectures identified through micro-magnetic modeling				■	

Task 2.7 Develop fine-grain RE permanent magnet with high coercivity at high temperature

Challenge: ***Highly refined grain size RE-PM with magnetic & mechanical strength***

Advantages



- Dy in RE-PM for drive motors maintains high coercivity at high operating temperatures.
- Ultrafine grain non-Dy RE-PM also raises coercivity and stabilizes high temperature properties.

Hono et al. Scripta Materialia 67, 2012 (530)

Challenges

- Difficult to produce and handle fine powder in manufacturing process
  - Additional milling time/intensity is required for finer powder
  - High flammability of the fine powder requires super low oxygen control, leads to extra cost
- Difficult to fabricate into bulk magnet
  - Increased surface area impedes grain alignment and promotes grain growth during sintering
- Deterioration of bulk mechanical properties
  - Residual surface oxides embrittle microstructure

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Approach: *Processing Ultrafine Grain Size RE-PM*

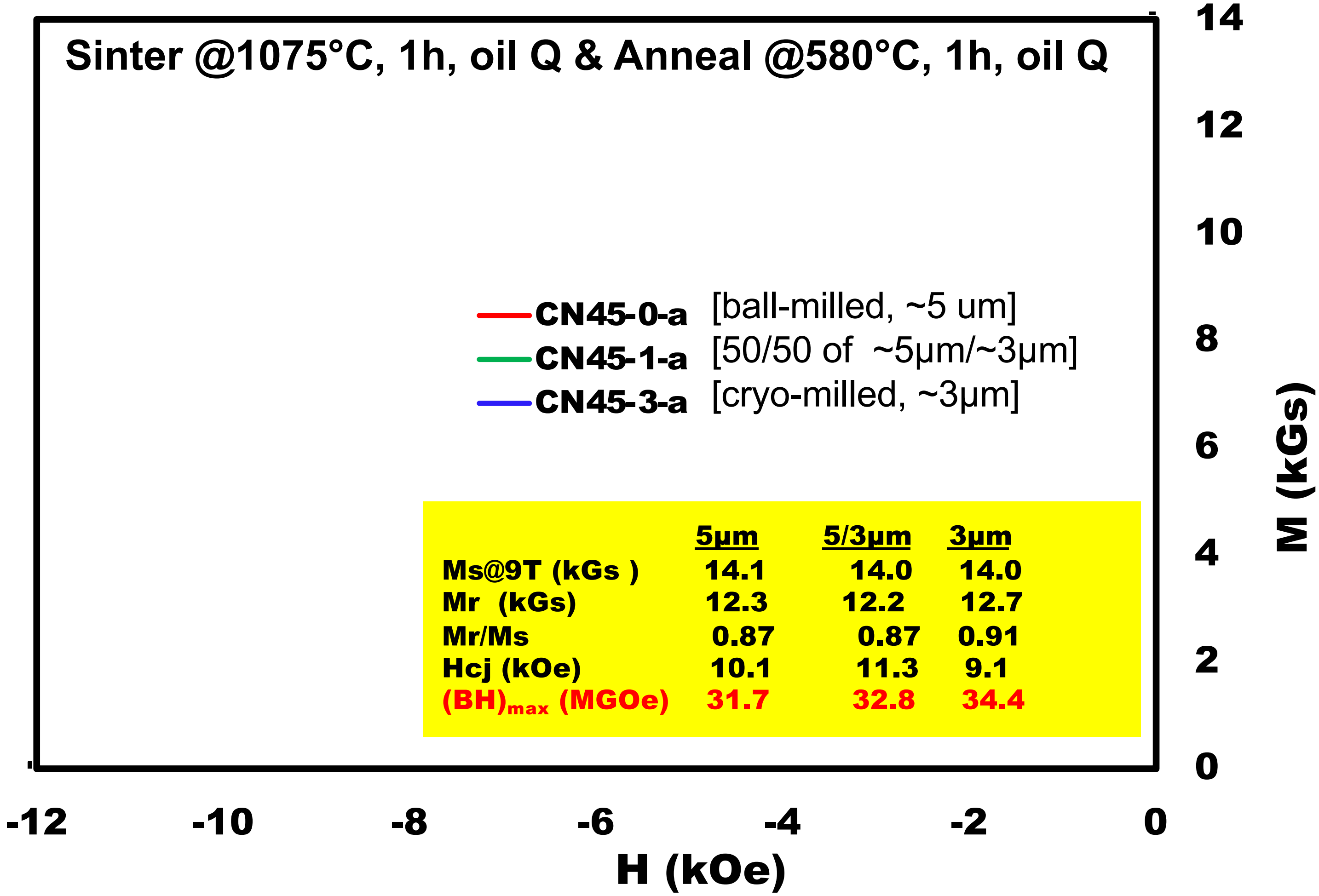
- Investigate production of ultrafine powder/uniform composition
  - Feedstock: strip cast, planar-flow cast, melt spun (fine grain, low surface area)
  - Size Refinement: ball-mill (BM), cryo-mill (CM), jet-mill (JM), HD
- Surface oxidation protection
  - Minimal oxide growth (glove box processing) or alternative surface reaction
- Investigate processing of aligned, ultrafine grain bulk magnets
  - Loose powder aligned: die compact or CIP
  - Full density sintering: pressure-less or vacuum hot press
- Alternative novel processing approaches
  - Additions to stabilize grain size, metal bonding

	Planned milestones and annual go/no-goes
2019	• Down select fine powder production methods • Validate the mechanism of enhancing coercivity through fine grain approach
2020	• Fabricate ultrafine grain bulk magnet

Accomplishments: *Ultrafine Grain Size RE-PM*

Commercial HD powder → BM/CM fine powder → Field align Press → Sintering Post annealing → Characterization

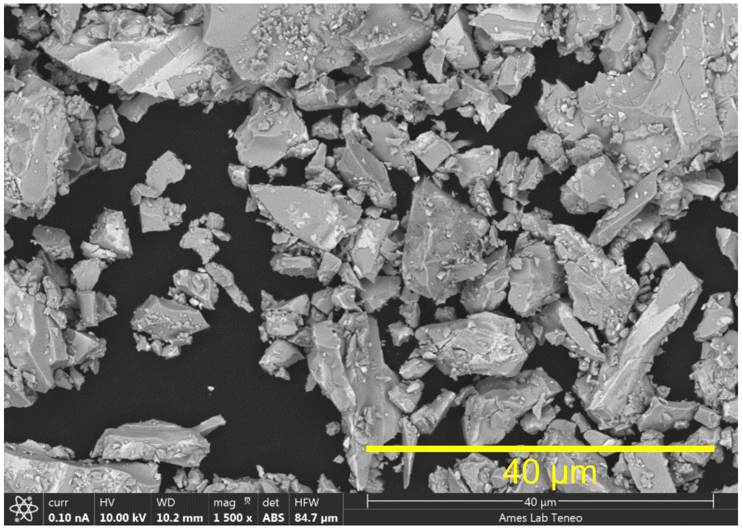
$Nd_{2.2}Fe_{14}B$

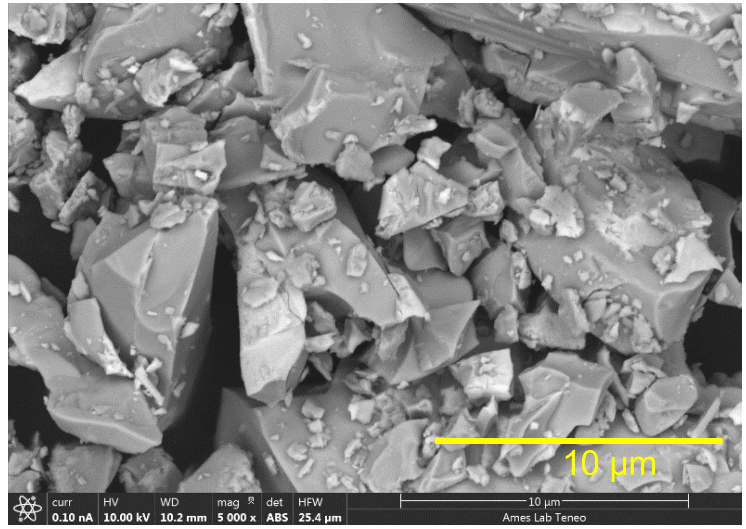


	5µm	5/3µm	3µm
Ms@9T (kGs)	14.1	14.0	14.0
Mr (kGs)	12.3	12.2	12.7
Mr/Ms	0.87	0.87	0.91
Hcj (kOe)	10.1	11.3	9.1
$(BH)_{max}$ (MGOe)	31.7	32.8	34.4

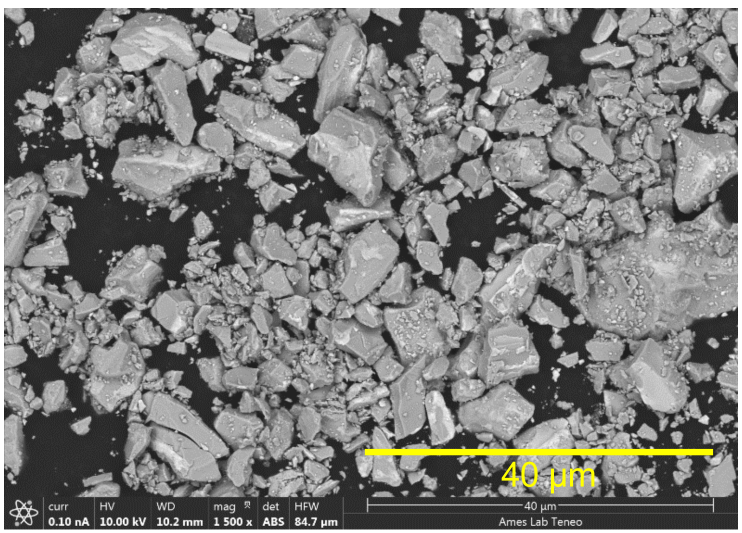
- Magnet from blended powders obtains highest Hcj, but magnet from "finer" powder obtains a higher Br (kGs), alignment (Mr/Ms) and $(BH)_{max}$ [more uniform size?]
- Highest Hcj probably from microstructure with finest average grain size.

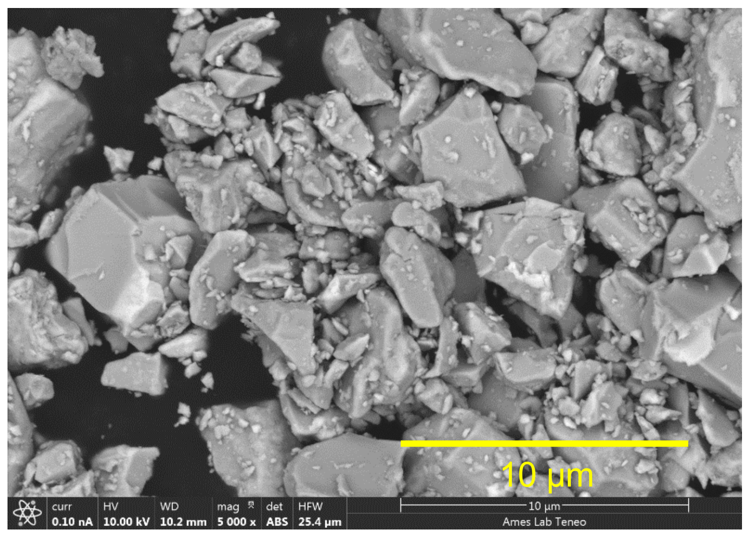
Milling effects on morphology and size of Nd-Fe-B powder





Ball-milled (3h) to ~5 µm



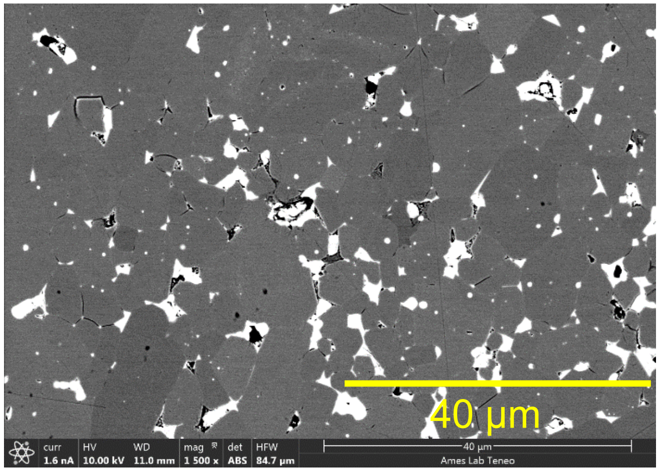


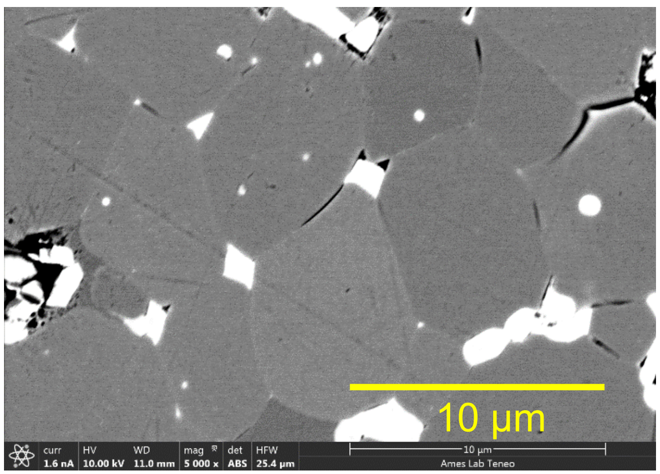
Ball-milled (3h) to ~5 µm + cryo-milled (2h) to ~3 µm

- Cryo-milling for 2h reduced ball-milled powder size from ~5 µm to ~3 µm.
- Milling needs improvement (size reduction/uniformity); try jet milling.

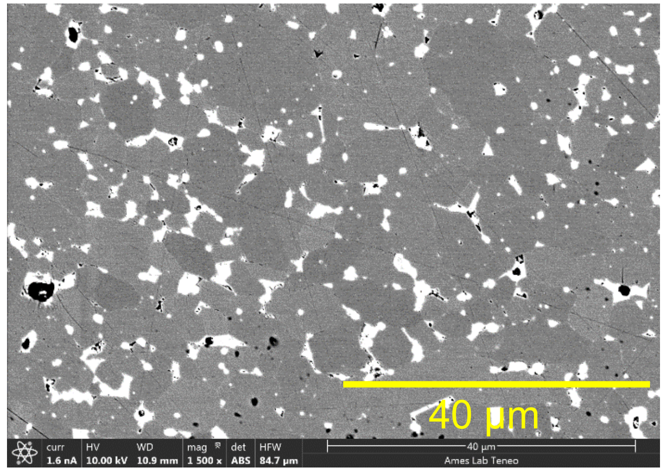
Sintered magnet microstructures: grain size/boundary phases

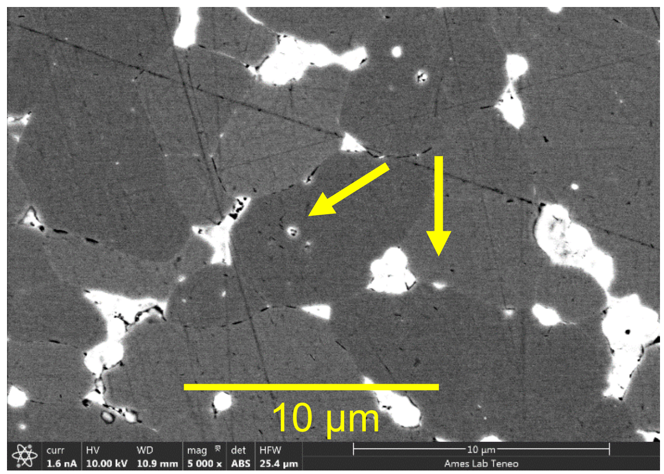
BM(3h) to ~5 μm



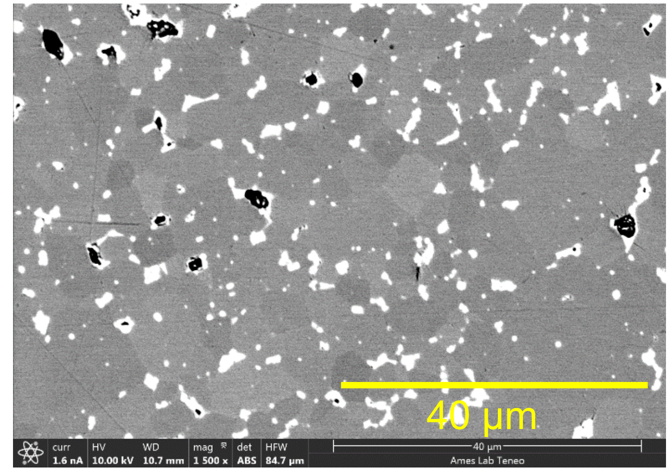


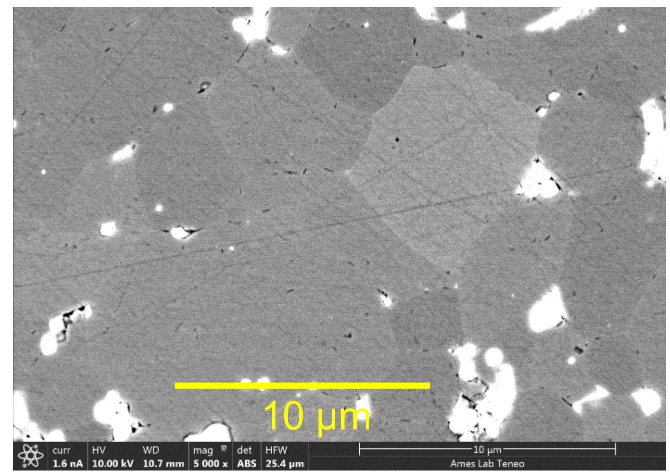
BM + CM (> ~3 μm?)





BM(3h) + CM(2h) to ~3 μm

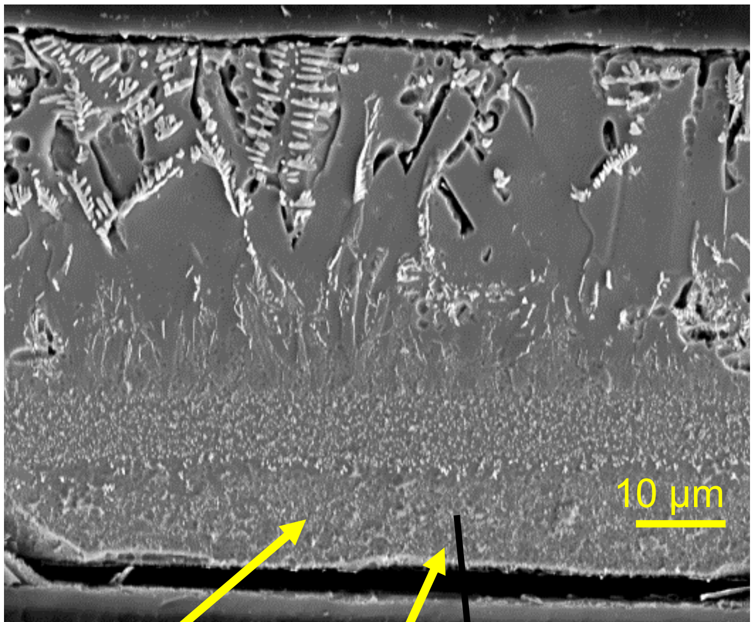




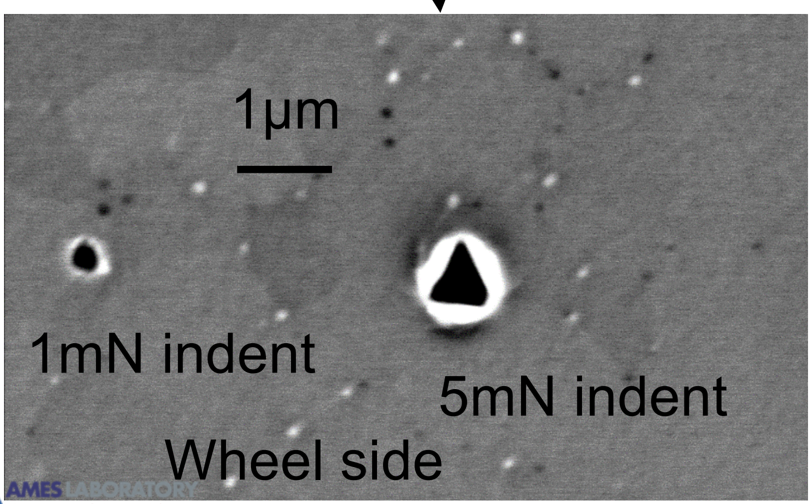
- Magnet from 50/50 blend shows a smaller average grain size while magnets from 100% BM or BM+CM powders shows a larger average grain size, consistent with coercivity results.
- Blended powder seemed to produce magnets with most detectable g.b. oxides.
  - possible fracture sites.

Test of cracking tendency with “clean” grain boundaries: As-solidified grains of different sizes on ribbon X-section

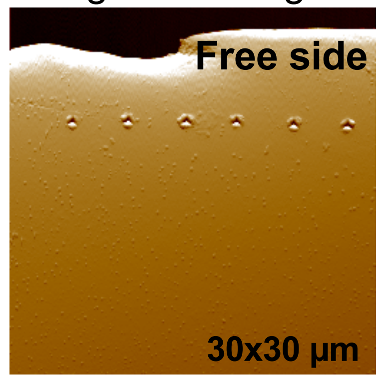
[Free side]

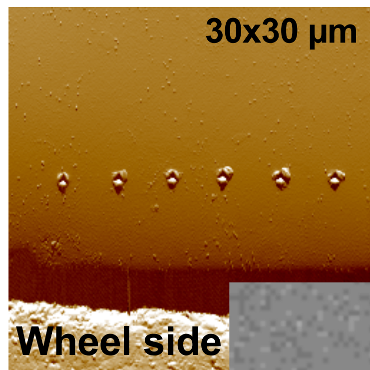


1 µm 300nm [Wheel side]

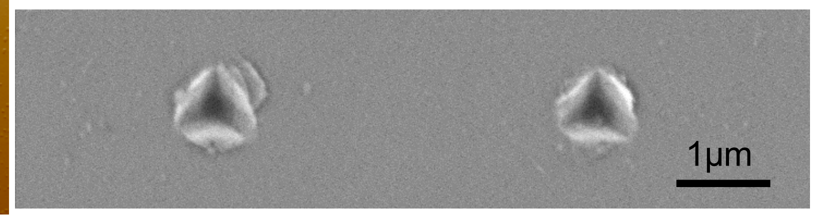


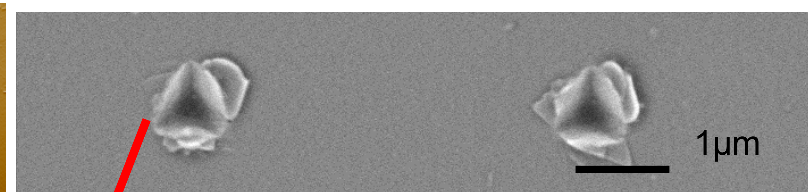
AFM images showing indents for 5mN load



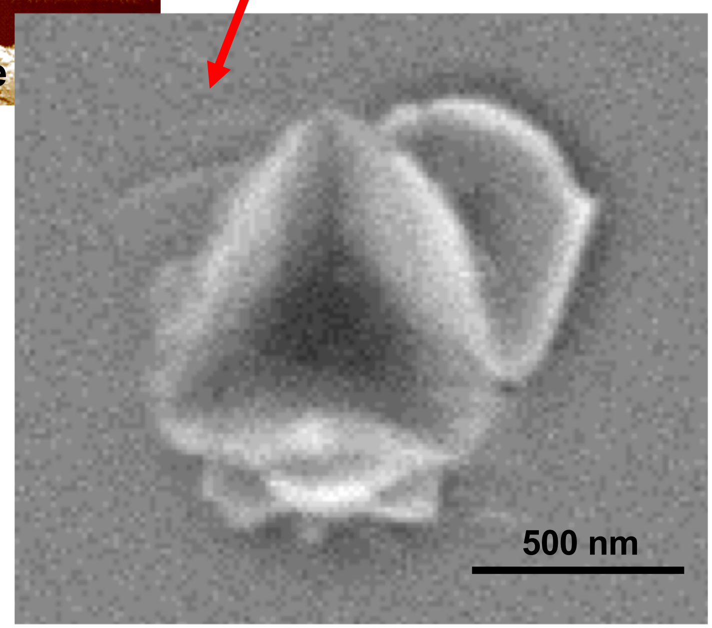


Free side





Wheel side



Plastic surface rumpling.

No signs of cracking in ultrafine grains, if “clean” interfaces.

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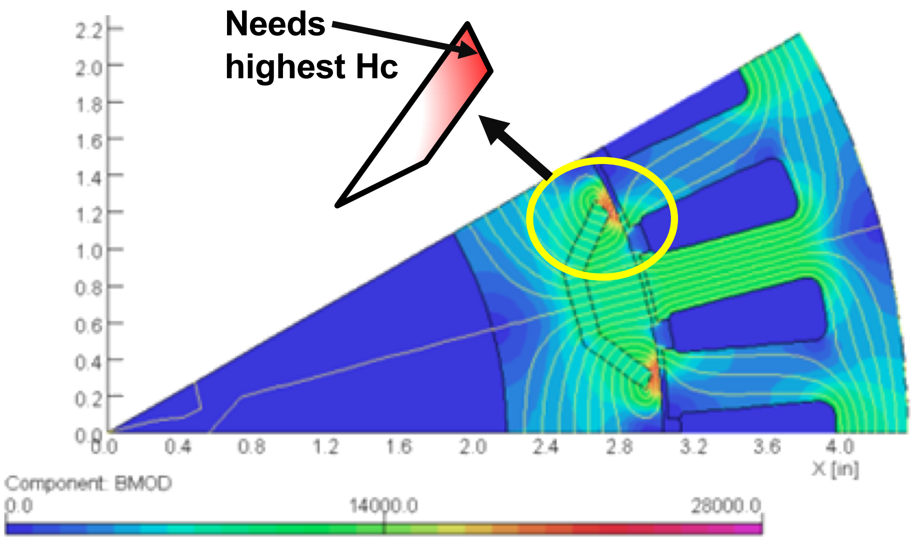
2.8 Develop graded HRE-free magnet with high performance at high temp.

***Challenge:* Design/produce graded HRE-free magnet with surface of high coercivity and core of high magnetic saturation.**

Advantages



- During IPM motor operation, only a minor portion of the bulk permanent magnets (adjacent to the rotor gap) experience high demagnetization field.
- In this concept, a portion of the IPM rotor magnets is "shielded" by a high coercivity magnet "cap" with high temperature stability, e.g., $SmCo_5$, and a high saturation magnet with less Hci, e.g. alnico 5-7, provides the required magnetic torque for the motor.

Challenges

- Demagnetization lines are non-linear
  - The de-magnetization field distribution of a non-uniform high coercivity (shielded) magnet in realistic stator field needs to modeled in appropriate geometry.
- Assembly of two permanent magnets without air-gap requires
  - Compatible thermal-mechanical treatment during the bulk magnet fabrication process
  - Composite magnet processing method adaptable for both types.
  - Compatible CTE during operation.
  - Resistance to thermal fatigue.

Approach: *Modeling and Processing Graded Magnets*

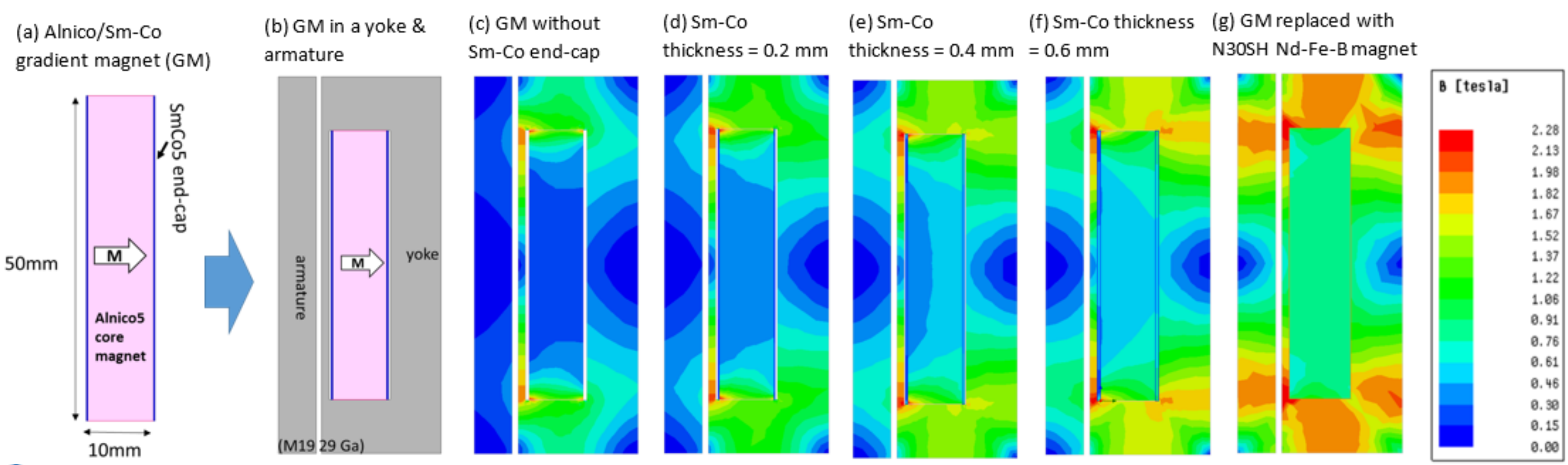
- Conduct preliminary composite magnetic modeling of High H_{ci} magnet shell on High M_{sat} magnet over range of field strength.
- Investigate metallurgical compatibility for thermal-magnetic heat treatment processes and consolidation processing of possible magnet pairs.
- Perform geometry-corrected modeling of demagnetization lines with preliminary choice of High M_{sat}/High H_{ci} magnet types (alnico 5-7/$SmCo_5$)
- Assess technology prospects for graded magnets (alternative approaches for graded magnet processing) and scale-up feasibility.
- Develop methods for achieving spatially varying composition & architectures to maximize coercivity, as needed.
- Validation and initial tests of graded magnet architectures identified through micro-magnetic modeling

	Planned milestones and annual go/no-goes
2019	• Determine architecture of the graded-magnets • Investigate process compatibility for a model system (SmCo-AlNiCo)
2020	• Validate the graded magnet concept by fabricating and testing a model system.

Accomplishments: *Preliminary Modeling of Graded Magnets*

Completed preliminary simulation of demagnetization field distribution in interior permanent motor (IPM) during normal motor operation

- Exploring fundamental principles for predicting the effects of spatially varying grain size on magnetic and mechanical properties.
- Identifying trade-off between improved magnetic and physical properties (electrical resistivity and mechanical properties, e.g., fracture toughness).



Responses to Previous Year Reviewers' Comments

- N/A (this is the first review).

Collaboration and Coordination

- Collaboration on motor designs after sharing of material thermo-mechanical properties.
- Cooperative modeling of geometry-corrected demagnetization lines of High M_{sat}/High H_{ci} magnet types.
- System level performance modeling.

- Investigation of thermal mechanical properties of developed materials.

- Coordination of efforts of university partners who are actively engaged in permanent magnet development for associated motor designs.
- Cooperative development of composite permanent magnet designs.

Remaining Challenges and Barriers

- **Select beneficial production of ultrafine powder/uniform composition.**
  Feedstock by melt spinning (fine grain, low surface area)
  Size refinement by jet-mill with intense energy and controlled atmosphere
  Minimize oxide growth by glove box processing with surface reaction design

- **Investigate improved processing to produce highly aligned, ultrafine grain bulk magnets.**
  Pulse magnet for loose powder alignment and die compact or CIP
  Utilize compact with improved alignment for full density sintering by either pressure-less (preferred) or vacuum hot press methods.

- **Test temperature stability of resulting ultrafine grain magnets.**

- **Model geometry-corrected demagnetization lines with preliminary choice of High M_{sat}/High H_{ci} graded magnet types.**

- **Further investigate compatibility of magnet pairs for thermal-magnetic heat treatment and consolidation processing.**

Proposed Future Research

Key Challenges

- Current SOA is high performance RE-PM alloy Nd-Dy-Fe-Co-B with reduced Dy level for drive motors with optimized design.
- If processing challenges overcome for ultrafine grain RE-PM without Dy, need to demonstrate advantage in alloy and processing cost to motivate motor redesign.
- Further sustainable PM alloy design with high performance may be achieved with graded magnets, but must have similar cost to ultrafine grain RE-PM.

Future work

- For ultrafine grain RE-PM magnets, should develop final shape processing to minimize material waste, only needing final grinding to dimensions.
- Develop new alloy to maximize ultrafine grain size retention during full density consolidation.
- For graded magnets, determine minimum layer thickness for High H_{ci} surface to conserve most valuable magnet component.

Any proposed future work is subject to change based on funding levels.

Summary

- **Production of ultrafine grain size RE magnets was demonstrated with commercial HD feedstock of RE-rich (HRE-free) alloy.**
  - Highest coercivity from (presumed) most uniform fine grain size.
  - Blending may have introduced additional oxide on grain boundaries.

- **Improved ultrafine grain size RE-PMs are likely from crystallized melt spun ribbon of similar alloy previously developed with carbide additions to stabilize grain size.**
  - Additional particulate refinement could come from jet-milling with strict atmosphere control.
  - Improved alignment also may be improved by refinement, especially with pulse magnet during compaction.

- **Preliminary graded magnetic modeling of High H_{ci} magnet shell on High M_{sat} magnet core was conducted over range of field strength and encouraged this approach to magnet design.**
  - Initial test of metallurgical compatibility for thermal-magnetic heat treatment of a possible magnet pair ($SmCo_5$/alnico 8) indicated that another choice was needed.