SAND2018-9971C

Additive Manufacturing of Soft Ferromagnetic Alloys (LENS and powder bed)

Solid Freeform Fabrication, Austin, TX

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PRESENTED BY

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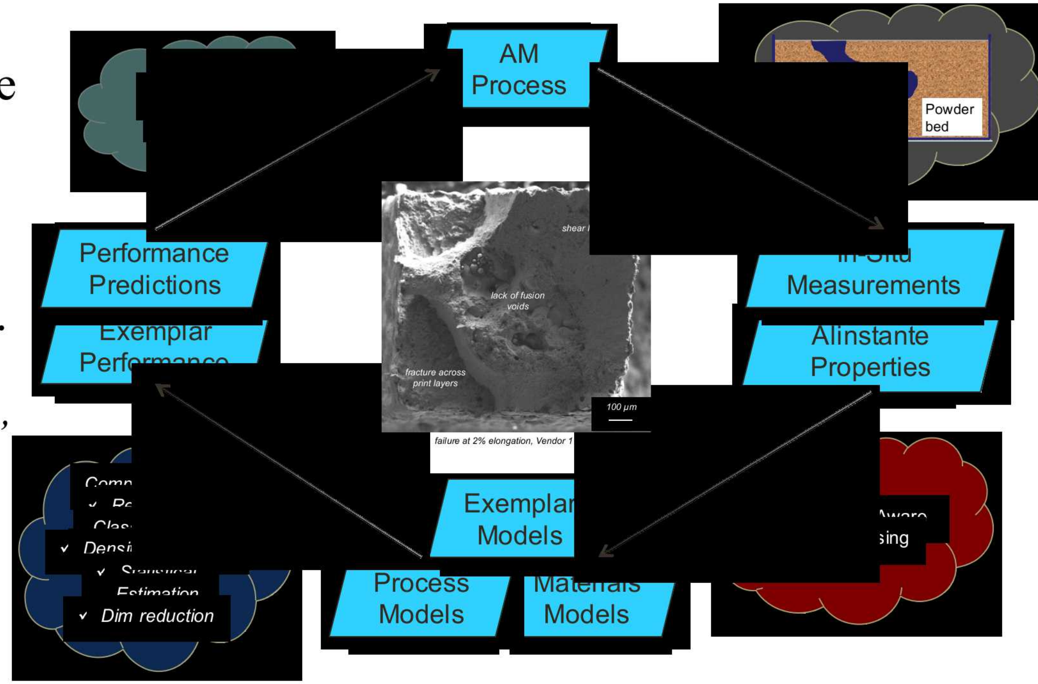
Sandia AM Program (Born Qualified)

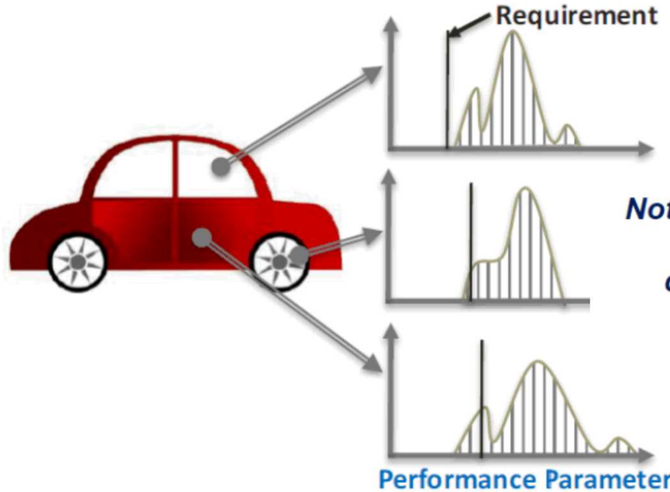
Goal: 15+ year vision to combine promise of **metal additive manufacturing (AM)** with **deep materials & process understanding** to revolutionize design, manufacturing, & qualification paradigms.

- Materials, designs, and ultimately components are "*Born Qualified/Certified*"



Promise of metals AM:

- Disruptive technology that allows simultaneous creation of optimized part geometries and materials-by-design
- Ideal for low volume, high value, high consequence, complex parts
- Inherently flexible and agile
- Ability to create near-net shape parts

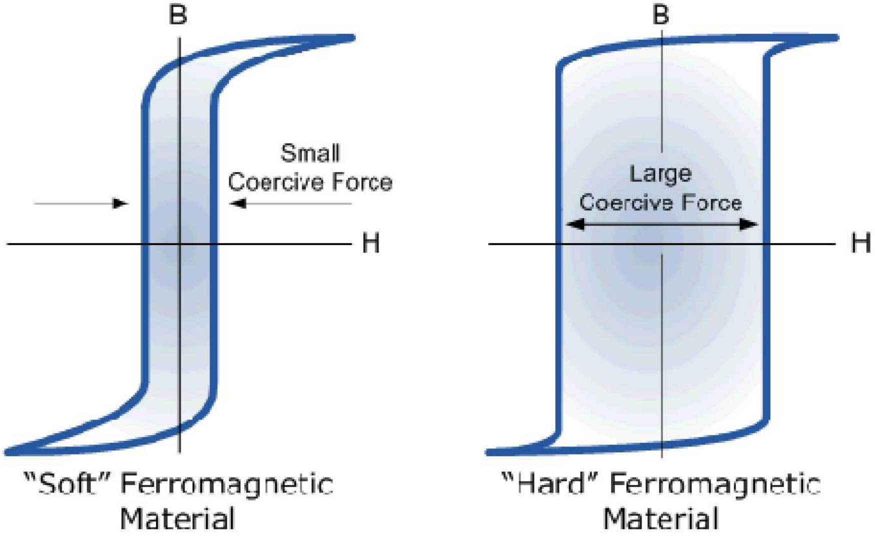


Notional example of margins and uncertainty quantification for every part/material

Attributes of soft ferromagnetic alloys

Excellent soft magnetic properties:

- High saturation induction
- High permeability (High *B* for low *H*)
- Low coercivity (narrow loops)
- Low core loss (narrow loops)
- Electric motors, transformers, switches, etc.



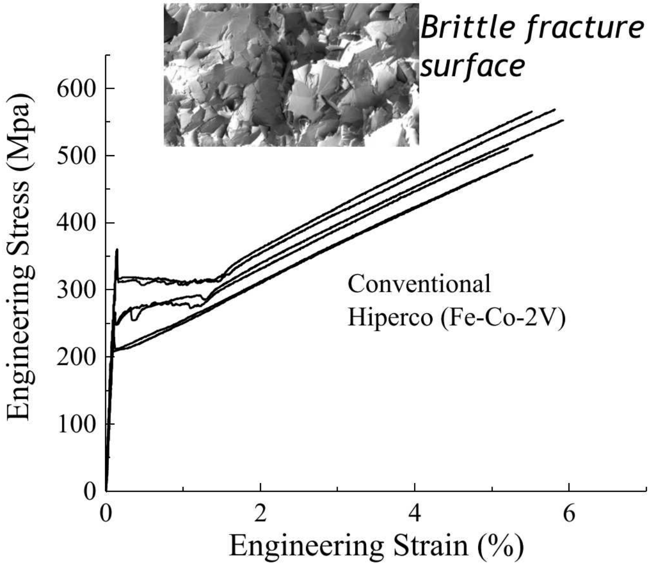
https://www.electronics-tutorials.ws/electromagnetism/magnetic-hysteresis.html

- However -

Poor mechanical properties:

- Result of ordered phase transformations
- Low yield strength
- Low ductility
- High notch sensitivity
- Low fracture toughness
- Low fatigue resistance

High silicon content electrical steel (Fe-6.5wt%Si)



Fe-Co Metallurgy

Equiatomic or near-equiatomic Fe-Co alloys that undergo a γ-FCC $\rightarrow$ α-BCC$\rightarrow$ α_2 (B_2) transformations.

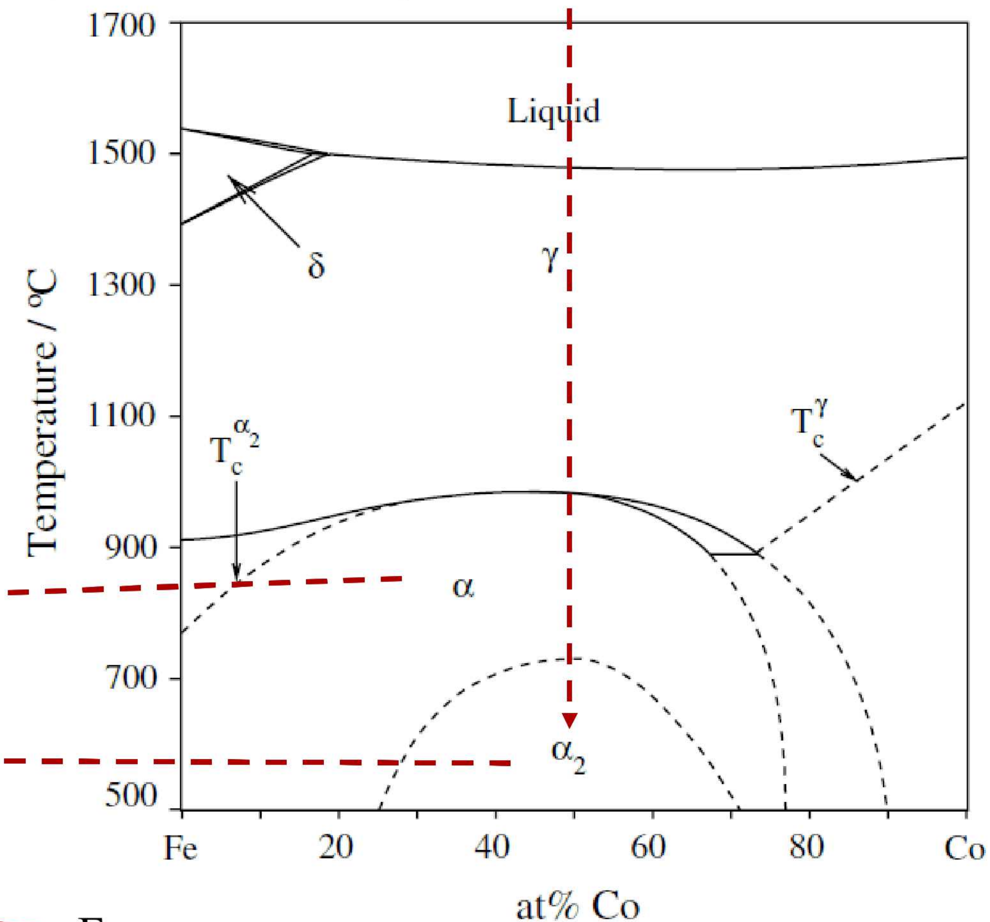
- Poor composition-driven workability, binary Fe-Co difficult to process.
- Commercialized as Fe-Co-2V (Hiperco®) in bar, sheet, strip, coil, and rod forms.

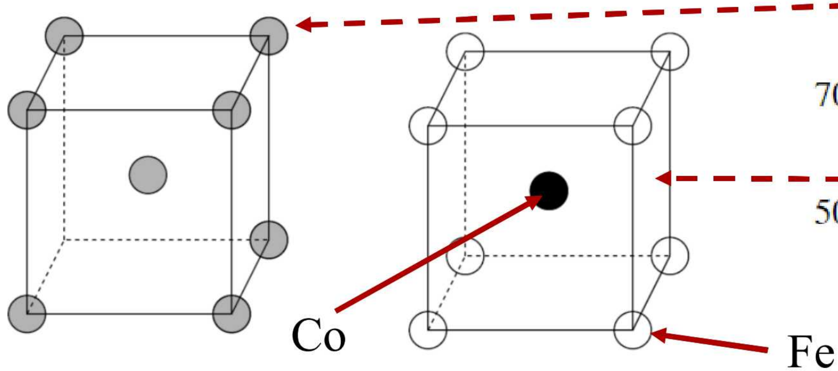
Hiperco® is a tradename of Carpenter Technologies, Reading, PA.

Excellent magnetic properties:

- Highest saturation induction of all engineering soft ferromagnetic alloys
- High curie temperature (> 900 °C)
- High permeability
- Low core loss

Atomic ordering is a big issue!

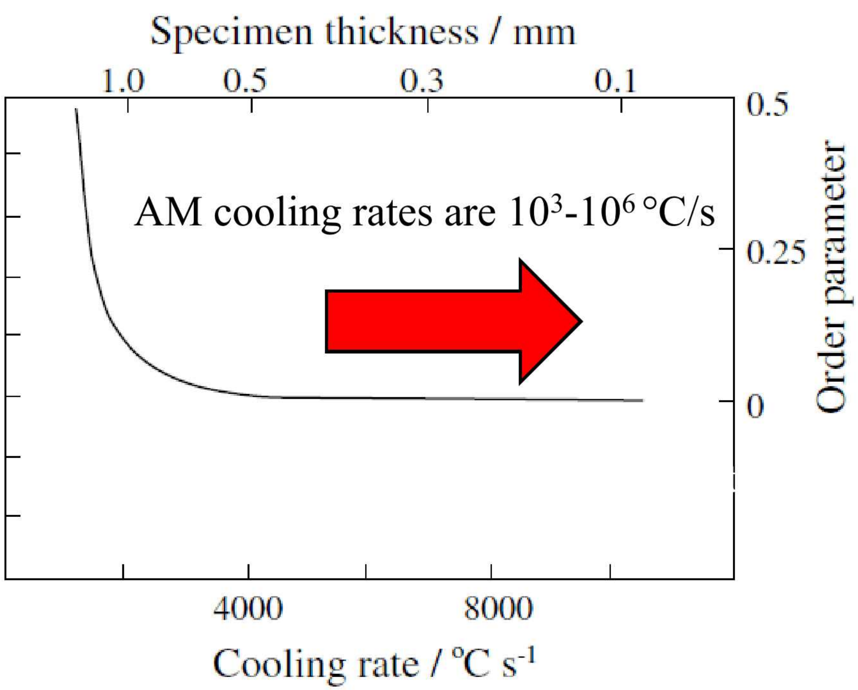




Additive Manufacturing: a processing solution?

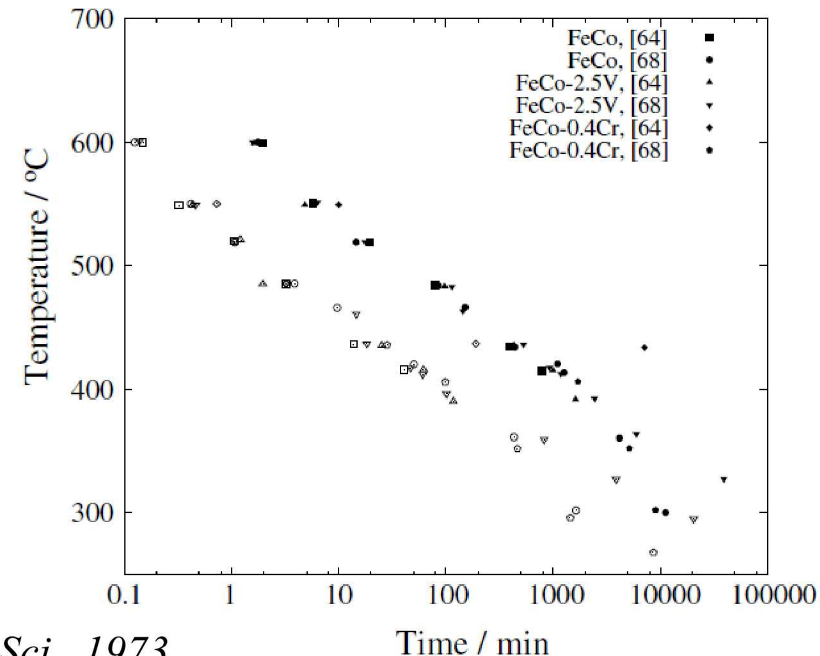
<u>Hypothesis:</u> The unique thermal history of layer-by-layer AM will inhibit ordered phase transformations in a controlled and predictable way.

Through AM, avoid workability issues that arise in conventional thermomechanical processes through a solidification-based processing solution – *enabling ideal compositions*



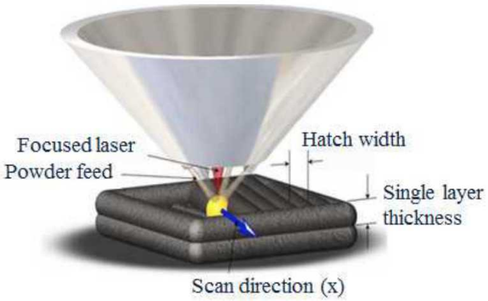
Clegg and Buckley, Met. Sci., 1973

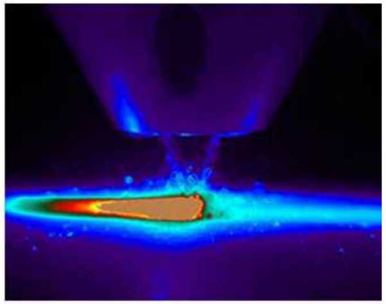
Time at temperature for 50% ordering

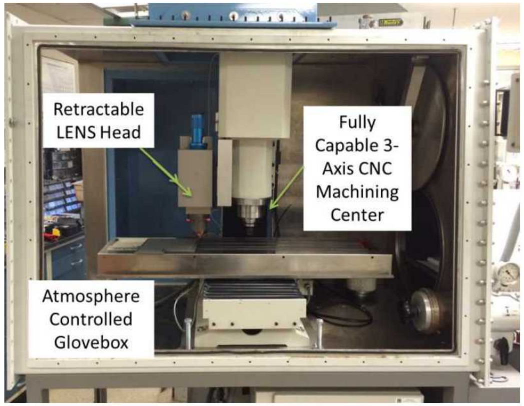


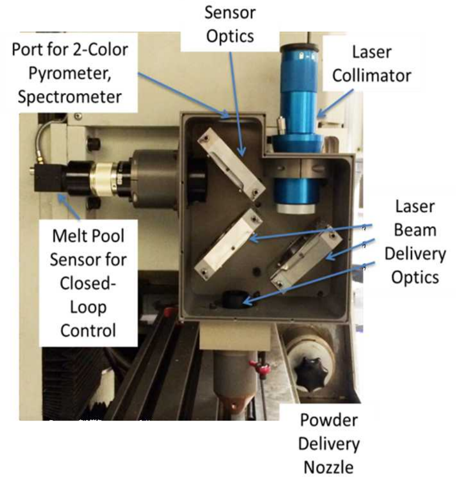
Additive Manufacturing tools

LENS®





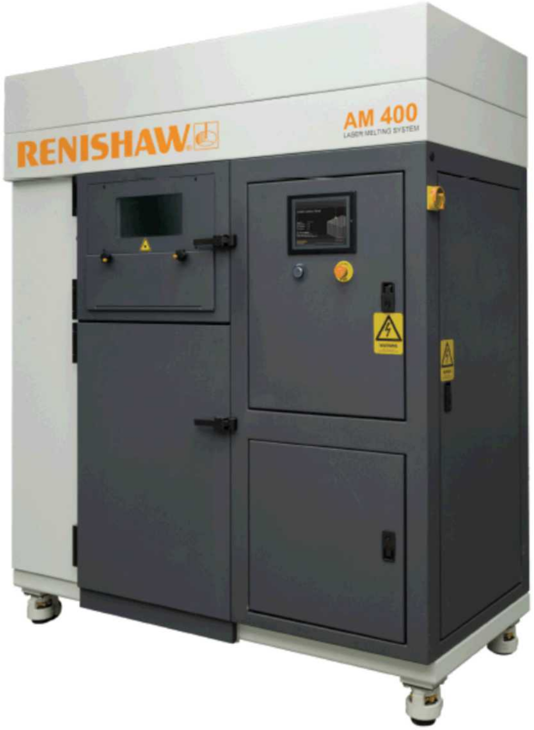




- Open architecture LENS system on Tormach CNC 770 frame.
- YLS-2000 Laser from IPG Photonics with 2 kW output at 1064 nm.
- Control the powder feed through feed wheel and carrier gas (independently) to fluidize the powder.

Selective Laser Melting-

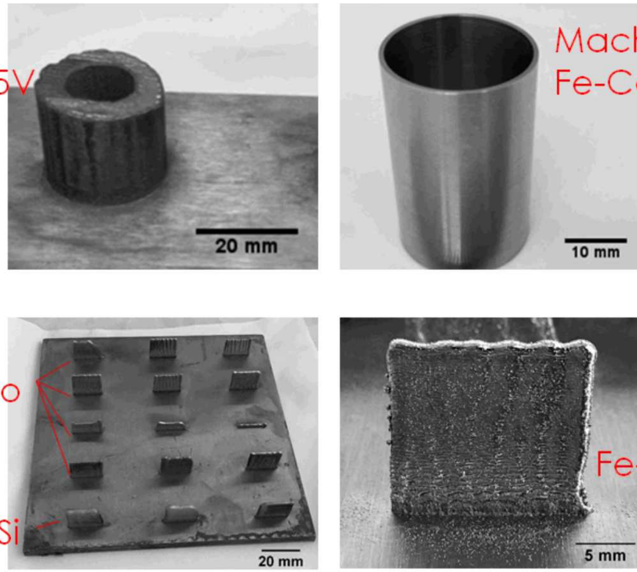
Renishaw AM400 pulsed laser (Lehigh University)



- Commercial SLM system with a 400 W laser.
- 70 micron beam diameter with a 250 mm x 250 mm x 300 mm build volume.
- Enclosed inert atmosphere.

AM processed soft ferromagnetic alloys

LENS®

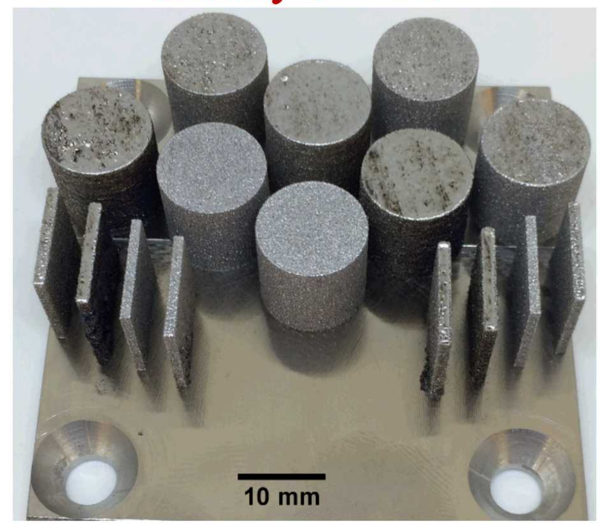


Hiperco

Fe-6wt%Si

Selective Laser Melting

Binary Fe-Co



Hypothesis Validated

- Bulk structures were produced from Fe-Co and Fe-Si alloys *via* LENS and SLM
  - Conventional Hiperco (Fe-Co-1.5V)
  - Binary Fe-Co and Fe-6%Si, too brittle for conventional thermomechanical processes!

Measuring of atomic ordering

Varied laser power, build speed, and time between subsequent layers (interlayer interval time) to:

1. Control the degree of retained heat within LENS thin walls.
2. Impose near order of magnitude variation in predicted cooling rate.

Rosenthal Model: $$\frac{dT}{dt} \cong \frac{\kappa v_b}{\alpha Q}(T_m - T_o)^2$$

Processing Parameters				Output Parameters
Specimen	Laser Power, Q (W)	Build Speed, v_b (mm/s)	Interlayer Interval Time, t_l (s)	Rosenthal Predicted Cooling Rate (K/s)
1	150	3	0.4	3.6 E3
2	150	7	0.4	9.5 E3
3	300	4	0.4	2.7 E3
4	300	8	0.4	5.9 E3
5	450	10	0.4	4.8 E3
6	150	3	11	3.6 E3
7	150	7	11	9.5 E3
8	300	3	11	1.8 E3
9	300	4	11	2.7 E3
10	300	8	11	5.9 E3

Measuring of atomic ordering

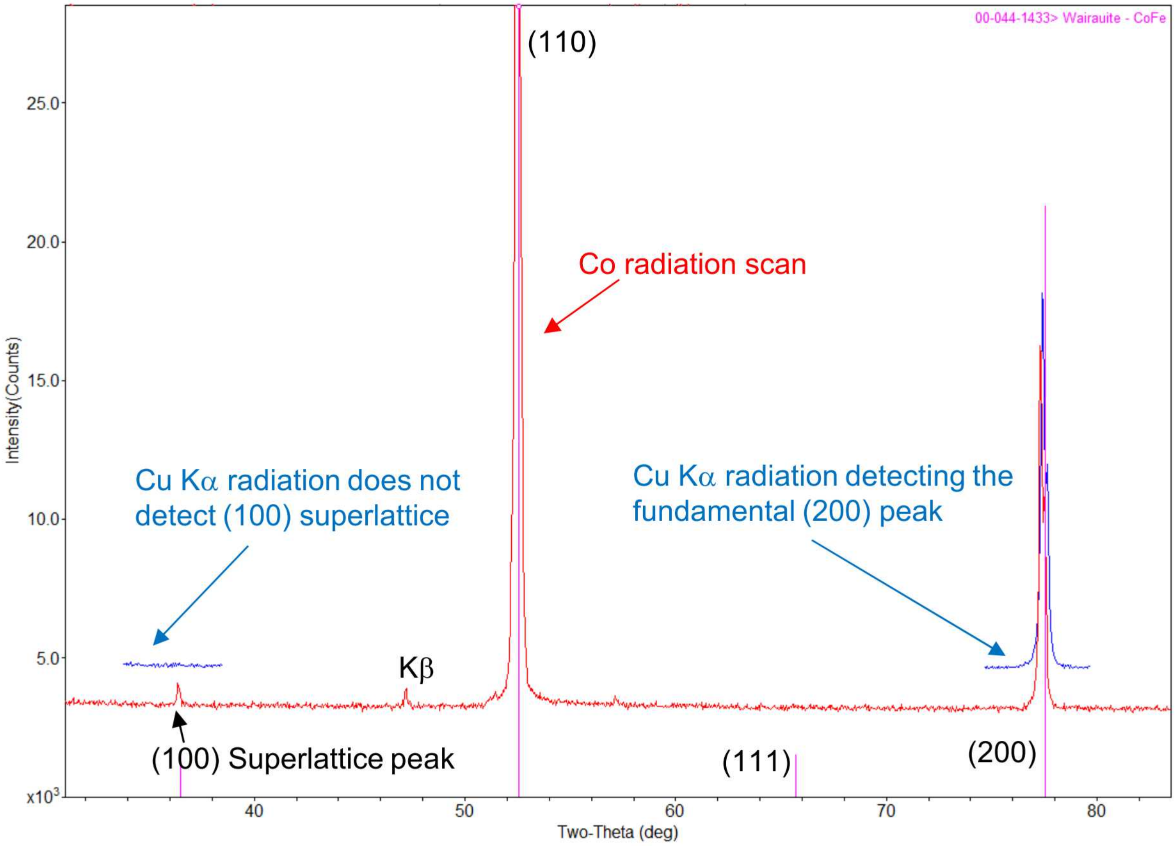
Characterization of ordering:

- Tracked (100) superlattice peak count intensity relative to (200).
- Ratios were normalized to an annealed condition for ***relative*** ordering.
- Used Cobalt X-ray radiation to characterize samples - Cobalt source required to see superlattice!

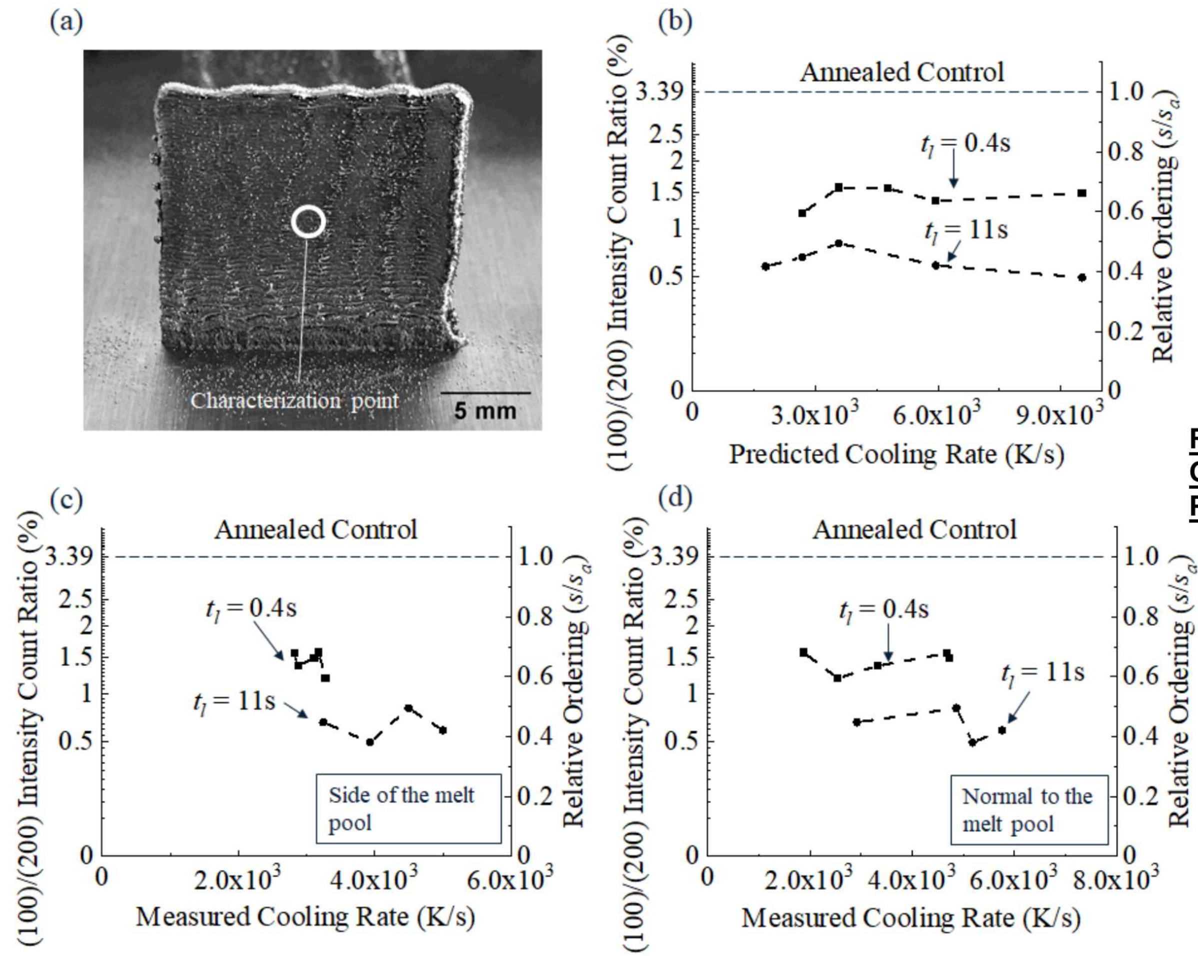
Relative Ordering Parameter

$$\frac{s}{s_a} = \sqrt{\frac{\frac{I_{100}}{I_{200}}}{\left(\frac{I_{100}}{I_{200}}\right)_a}}$$

Connect the atomic ordering parameters with the LENS processing conditions



Reduced ordering in AM-processed material



Relative Ordering Parameter

$$\frac{s}{s_a} = \sqrt{\frac{\frac{I_{100}}{I_{200}}}{\left(\frac{I_{100}}{I_{200}}\right)_a}}$$

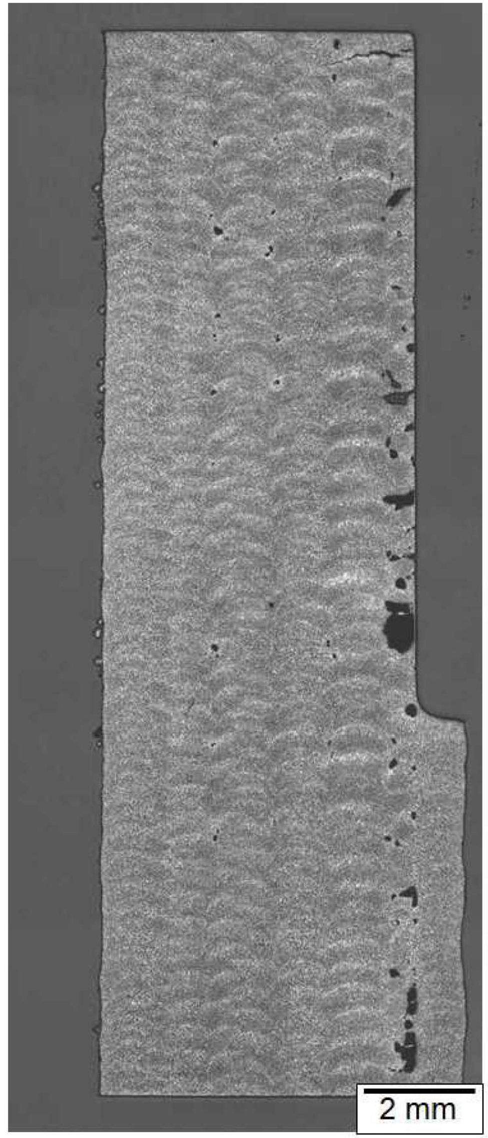
- Hypothesis validated: X-ray measurements suggest AM samples 30-60% less ordered than annealed sample.
- The interlayer interval time had significant effects on ordering. With increased interval time, ordering dropped due to increased cooling rate and sharper thermal gradient.

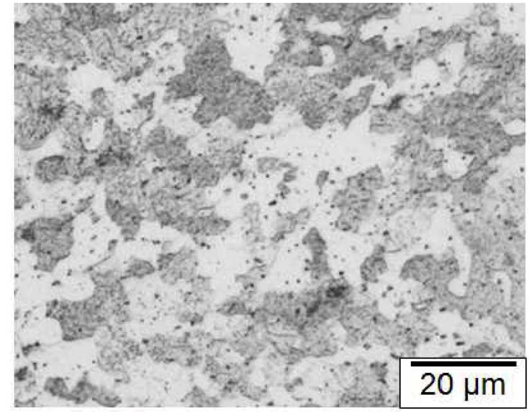
Refined as-built microstructure

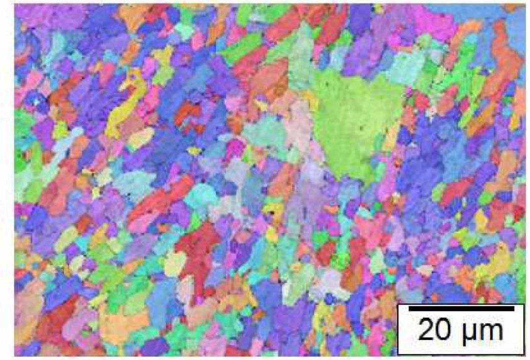
- Fine equiaxed grains throughout the cylinder.
- Crystallographic texture was weak (near-random).

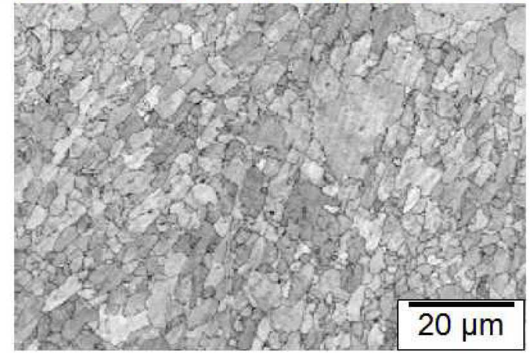
Implications of disordered fine grain Fe-Co alloys?

Build Direction

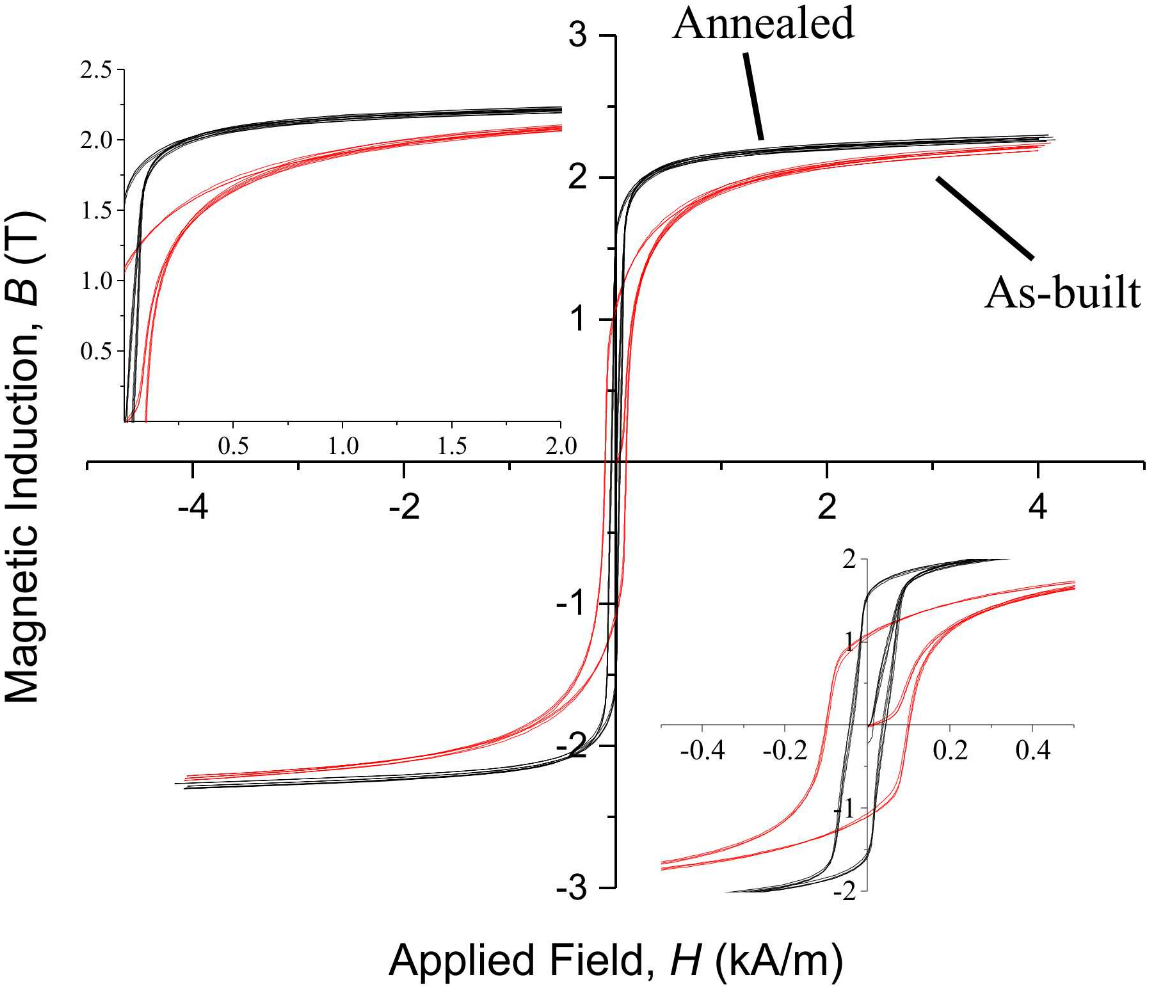








Retained soft ferromagnetic performance



As-built condition exhibited a more ‘sheared’ hysteresis loop – magnetically harder

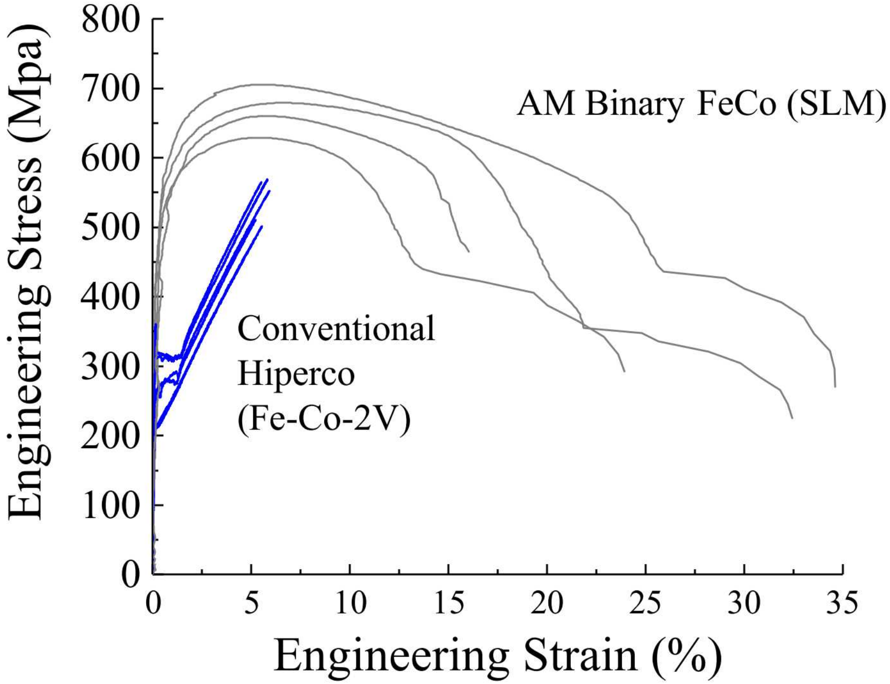
Magnetic properties comparable to conventional Hiperco

Goal is high permeability, low coercivity, and high full-field/saturation induction

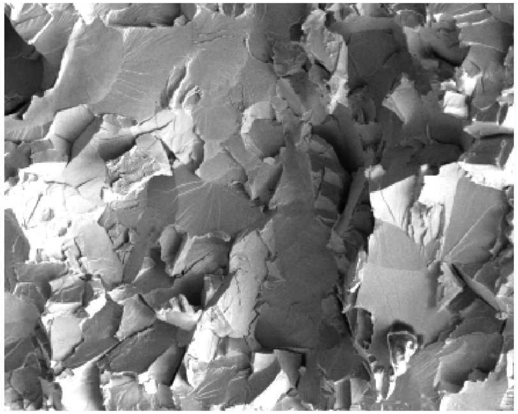
- Annealed LENS condition: higher permeability and lower coercivity
- Values were within extremes of conventionally processed Fe-Co alloys.
- Tuning of post-processing annealing will continue to improve performance.

Condition	Specimen	Full-field Induction, B_{40}, (T)	Coercivity, H_c, (A/m)	Maximum Permeability, μ_m
As-built Fe-Co-1.5V	1	2.23	1013	511
	2	2.24	966	532
	3	2.21	1006	512
Average	--	2.23 +/- 0.5%	995 +/- 2%	518 +/- 2%
Annealed Fe-Co-1.5V	1	2.30	383	1639
	2	2.28	351	1733
	3	2.26	439	1571
	4	2.30	431	1517
Average	--	2.29 +/- 0.7%	401 +/- 9%	1615 +/- 5%
Fe-Co	--	2.4[25]*	150[25]	5000-8000[25]
Fe-Co-2V	--	2.3[25]*	90-200[62] 95-160[63] 393[25]	4000-8000[25]
Fe-Co-2V (as-rolled, 90%)	--	2.2[25]*	2900[25]	--

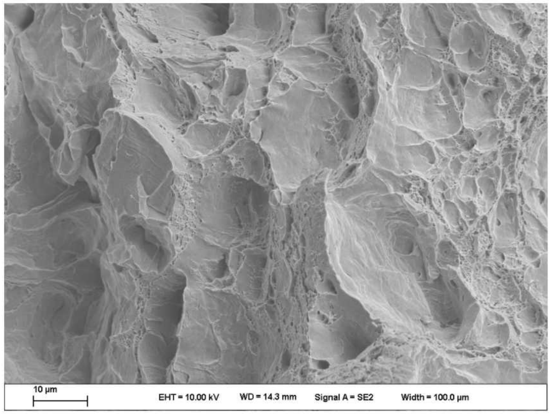
High strength and high ductility Fe-Co



- AM (SLM) processed binary Fe-Co showed high strength and ductility compared to conventional (commercial) Hiperco with extensive necking and ductile fracture.

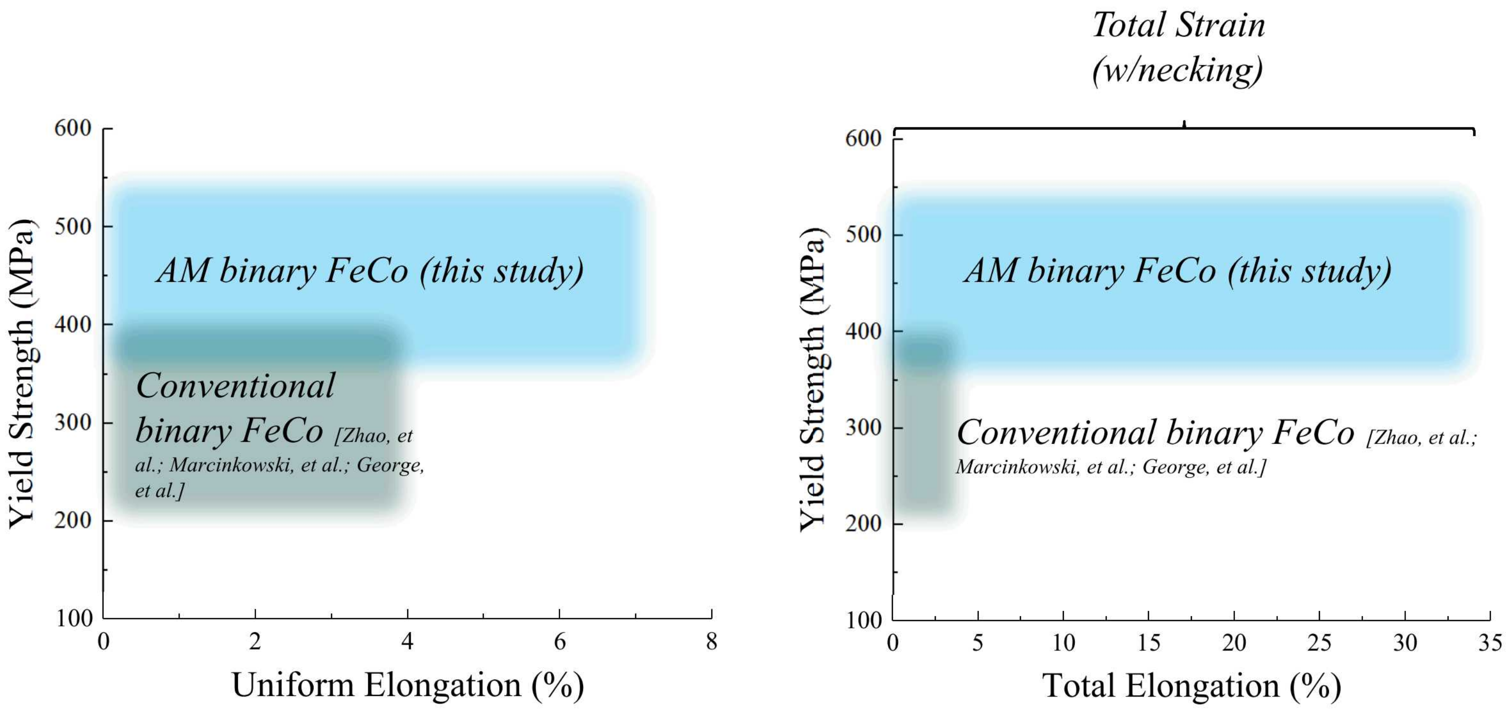


Conventional Hiperco
Brittle fracture



AM binary FeCo
Ductile fracture

Implications for next-generation electromagnetic devices



- AM opens the door for processing of ideal soft ferromagnetic alloy compositions that are impractical with conventional methods.
- Preliminary results suggest revolutionary performance with opportunities to tailor microstructure and magnetic/mechanical properties.

Summary

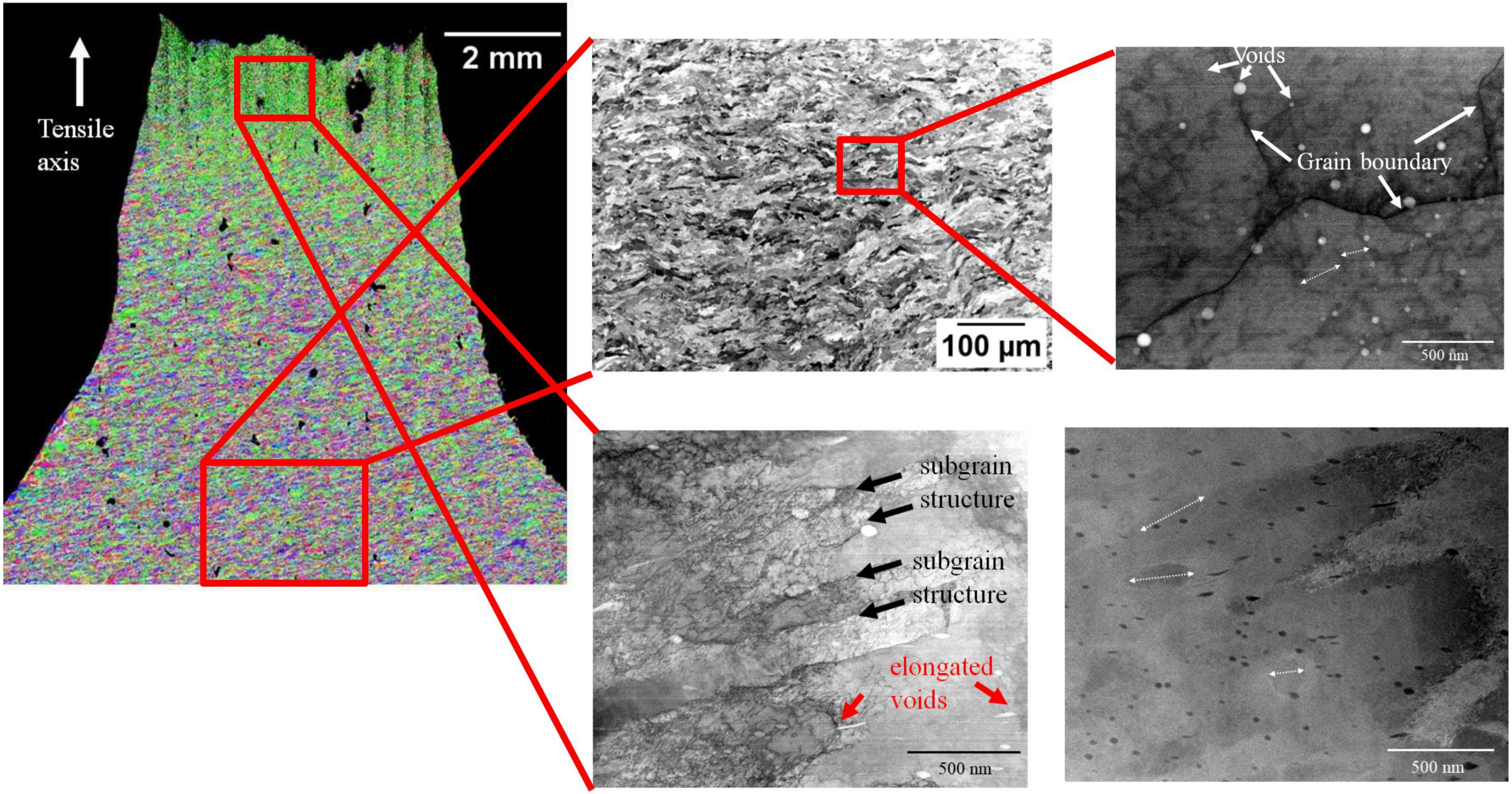
1. AM was shown to enable ideal soft ferromagnetic alloy compositions in bulk that are impractical to produce with conventional thermomechanical processing.

2. Fe-Co alloys were characterized by more ideal microstructures with reduced atomic ordering.

3. AM processed soft ferromagnetic alloys retained a soft magnetic performance with high saturation induction, which could then be tuned via annealing.

4. Mechanical properties of the soft magnetic alloys were superior to available data on the binary Fe-Co alloy.

Is an AM multiscale microstructure responsible?



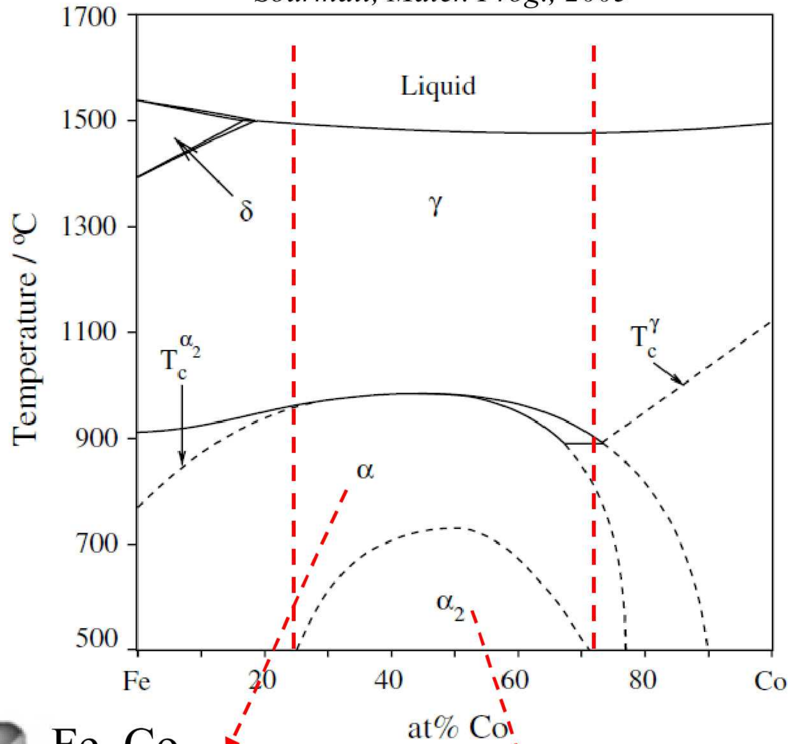
Potential mechanism: multiscale microstructural features (nm - µm) with atomic disorder lead to increased dislocation pinning (for strength) and dislocation accommodation for greater ductility/work hardening[1-3].

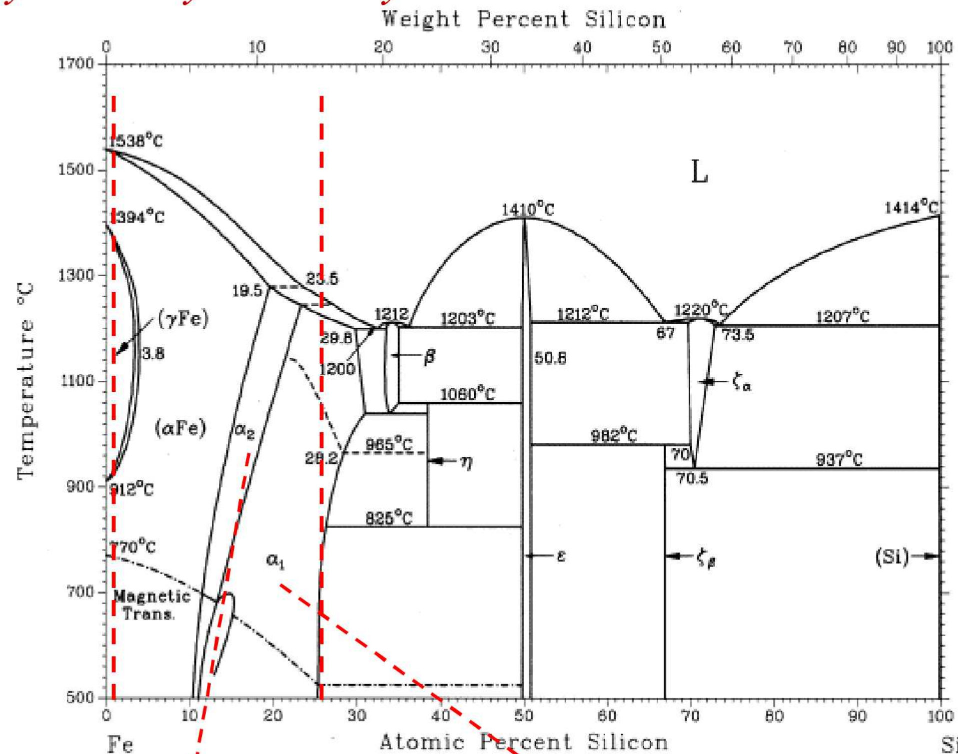
1. *K. Lu, et al., Science, 2009*
2. *Y. M. Wang., et al., Nat. Mater., 2018*
3. *J. E. Flinn, et al., Metall Trans A., 1992*

Why? Physical metallurgy tells us

- Phase transformations from α-BCC→ α_2 (B2) or α_1 (DO_3) lead to low ductility
- Conventional mitigation tactic: *modify the alloy chemistry*

Sourmail, Mater. Prog., 2005





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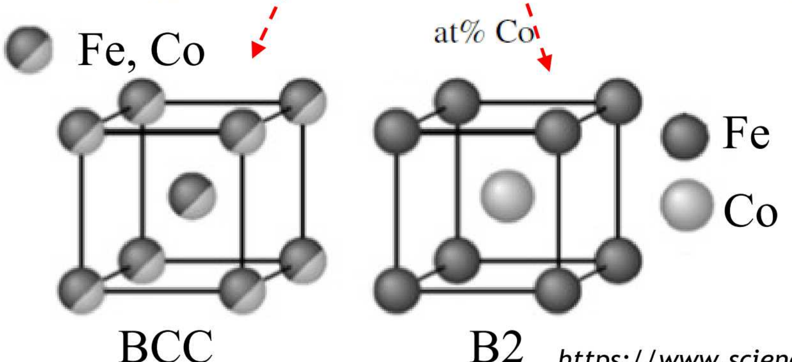

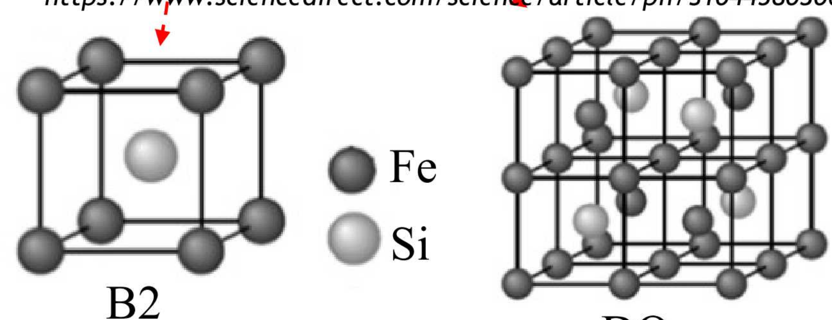

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