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Novel Processes and Materials Solutions for Metal Additive Manufacturing

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PRESENTED BY

Presenter: Andrew Kustas

Team: Nicolas Argibay, Michael Chandross, Shaun Whetten, David Keicher, Joseph Michael, Donald Susan, Kyle Johnson, Mark Rodriguez, Daryl Dagel, Mark Wilson, Ping Lu, R. Allen Roach

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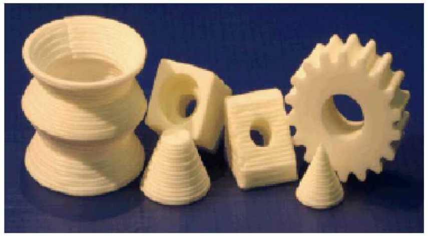
Sandia Additive Manufacturing Overview

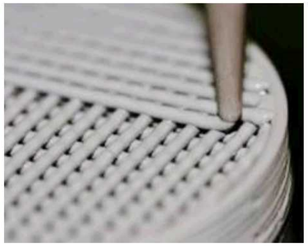
Selective Laser Melting

ProX 200

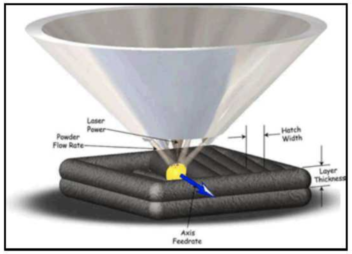
ProX 300

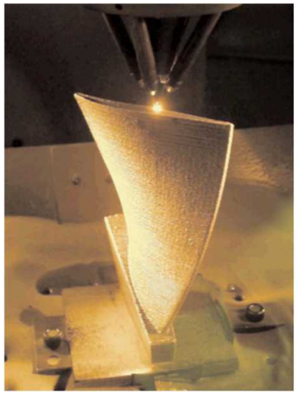
Ceramic AM

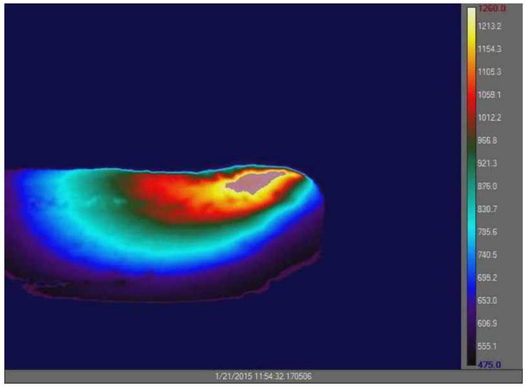




LENS®

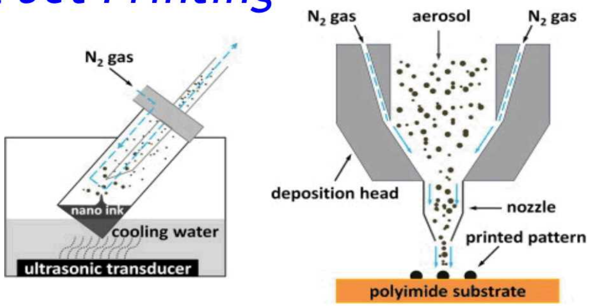




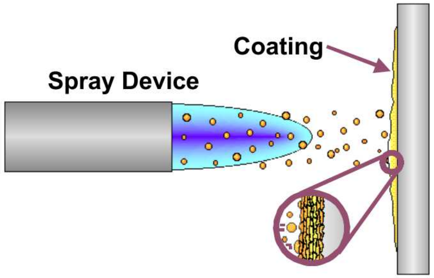


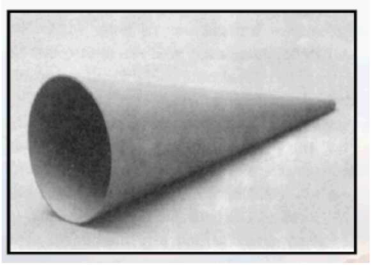
thermal history during bi-directional metal deposition

Aerosol Jet Printing



Thermal Spray/Cold Spray





Outline

Model materials: Soft ferromagnetic alloys and High Entropy alloys

Soft Ferromagnetic Alloys:

- Exceptional functional properties but poor mechanical properties
- Conventional mitigation tactic: *modify the alloy chemistry*
    - Ternary additives to binary Fe-Co (e.g., Fe-Co-X)
    - Low Si content in Fe-Si alloys (e.g., Fe-4wt%Si vs. *ideal* Fe-6.5wt%Si)
    - Functional performance is limited!

High Entropy alloys:

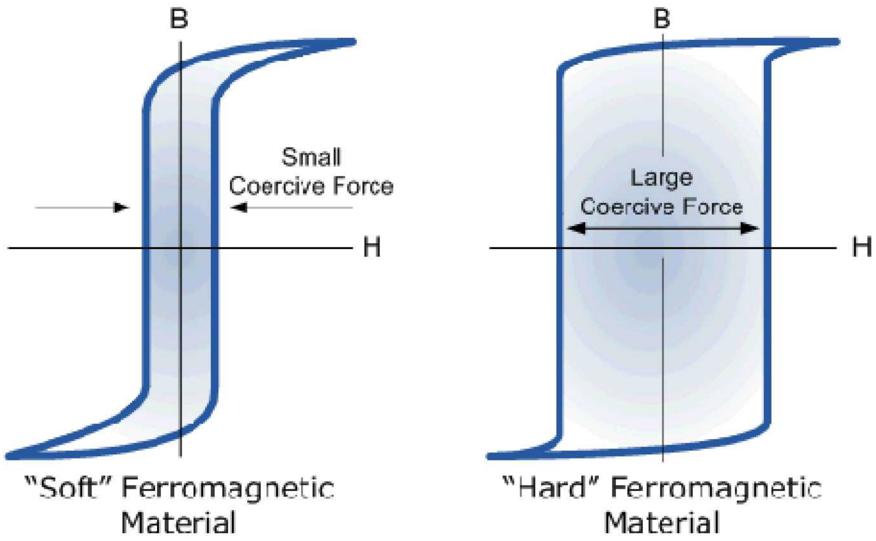
- Unusual microstructure and properties → attractive candidates for layer-by-layer AM processes
- Materials-centric solution to enabling structural AM applications?

Theme: Utilize AM processes to enable improved material performance OR use advanced materials to enable the promise of AM for structural applications

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.



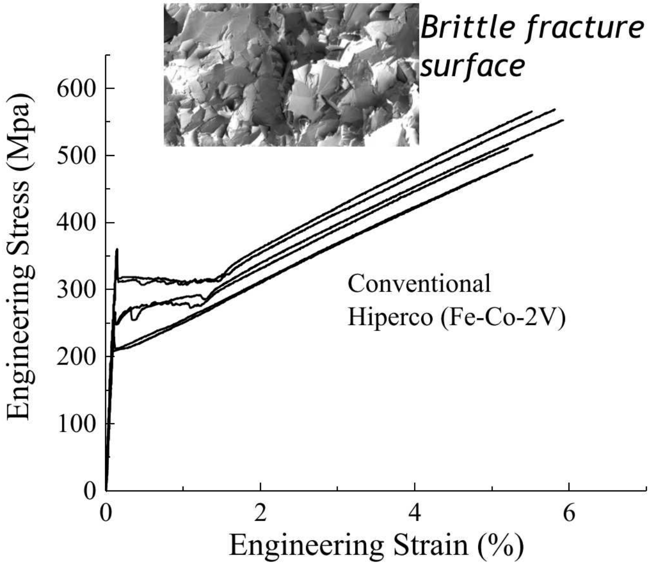
https://www.electronics-tutorials.ws/electromagnetism/magnetic-hysteresis.html

- However -

Poor mechanical properties:

- Result of ordered α_2 (B2) and α_1 (DO_3) phase transformations
- Low yield strength
- Low ductility
- High notch sensitivity
- Low fracture toughness
- Low fatigue resistance

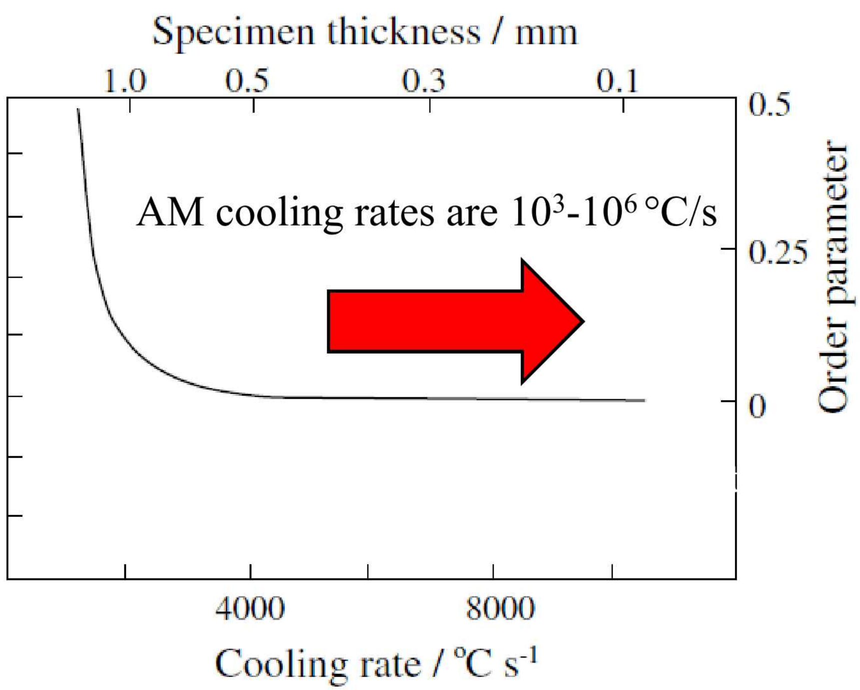
High silicon content electrical steel (Fe-6.5wt%Si)



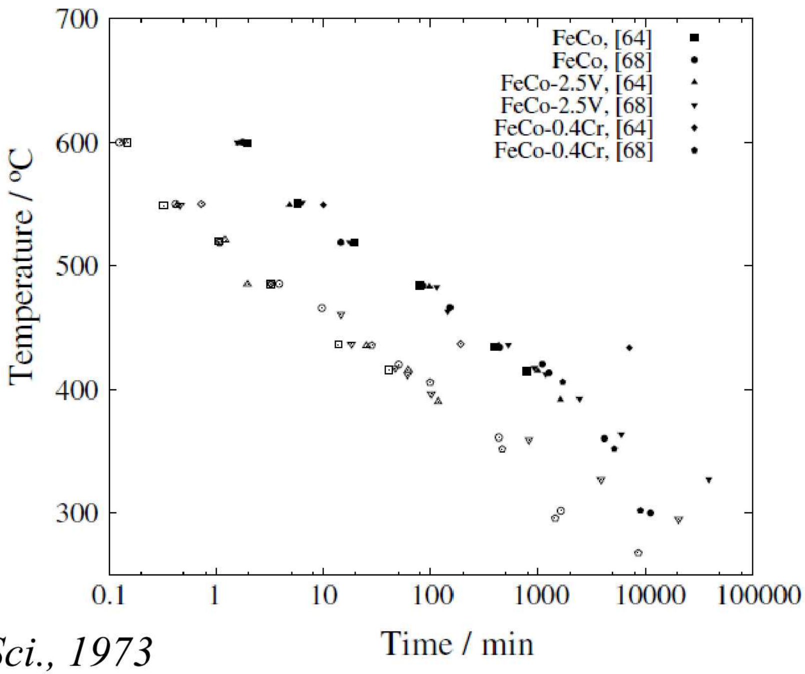
Additive Manufacturing: a processing solution?

<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*



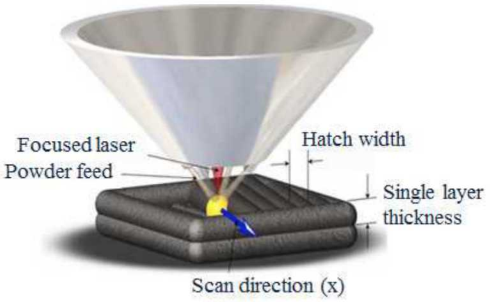
Time at temperature for 50% ordering

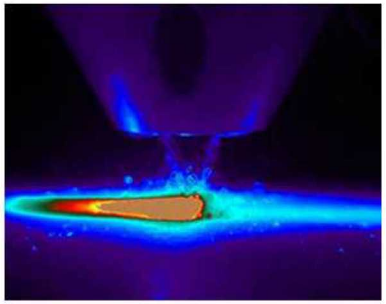


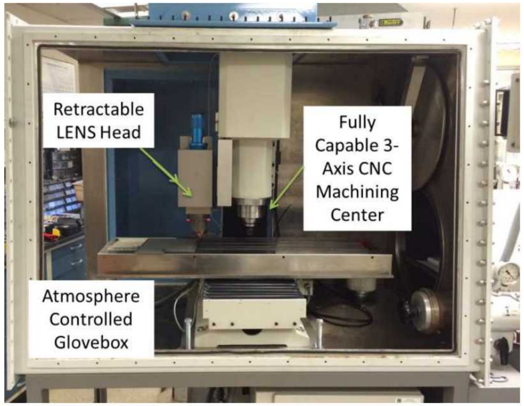
Clegg and Buckley, Met. Sci., 1973

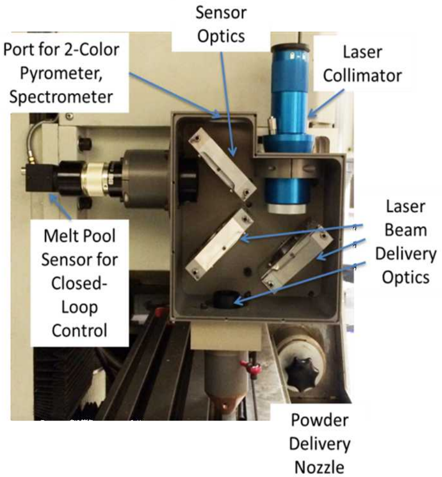
Additive Manufacturing tools

LENS®





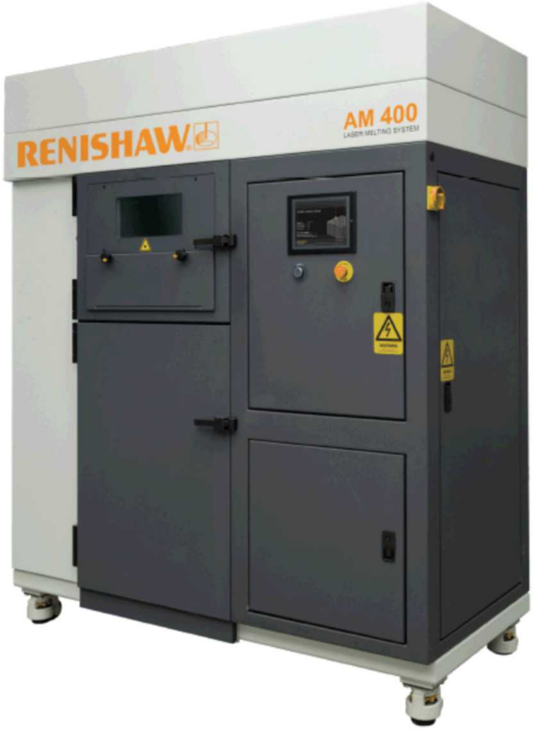




- Open architecture LENS system on Tormach CNC 770 frame.
- YLS-2000 Laser from IPG Photonics with 2 kW output at 1064 nm.
- Control the powder feed through feed wheel and carrier gas (independently) to fluidize the powder.

Selective Laser Melting-

Renishaw AM400 pulsed laser (Lehigh University)

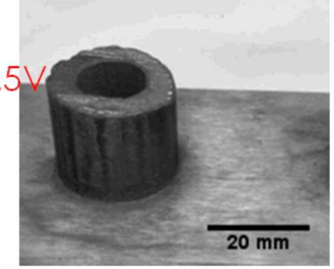


- Commercial SLM system with a 400 W laser.
- 70 micron beam diameter with a 250 mm x 250 mm x 300 mm build volume.
- Enclosed inert atmosphere.

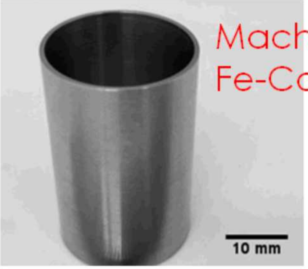
AM processed soft ferromagnetic alloys

LENS®

As-built
Fe-Co-1.5V

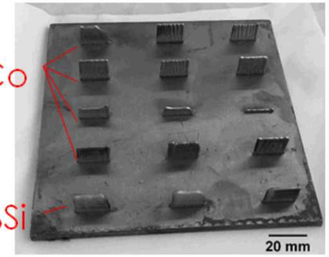


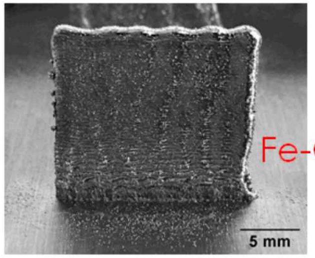
Machined
Fe-Co-1.5V



Fe-Co

Fe-6wt%Si

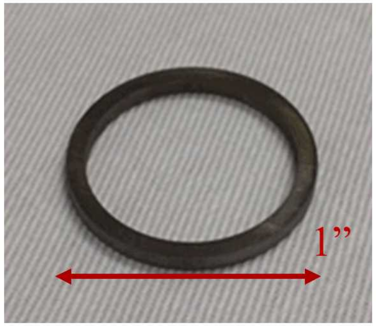




Fe-Co

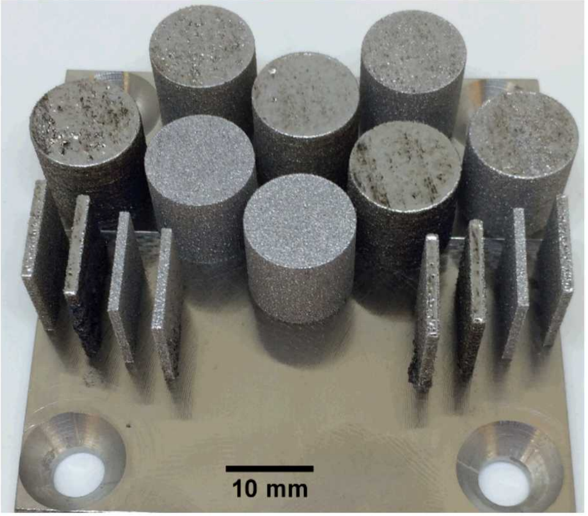
Hiperco

Fe-6wt%Si



Selective Laser Melting

Binary Fe-Co



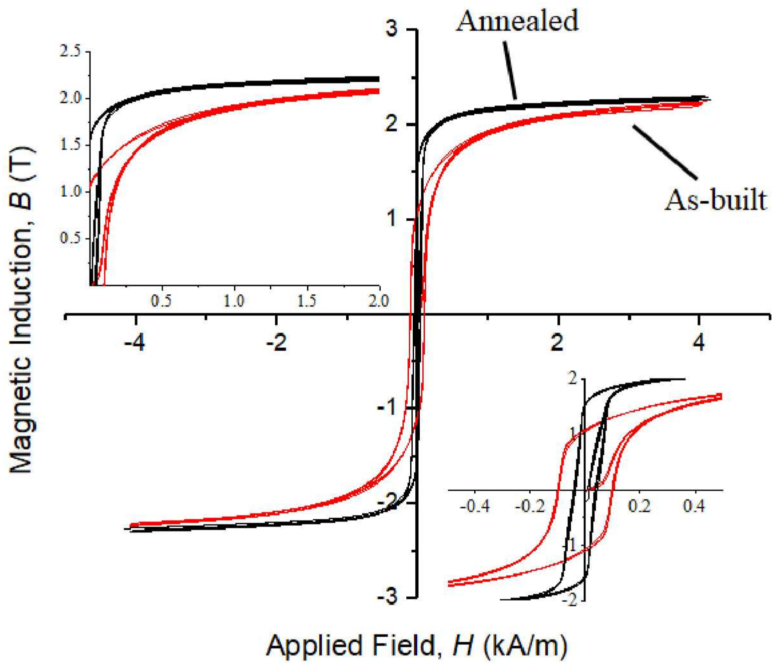
Hypothesis Validated

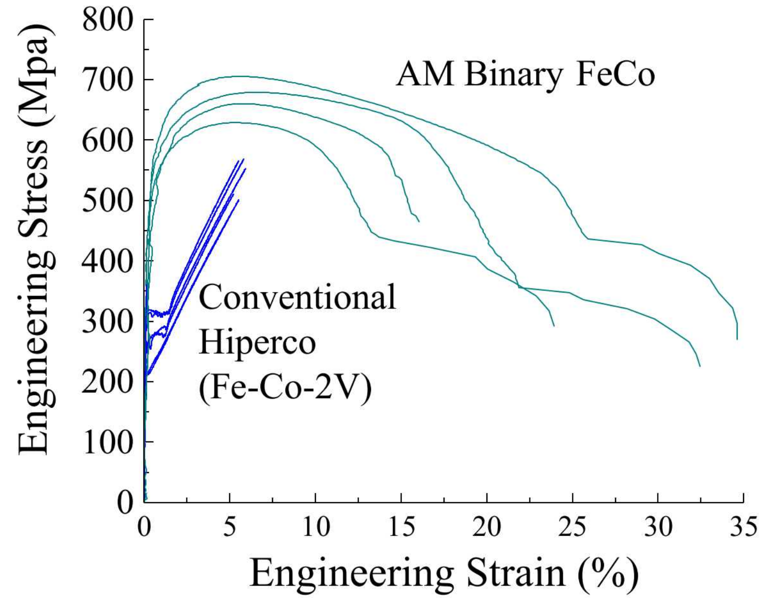
- Bulk structures were produced from Fe-Co and Fe-Si alloys *via* LENS and SLM
  - Conventional Hiperco (Fe-Co-1.5V)
  - Binary Fe-Co and Fe-6%Si, too brittle for conventional thermomechanical processes!

- Fe-Co alloy structures were *40-70% ordered* relative to annealed condition and were controlled by AM processing parameters.

Preliminary properties are promising

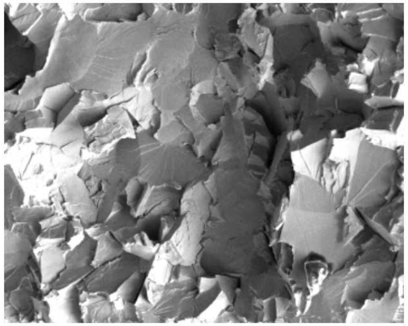
AM Hiperco (Fe-Co-1.5V)



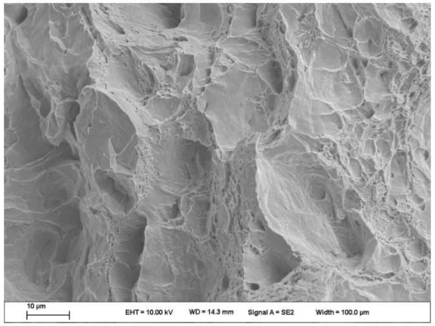


Fe-Co alloys

- Soft ferromagnetic performance in as-built condition.
- AM processed binary Fe-Co showed high strength and ductility compared to conventional (commercial) Hiperco with extensive necking and ductile fracture.

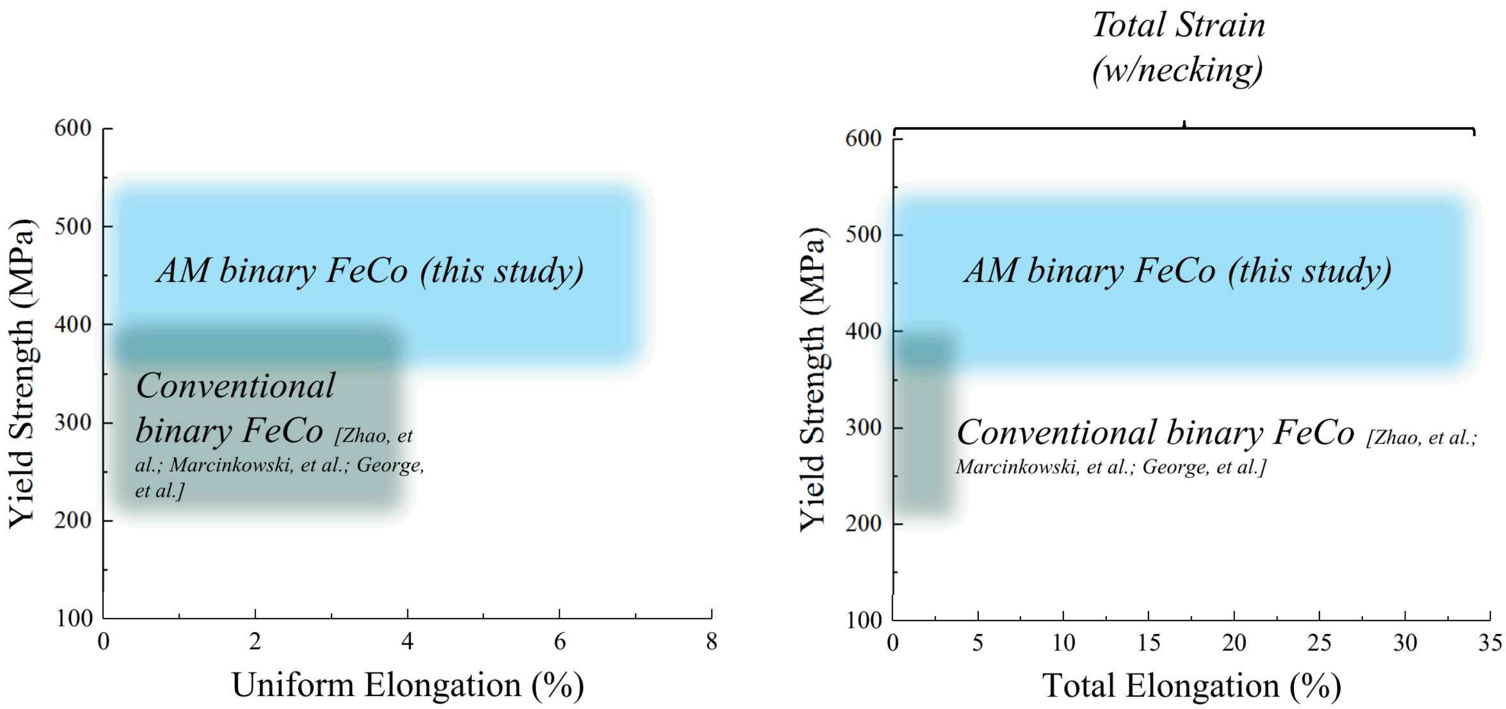


Conventional Hiperco
Brittle fracture



AM binary FeCo
Ductile fracture

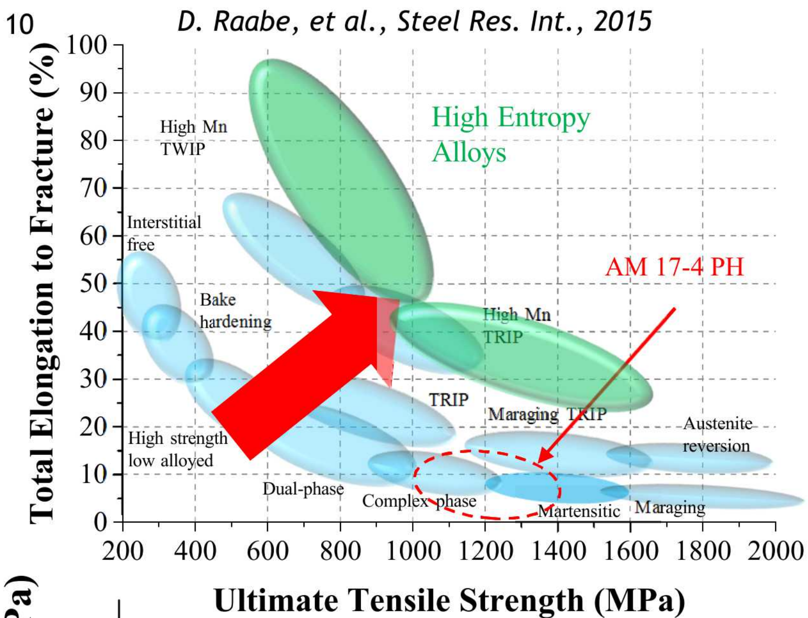
Implications for next-generation electromagnetic devices

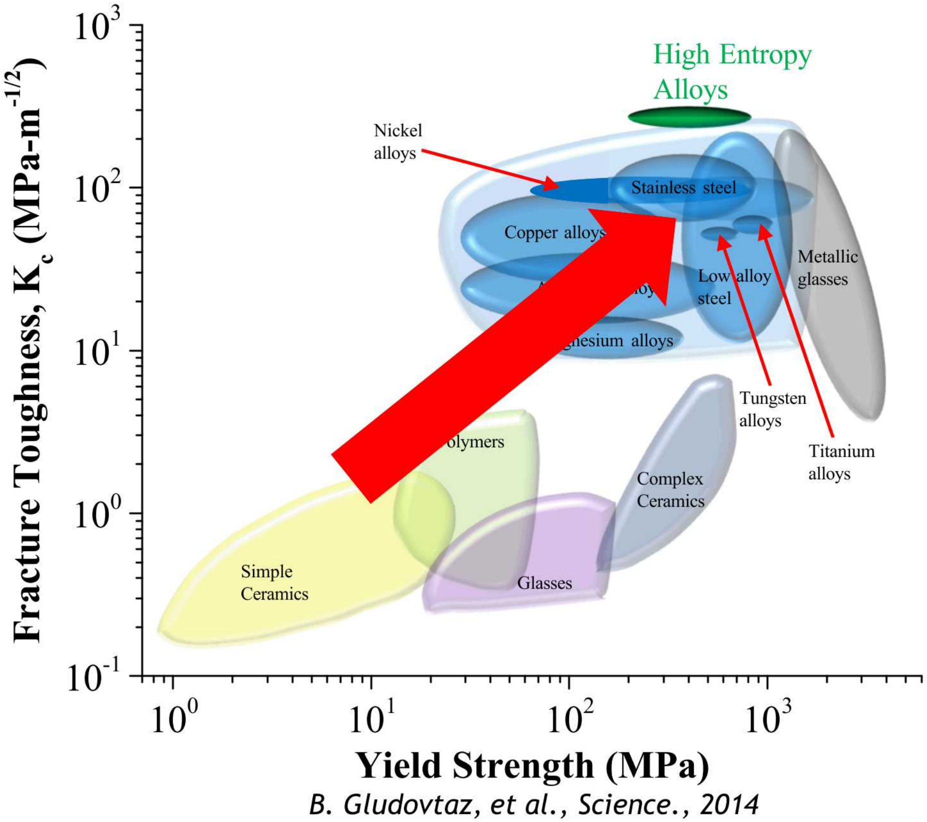


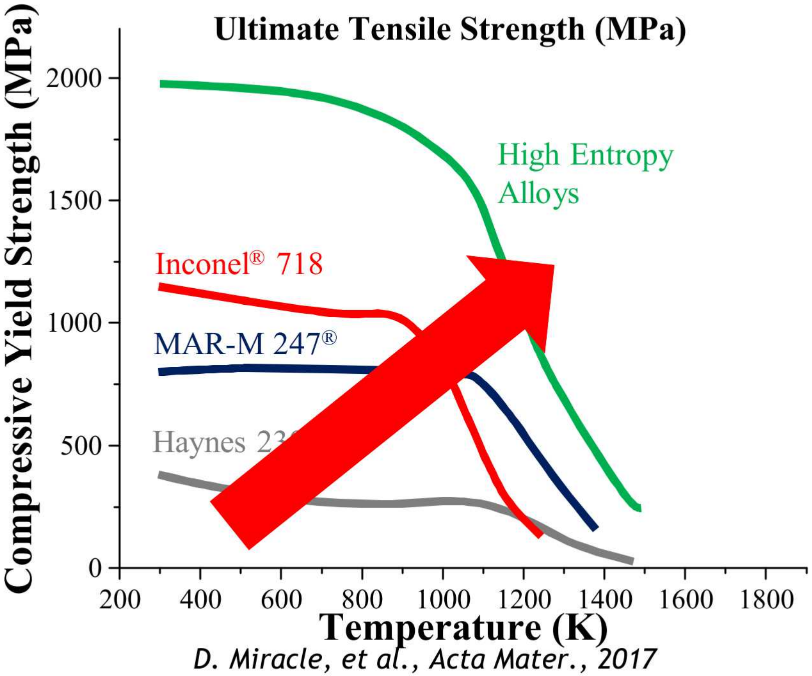
- AM opens the door for processing of ideal soft ferromagnetic alloy compositions that are impractical with conventional methods.

- Preliminary results suggest revolutionary performance with opportunities to tailor microstructure and magnetic/mechanical properties.

Attributes of High Entropy Alloys







HEAs have properties exceeding most conventional alloys, suggesting improved resistance to failures associated with defects in AM parts.

Goal: demonstrate these alloys as a materials-based solution to ***achieve the promise of metals AM, i.e. insertion into structural applications***.

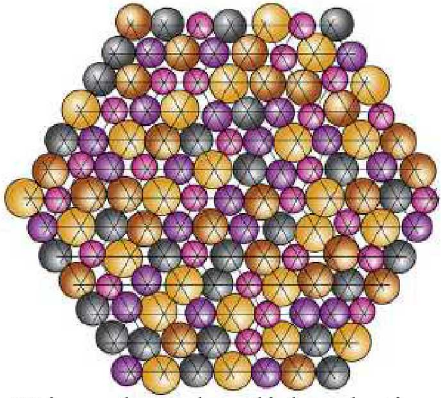
What are HEAs?

High Entropy Alloys: primarily solid solutions* containing 5+ alloying constituents, where the solutions have high configurational entropy ($\Delta S_{conf} > 1.4R$, approx. 12 J/mol-K) .

High configurational entropy is believed to thermodynamically suppresses phase separation, a primary route for degradation of mechanical properties.

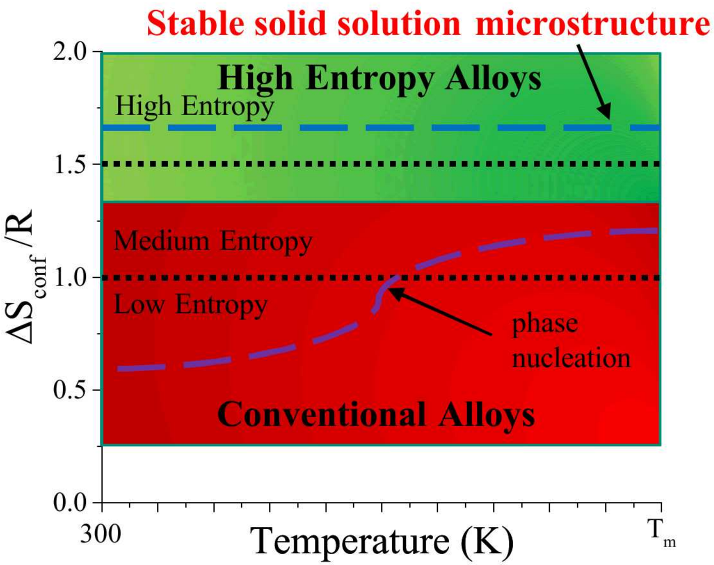
Competition between Gibbs energy for solid solution and intermetallic formation

$$\Delta G^{SS} < \Delta G^{IM} \quad \rightarrow \quad \Delta S^{SS} > \frac{\Delta H^{IM} - \Delta H^{SS}}{T}$$



Disordered solid solution

D. Miracle et al., Acta Mat., 2017



D. Miracle et al., Entropy, 2014

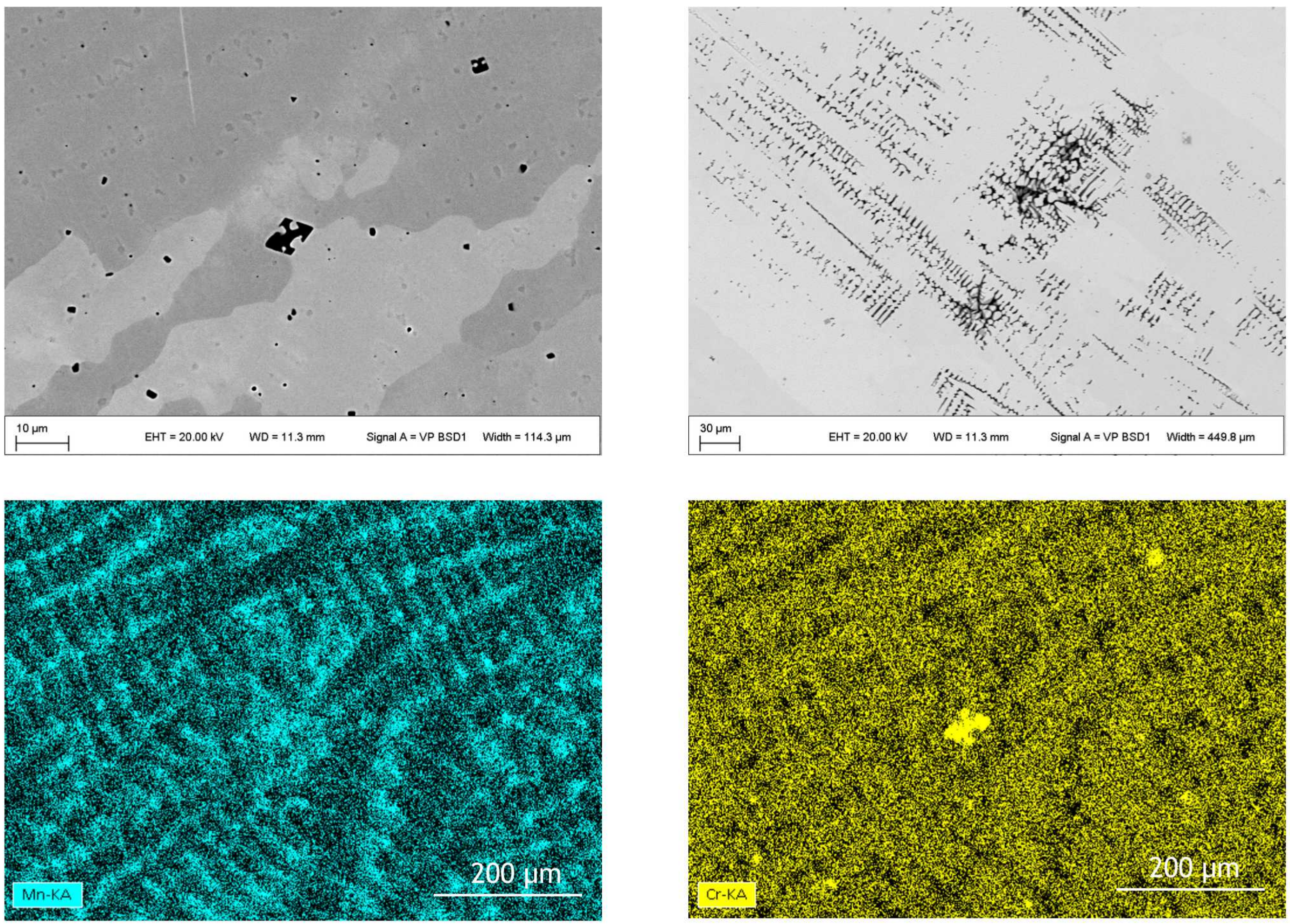
Thermodynamically stable and ***predictable*** solid solution microstructure, independent of processing!

Ideal for layer-by-layer melting/re-melting of AM…

This hypothesis remains controversial and highly-debated, and why the proposed work has high scientific impact potential.

Conventionally cast HEAs

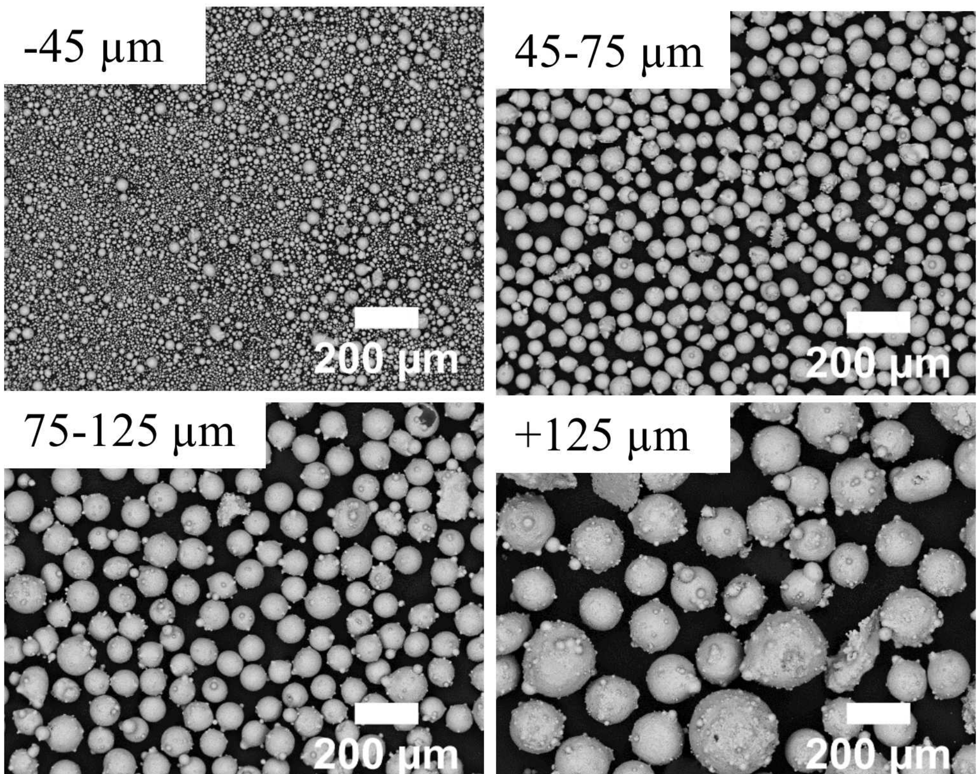
- Challenge with conventional processing (i.e., casting): Difficult to ensure sufficient mixing of elements to develop homogeneous microstructures – microsegregation.
- Example alloy: CoCrFeMnNi HEA – segregation of Mn and Cr and porosity.

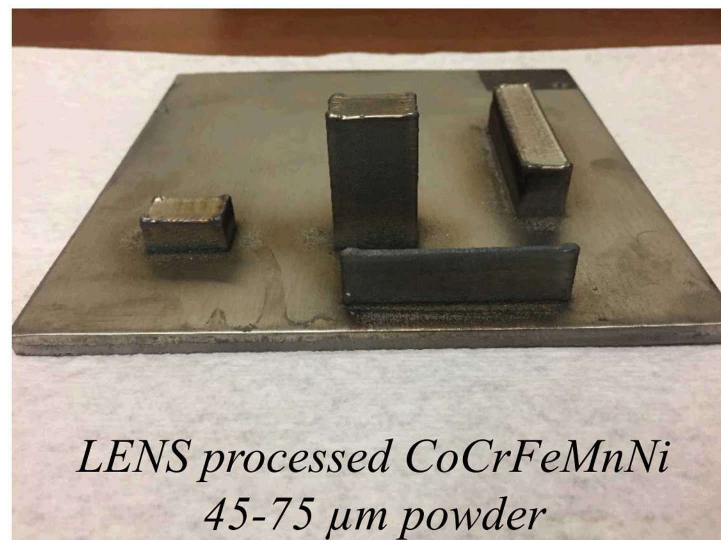


Additive Manufacturing of CoCrFeMnNi HEA

Pre-alloyed CoCrFeMnNi powder

Co	21.40%
Cr	18.38%
Fe	19.87%
Mn	19.23%
Ni	21.09%

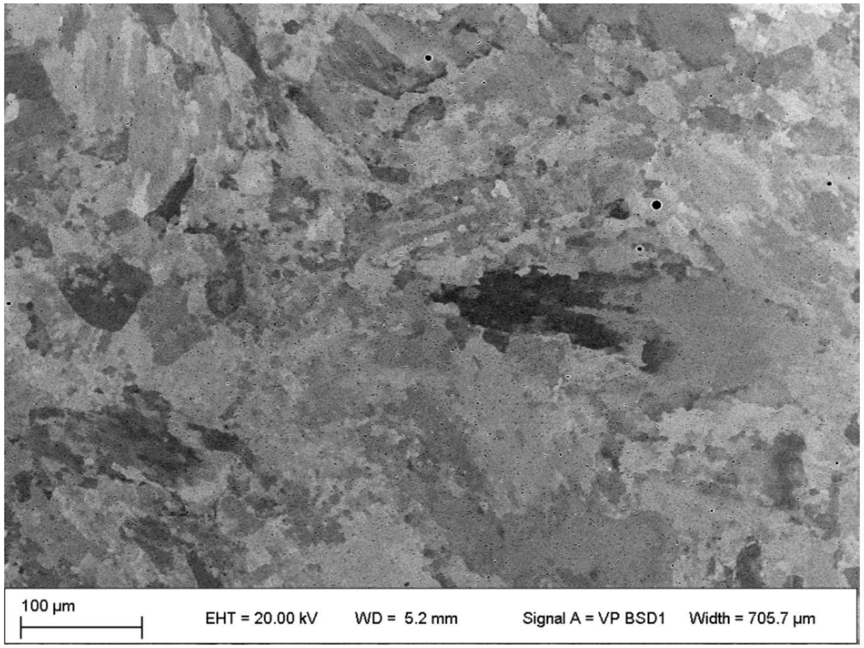


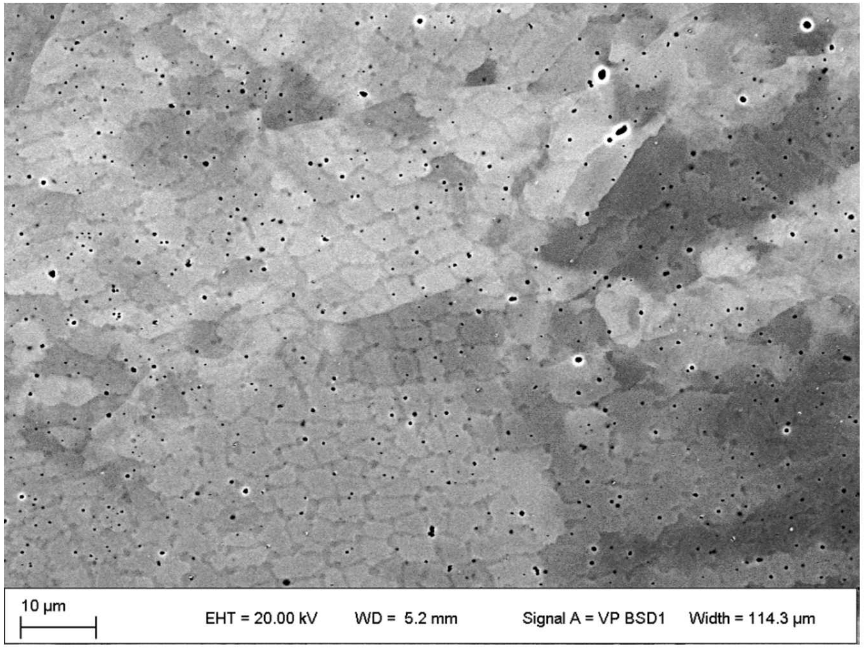


LENS processed CoCrFeMnNi 45-75 µm powder

AM – enabling refined homogeneous microstructures

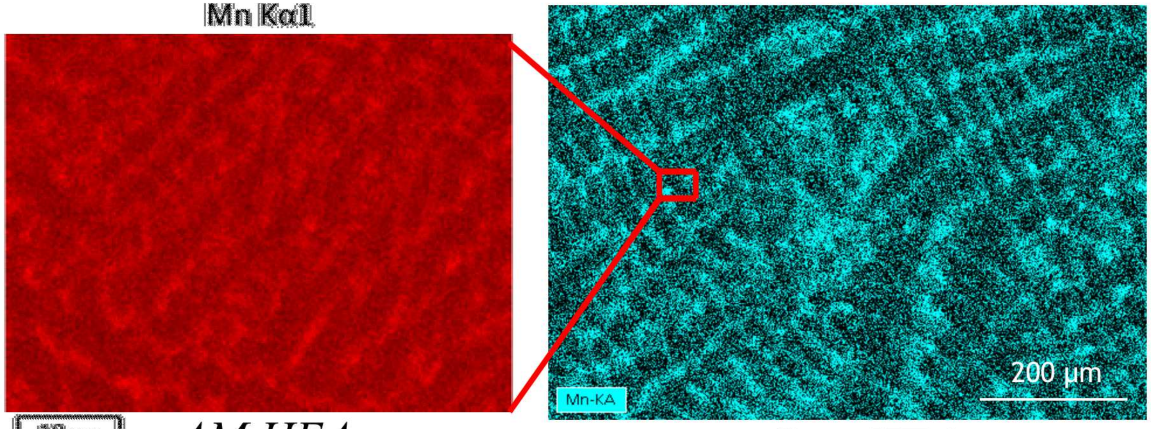
Single phase FCC solid solution





Predominately a fine cellular solidification substructure with significantly refined spatial partitioning of constituents.

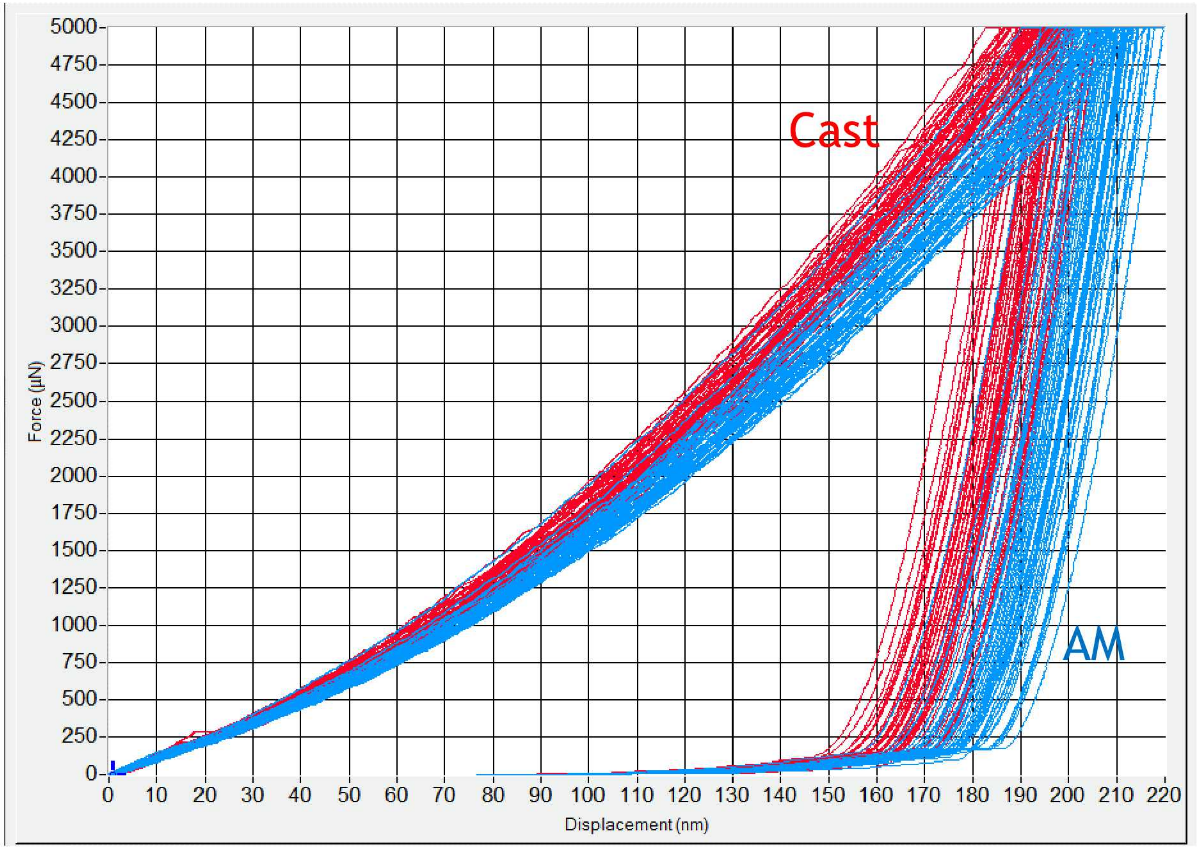
Small voids and oxides.

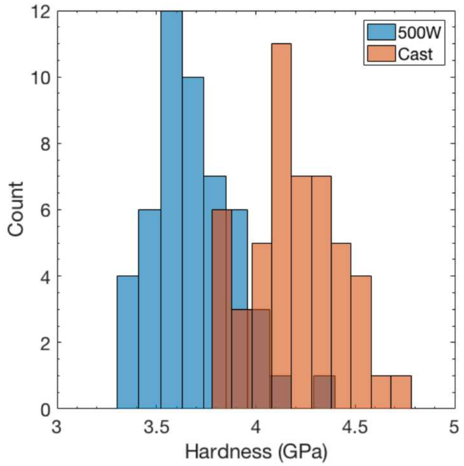


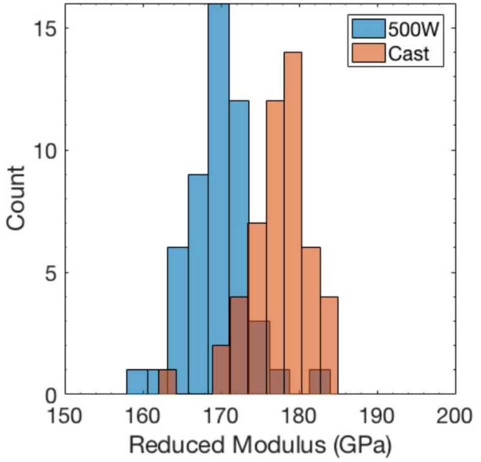
AM HEA

Cast HEA

Preliminary mechanical properties are robust in AM solidification





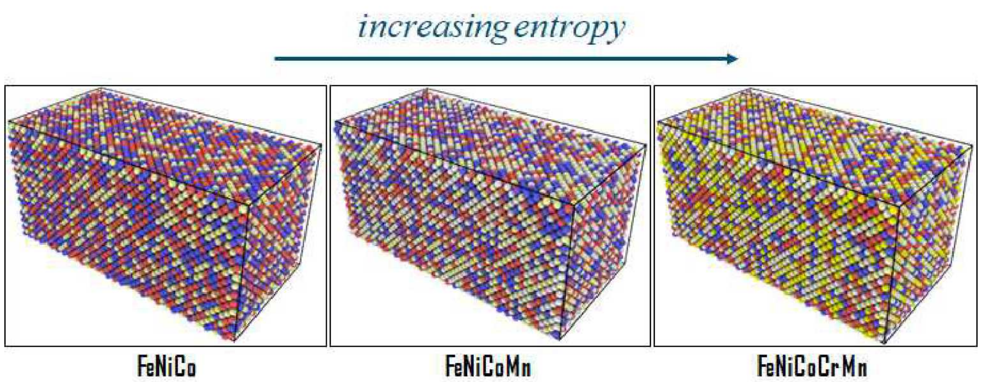


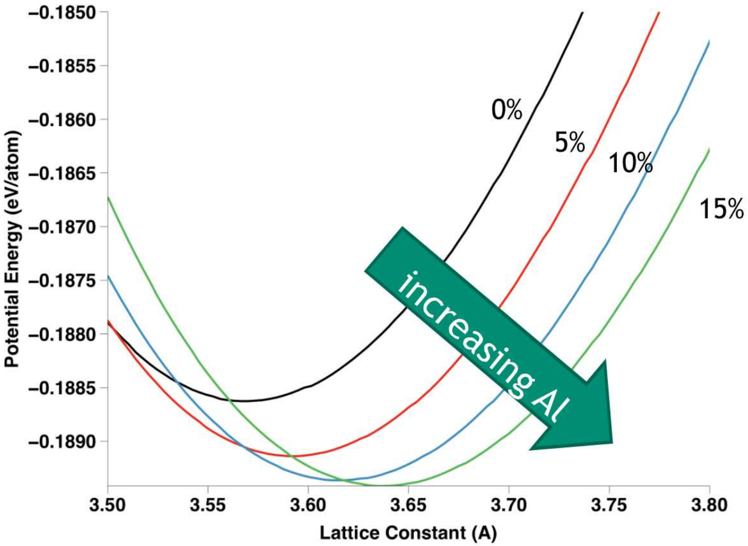
12% lower hardness in AM solidified sample compared to conventional casting

Implications and future work

- AM enables more effective mixing of alloy constituents for complex HEA compositions – critical to avoid undesired phase transformations.
- Preliminary data is promising for enabling structural AM applications *via* HEAs.

Molecular Dynamics (MD) effort to develop "**big data**" tool to enable parametric **alloy optimization**





Atomistic (MD) simulations will enable new thermodynamic predictions of stable HEAs

Summary

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

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

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

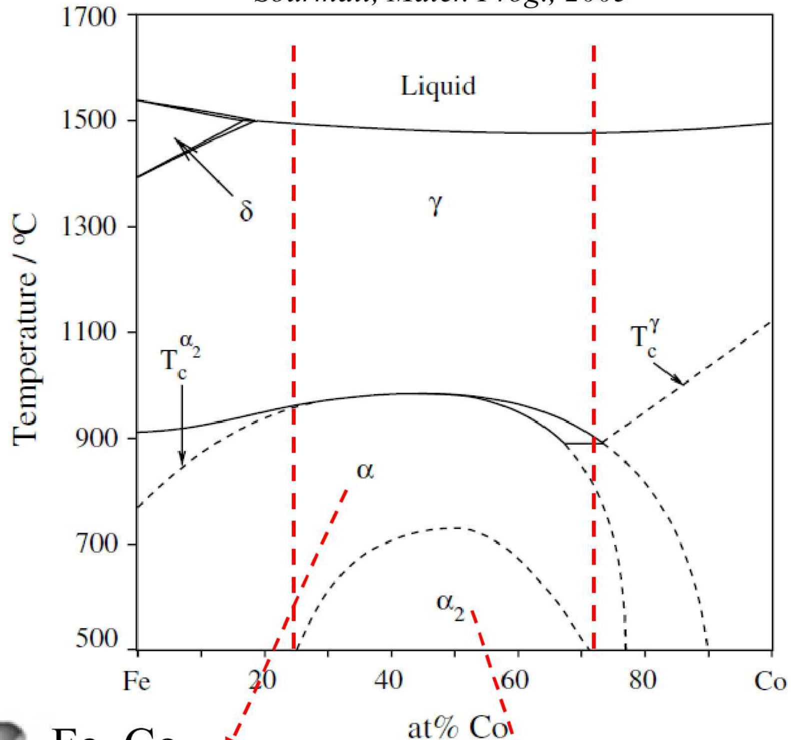
- Metal Additive Manufacturing was shown to promote more ideal microstructures in both soft ferromagnetic alloys and High Entropy alloys
    - For magnetic materials, atomic ordering was reduced.
    - For HEAs, a cellular solidification microstructure developed with refined spatial partitioning of elements.

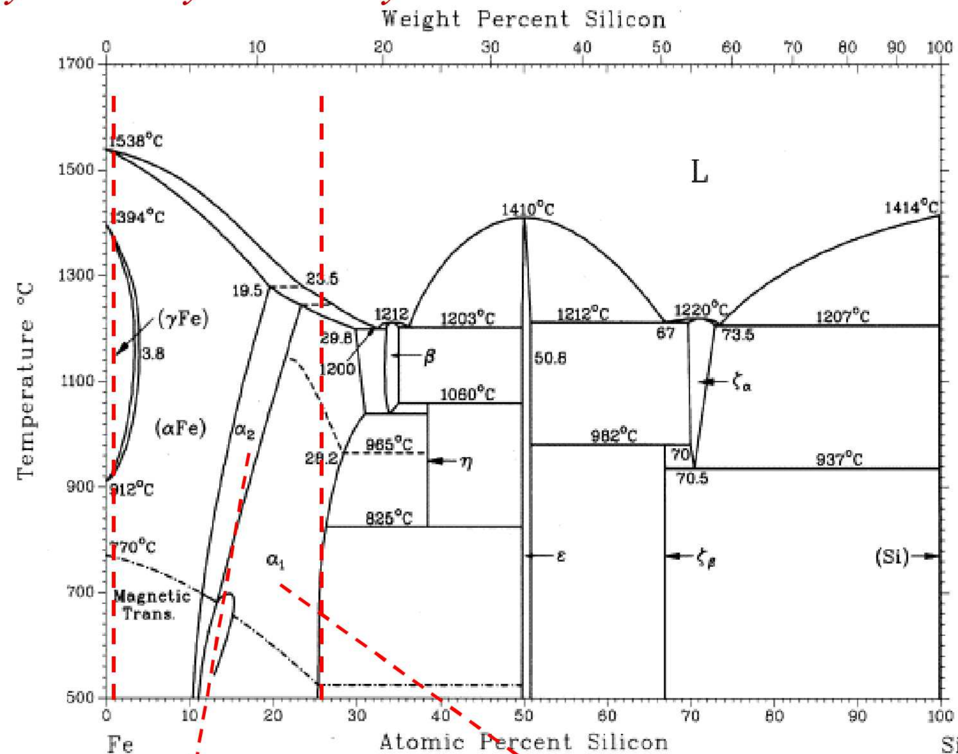
- Preliminary mechanical properties of the HEAs were generally insensitive to AM solidification – a promising outcome for AM structural applications.

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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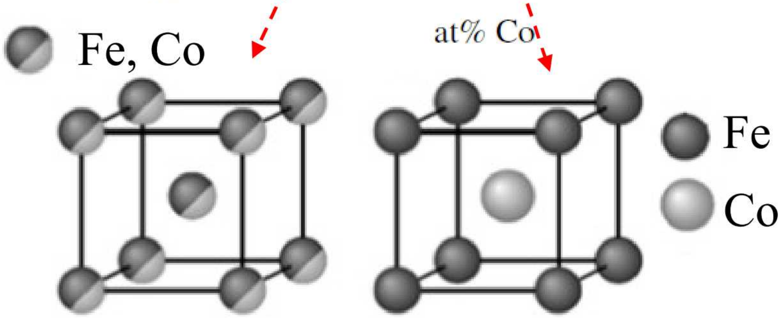

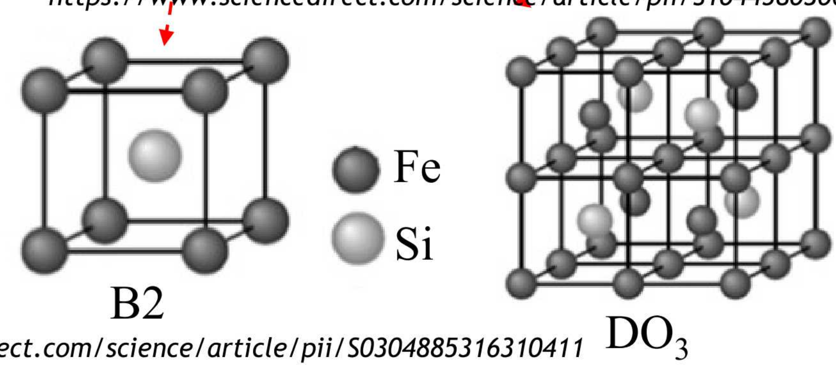

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