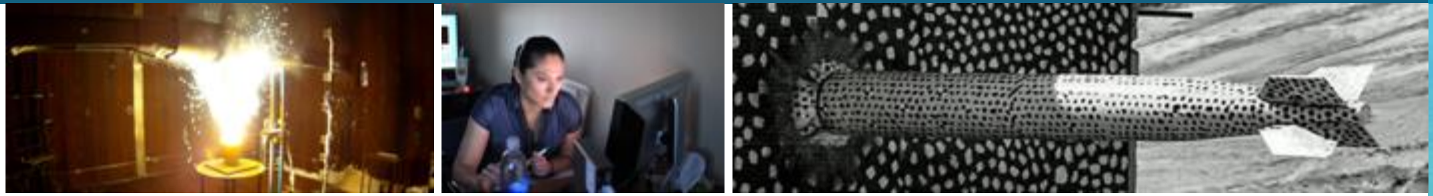
Additive manufacturing of soft-magnetic alloys for energy applications



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PRESENTED BY

Andrew Kustas, Sandia National Laboratories

2024 Power Electronics and Energy Conversion Workshop

Acknowledgements

Laboratory Directed Research and Development (LDRD) Program

LABORATORY DIRECTED
RESEARCH & DEVELOPMENT

Sandia is a collaborative environment…

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Soft Magnetic Alloys Background

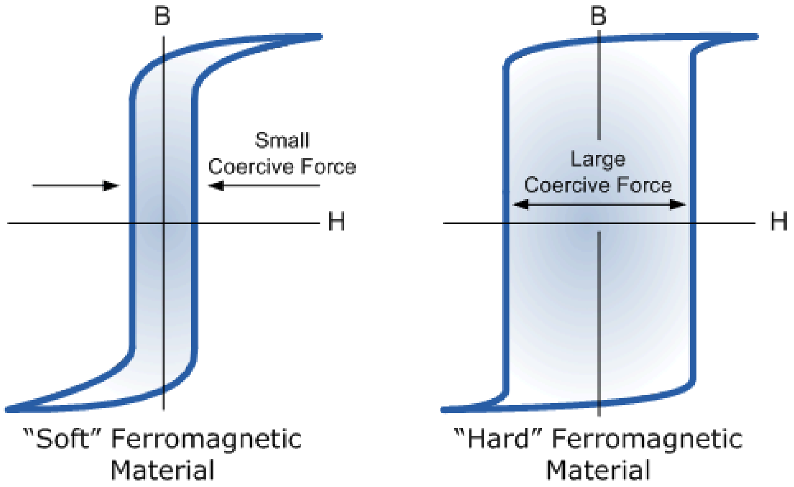
Excellent soft magnetic properties:
- High saturation induction
- High permeability
- Low coercivity (narrow loops)
- Low core loss (narrow loops)
- Electric motors, transformers, switches, etc.
- Produced conventionally as bar, sheet, plate, via thermomechanical methods

- However -

Poor mechanical properties:
- Result of atomically ordered phase transformations
- Low yield strength
- Low ductility
- High notch sensitivity
- Low fracture toughness

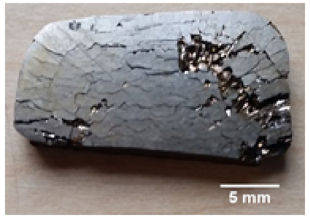
Limits opportunities for loading bearing electromagnetic devices

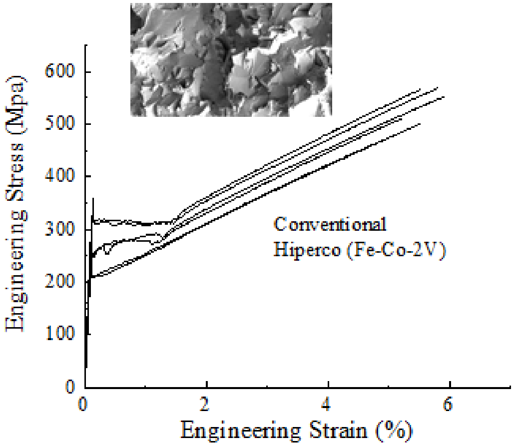
Magnetic properties



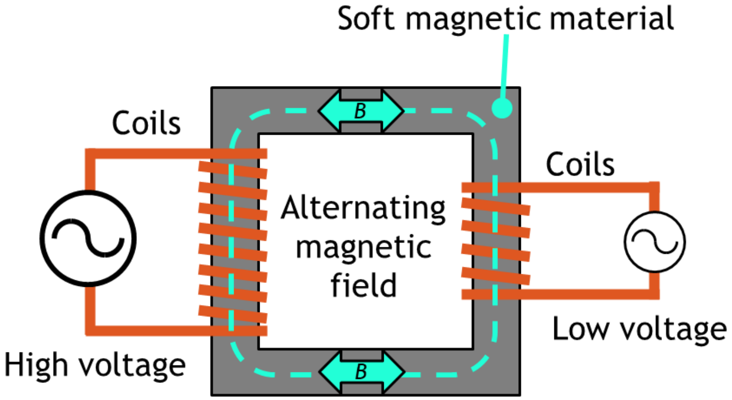
Mechanical properties

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

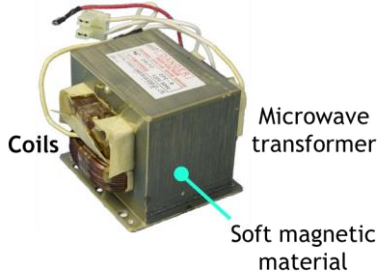




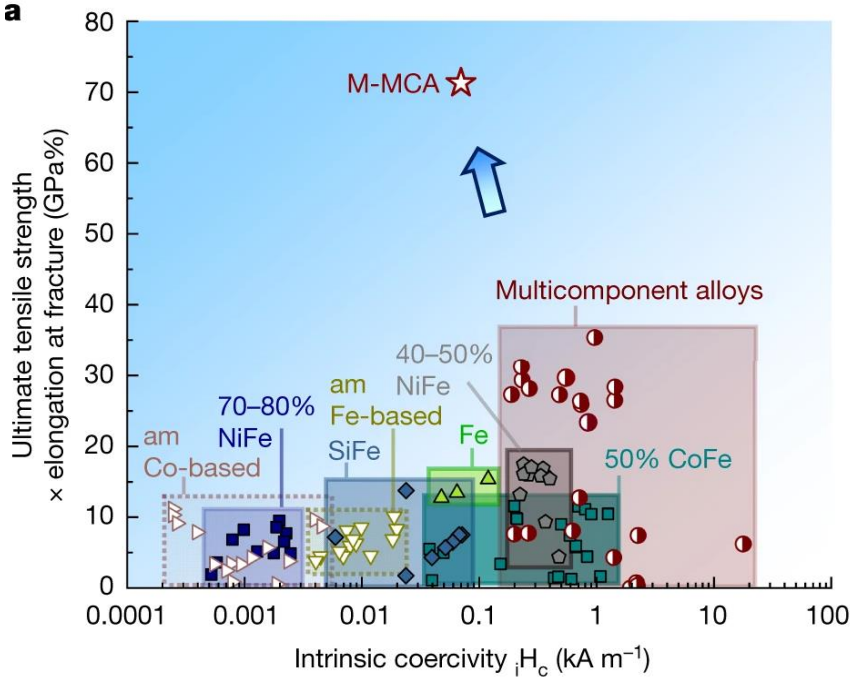
Electromagnetic devices



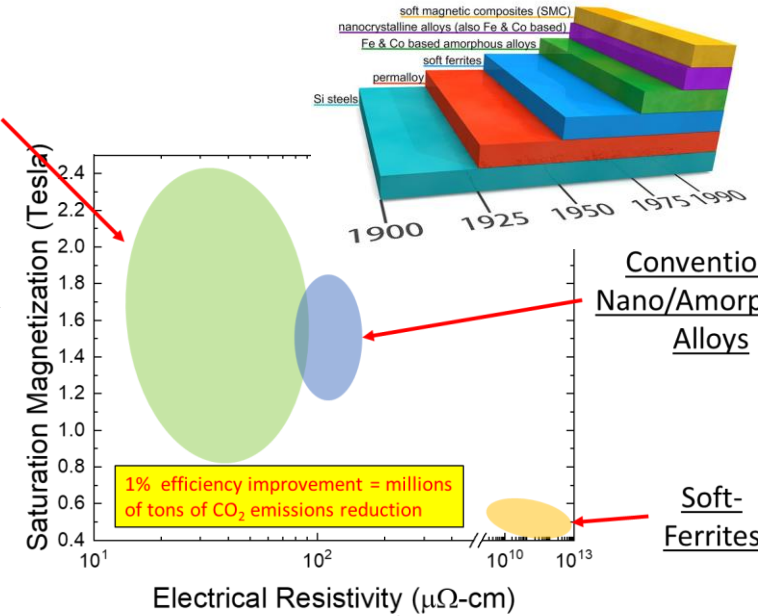
Stepper motor



Why these property tradeoffs?



Han, L., Maccari, F., Souza Filho, I.R. et al. A mechanically strong and ductile soft magnet with extremely low coercivity. Nature 608, 310–316 (2022). https://doi.org/10.1038/s41586-022-04935-3



Josefina M. Silveyra et al. ,Soft magnetic materials for a sustainable and electrified world.Science362,eaao0195 (2018).DOI:10.1126/science .aao0195

"Classical" Alloys

Conventional Nano/Amorphous Alloys

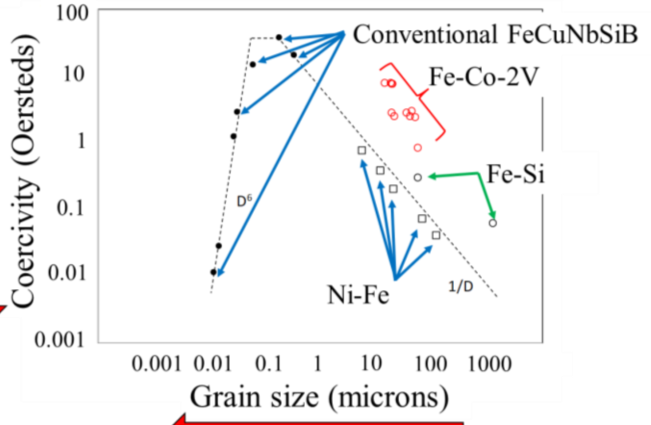
Soft-Ferrites

Higher Saturation; Higher Power-Density and Smaller Devices

1% efficiency improvement = millions of tons of CO_2 emissions reduction

Increasing Resistivity; Lower Core Loss and Higher Energy Efficiency

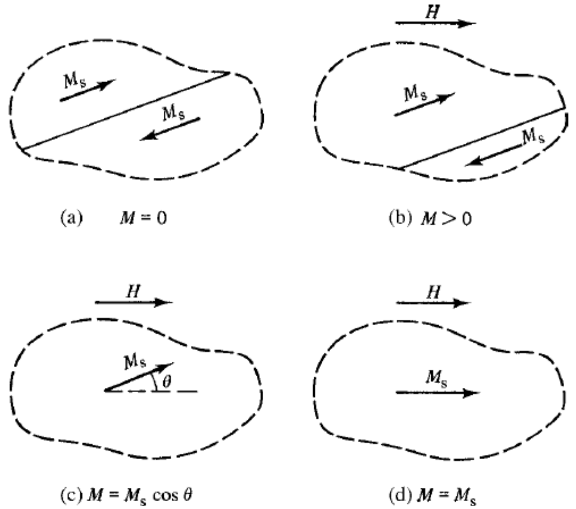
Adapted from: Gaoyuan Ouyang, Xi Chen, Yongfeng Liang, Chad Macziewski, Jun Cui, Review of Fe-6.5 wt%Si high silicon steel—A promising soft magnetic material for sub-kHz application, Journal of Magnetism and Magnetic Materials, Volume 481, 2019, Pages 234-250, https://doi.org/10.1016/j.jmmm.2019.02.089.



Increasing Magnetic Softness: Lower Hysteresis Loss

Increasing Resistivity: Lower Eddy Current Loss

Adapted from G. Herzer, "Grain size dependence of coercivity and permeability in nanocrystalline ferromagnets," in IEEE Transactions on Magnetics, vol. 26, no. 5, pp. 1397-1402, Sept. 1990, doi: 10.1109/20.104389



B. D. Cullity and C. D. Graham, "Introduction to Magnetic Materials," IEEE Press, 2009, 2nd edition, pg. 117

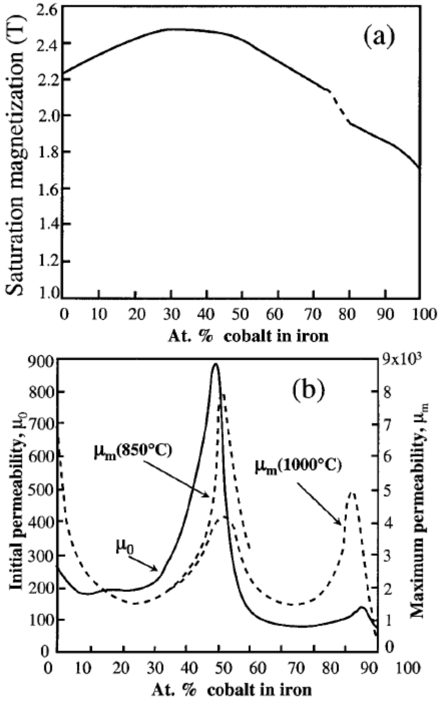
Fundamental challenge: structural barriers (i.e., line and area defects, etc.) in alloys increase strength/ductility (and resistivity) but inhibit microscale magnetization processes (decreasing energy efficiency).

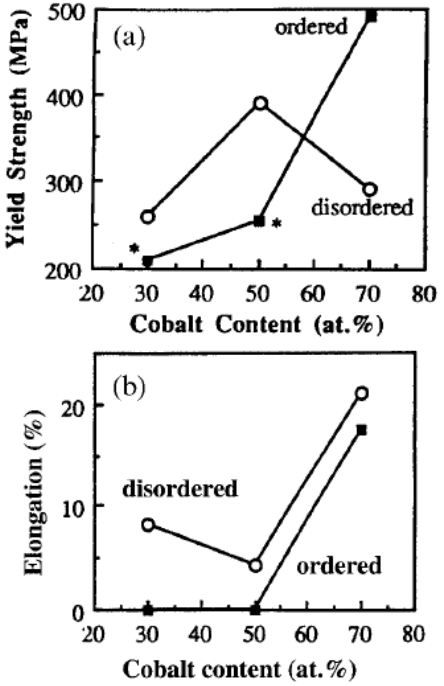
Conventional Mitigation Strategies Limit Material Performance

Modify alloy composition

1) Restrict alloying content.
2) Addition of ternary, quinary, etc. elements.

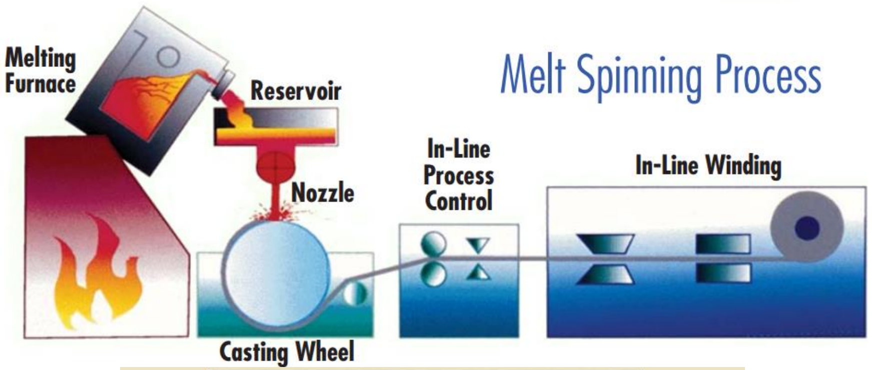
Using ideal alloy composition would enable 10,000+ Gigawatt-hour annual energy savings[1,2].

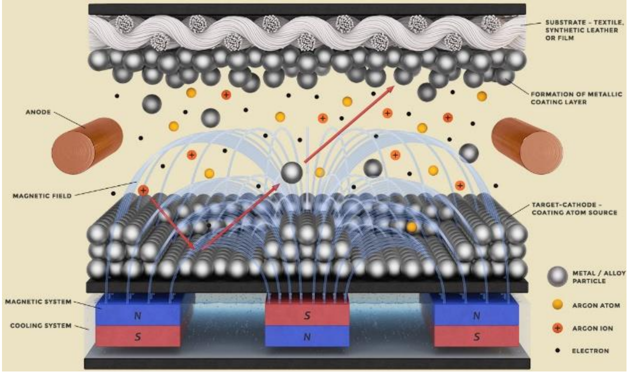




Alternative Manufacturing to Conventional Ingot Metallurgy Methods

30+ years trying advanced manufacturing methods [refs. 3-6] - limited to small material volumes, property tradeoffs remain.

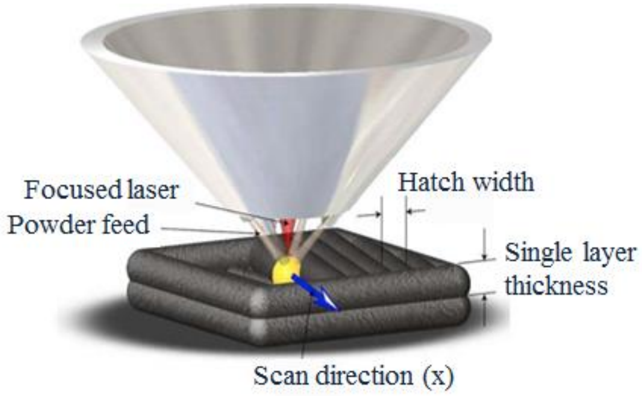


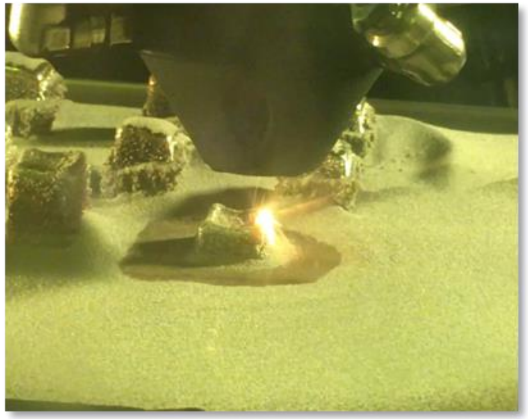


https://www.sputtertargets.net/blog/an-overview-of-magnetron-sputtering.html

[1] DOE, High-Silicon Sheet by Single Stage Shear-Based Processing, 2017.
[2] DOE, Development of New Steel Alloy to Reduce Core Losses in Electric Motors, 2017.
[3] R.S. Sundar, S. C. Deevi, Soft magnetic FeCo alloys: alloy development, processing, and properties, 2005.
[4] T. Sourmail, Near equiatomic FeCo alloys: Constitution, mechanical and magnetic properties, 2005.
[5] G. Ouyang, et al., Review of Fe-6.5wt.%Si high silicon steel – A promising soft magnetic material for sub-5Hz application, 2019
[6] A. Kustas, et al., Emerging Opportunities in Manufacturing Bulk Soft-Magnetic Alloys for Energy Applications: A Review, 2022

Additive Manufacturing Overview

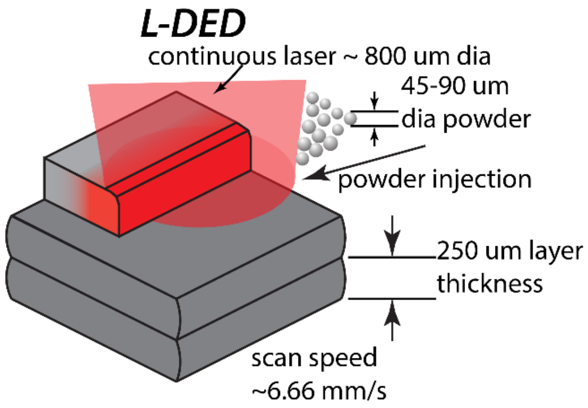


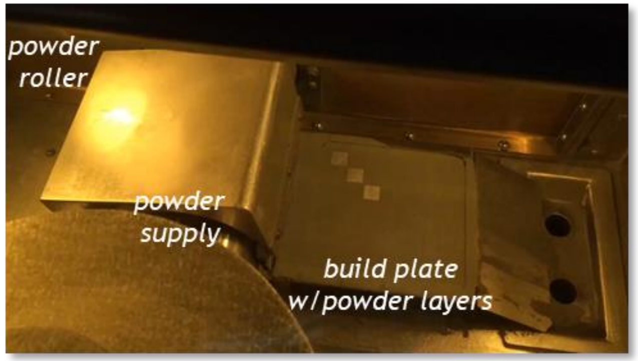


L-DED

- Open architecture system
- Five independent powder chemistries – combinatorial alloy synthesis.

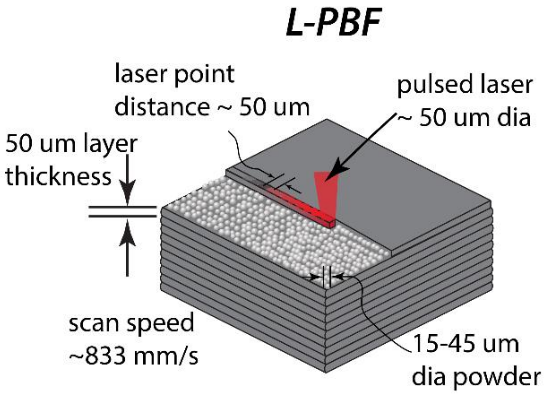
- ***Technical details:***
- Cooling rates: 10^2 - 10^4 C/sec
- 2 kW 1064 nm laser
- Spot size/melt pool: 0.4 – 4 mm
- Build velocity: 100 – 3000 mm/min
- Layer height: 0.2 – 0.5 mm
- Build volume: ~150 mm^3





L-PBF

- ProX 200 & 300, 350 Flex, Renishaw AM 400, and Xact Metal
- ***Representative technical details:***
- Build volumes: ~100 mm^3 to ~300 mm^3
- Cooling rates: ~ 10^5 – 10^7 C/sec
- Feature size: ~ 100 µm
- Layer height: ~ 30 – 50 µm
- Build velocity: ~ 1 m/s
- Complex geometries can be achieve that are impossible for conventional manufacturing.



Tomas F. Babuska, Brandon A. Krick, Donald F. Susan, Andrew B. Kustas, Comparison of powder bed fusion and directed energy deposition for tailoring mechanical properties of traditionally brittle alloys, Manufacturing Letters, Volume 28, 2021,Pages 30-34, https://doi.org/10.1016/j.mfglet.2021.02.003.

Case study 1: Fe-Co soft magnetic alloys

Equiatomic or near-equiatomic Fe-Co alloys that undergo a γ-FCC → α-BCC→ α2 (B2) transformations.

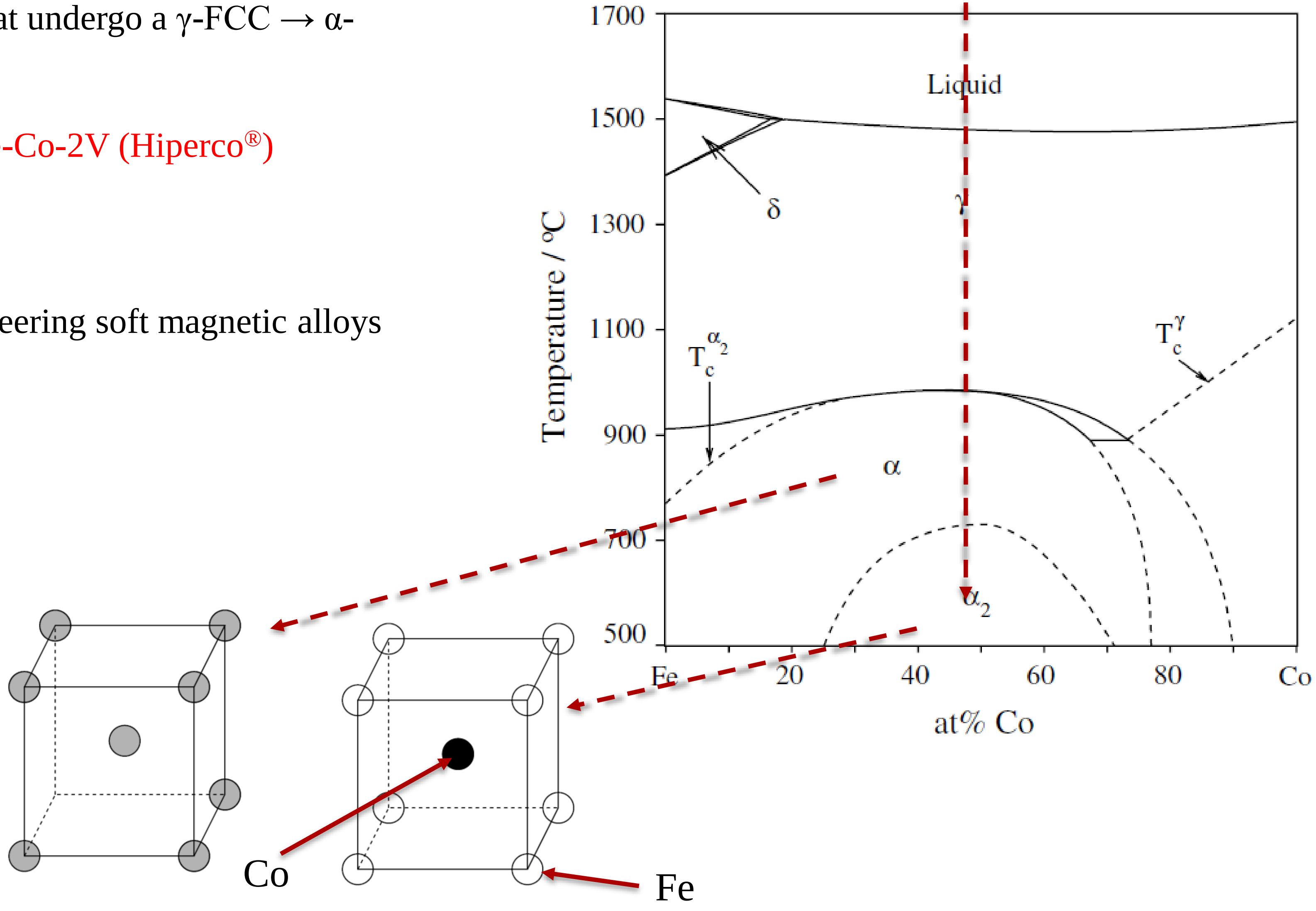
- Binary Fe-Co difficult to process.
- Commercialized as ternary alloys, e.g., Fe-Co-2V (Hiperco®)
- Bar and sheet/strip forms.

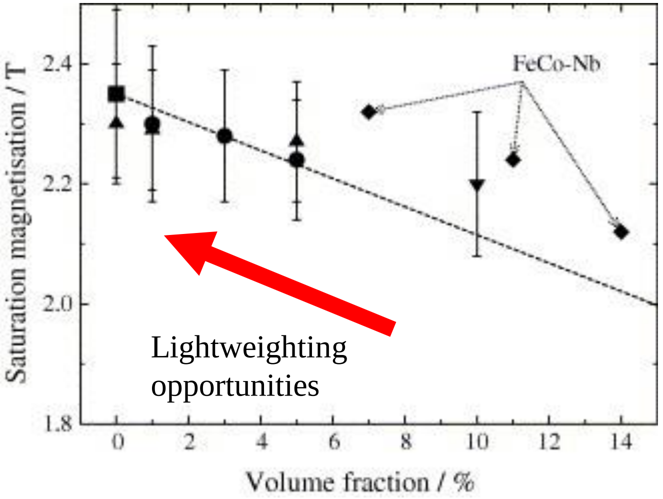
Hiperco® is a tradename of Carpenter Technologies, Reading, PA.

Excellent magnetic properties:

- Highest saturation magnetization of engineering soft magnetic alloys
  - Lightweighting opportunities
- High curie temperature (> 900 °C)
- High permeability
- Low core loss

Atomic ordering is a big issue!

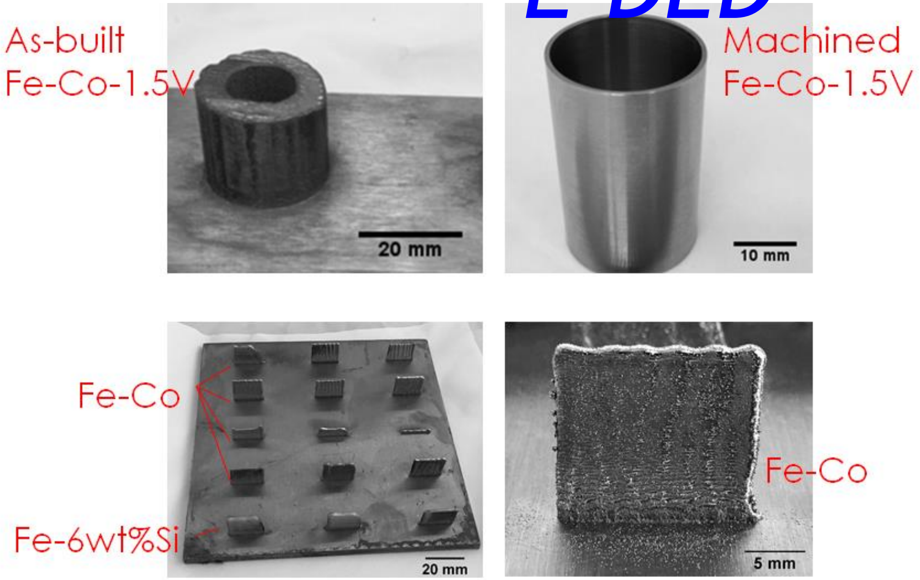




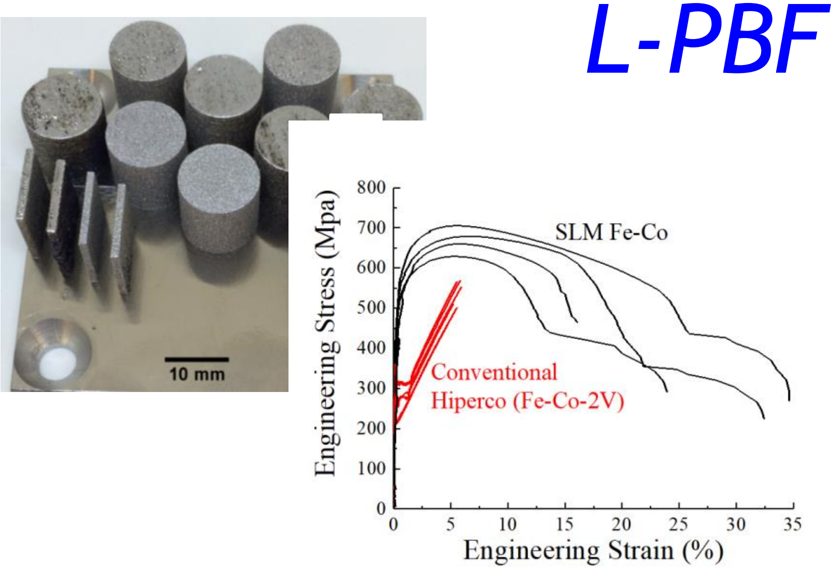
T. Sourmail, Near equiatomic FeCo alloys: Constitution, mechanical and magnetic properties, Progress in Materials Science, Volume 50, Issue 7, 2005, Pages 816-880, https://doi.org/10.1016/j.pmatsci.2005.04.001.

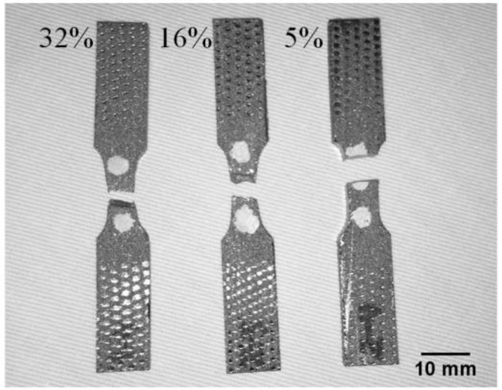
Case study 1: achieving strong and ductile Fe-50%Co magnetic alloys

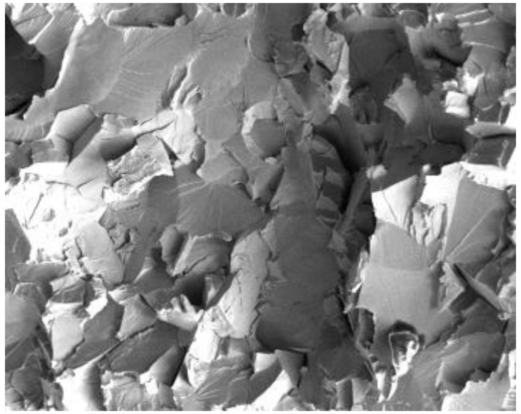
L-DED



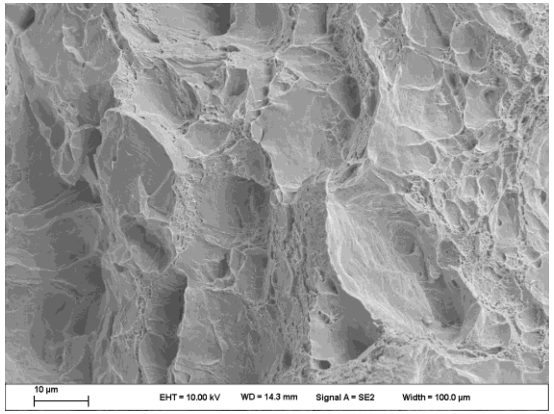
L-PBF



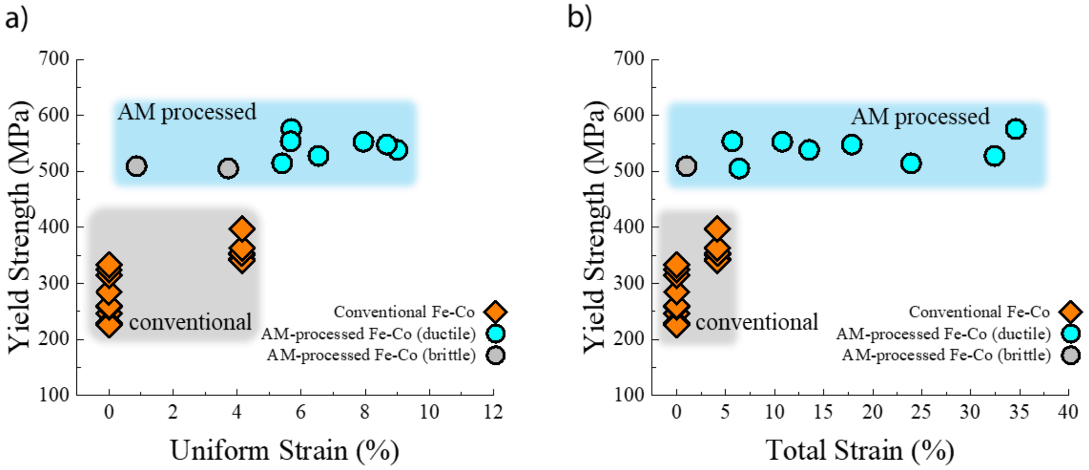




Conventional Hiperco
Brittle fracture



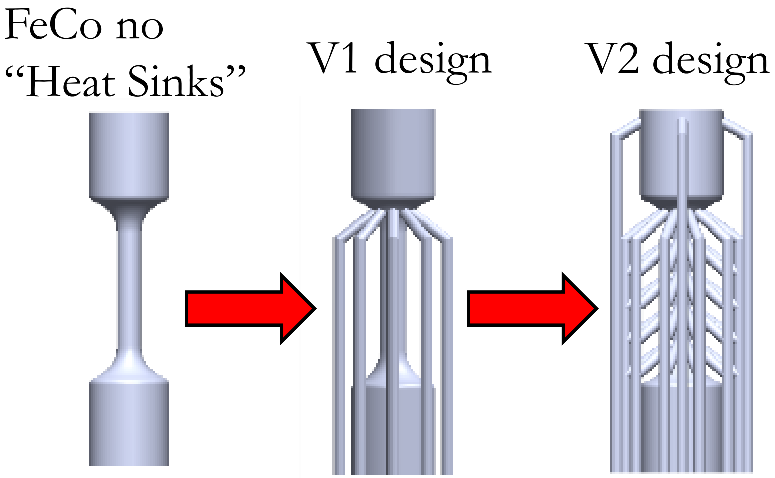
AM binary FeCo
Ductile fracture

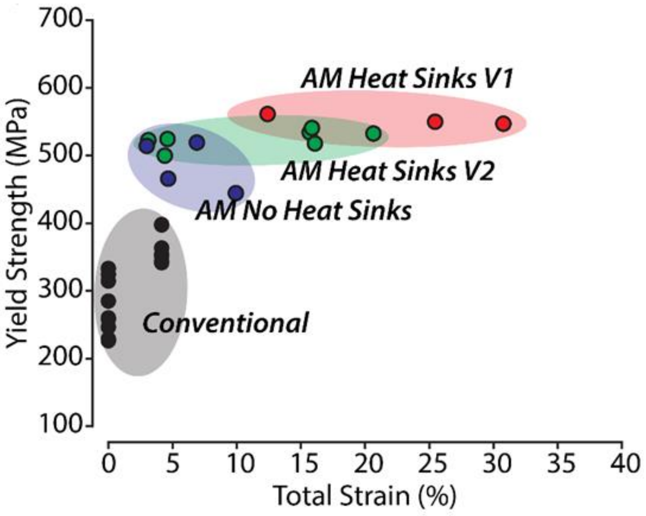


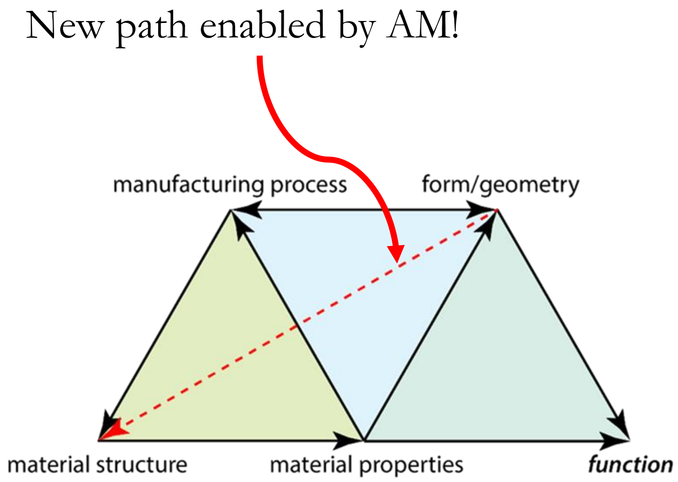
L-PBF Fe-Co showed high strength and ductility compared to conventional material with extensive necking, microscale plastic flow and ductile fracture.

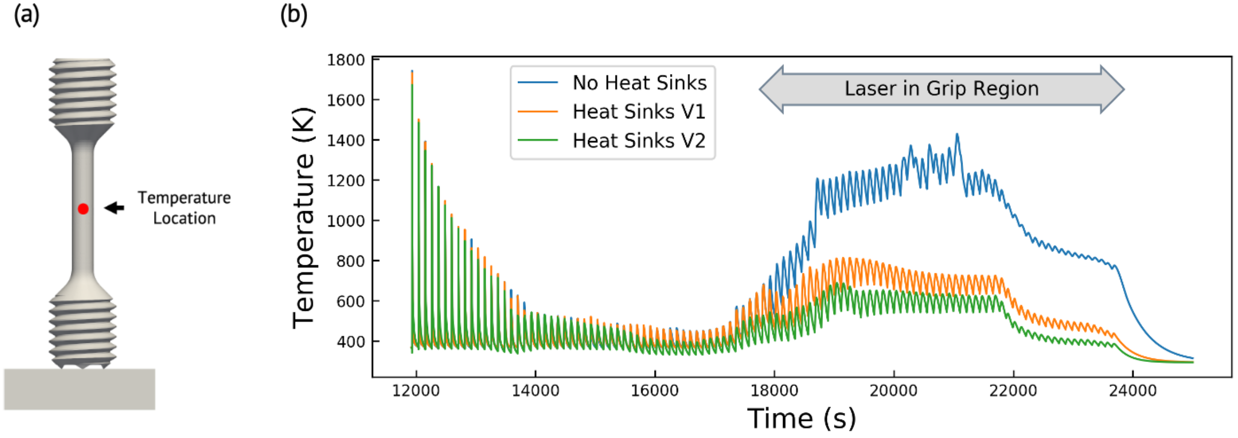
1. *Kustas, A. B., et al., Characterization of the Fe-Co-1.5V soft ferromagnetic alloy processed by Laser Engineering Shaping (LENS), Addit Manu. (2018).*
2. *Babuska, T.F., et al., Achieving high strength and ductility in traditionally brittle soft magnetic intermetallics via additive manufacturing. Acta Mater. (2019).*

Additive manufacturing enables new pathways for magnetic alloy synthesis









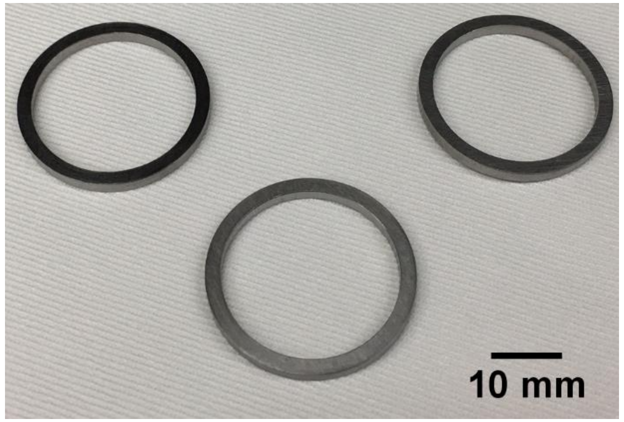
Finite element analysis showing time-dependent temperature profile during part – informing direct control of structure-property relationships.

AM creates additional pathways within traditional “material, form, and function” approaches to manufacturing, ***form/geometry of part directly controls material structure***.

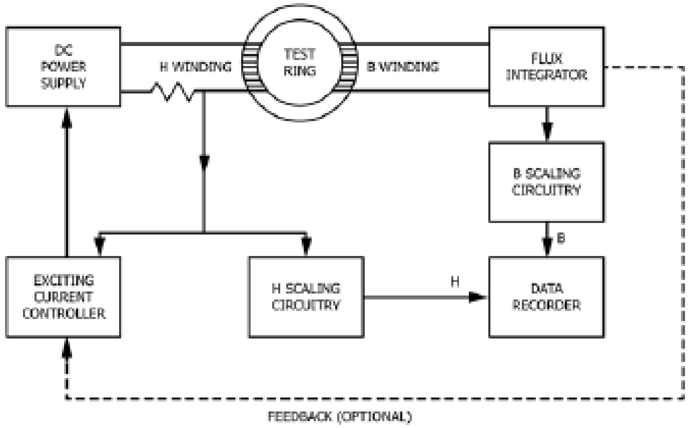
Babuska, T.F., et al., An additive manufacturing design approach to achieving high strength and ductility in traditionally brittle alloys via laser powder bed fusion. Addit. Manu. (2020).

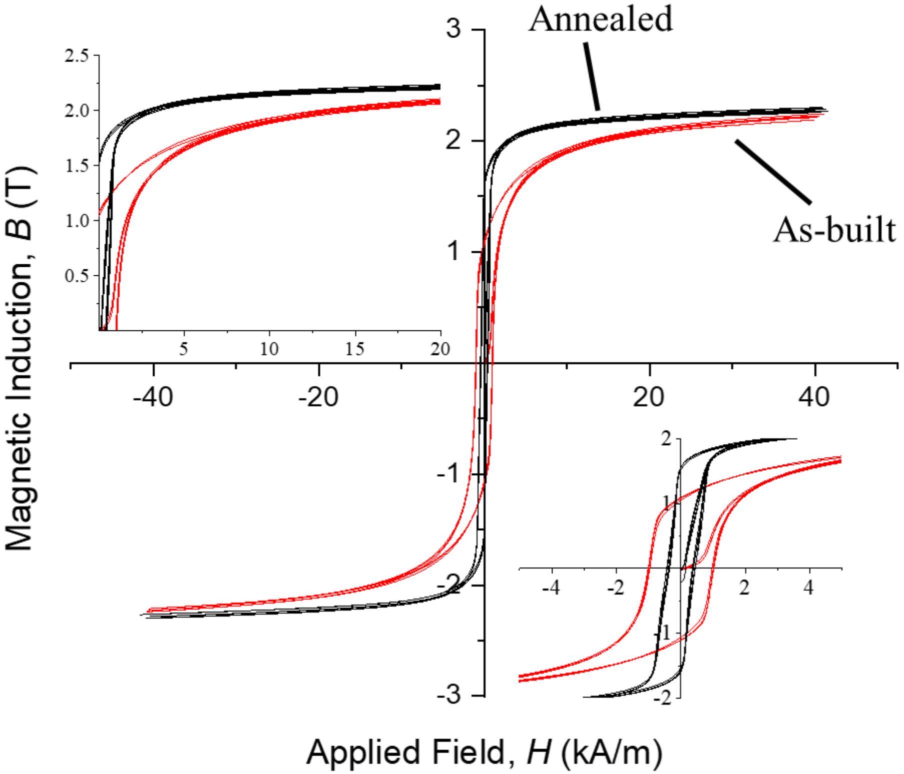
Magnetic properties

B-H rings for magnetic properties characterization



ASTM A773





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] 90-200[62]	5000-8000[25]
Fe-Co-2V	--	2.3[25]*	95-160[63] 393[25]	4000-8000[25]
Fe-Co-2V (as-rolled, 90%)	--	2.2[25]*	2900[25]	--

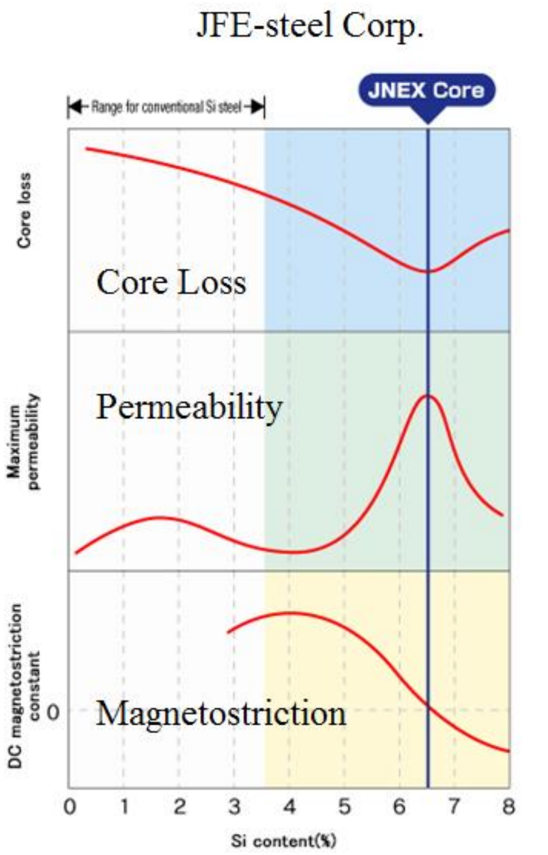
As-built AM material showed desired high saturation behavior but harder structure-sensitive properties.

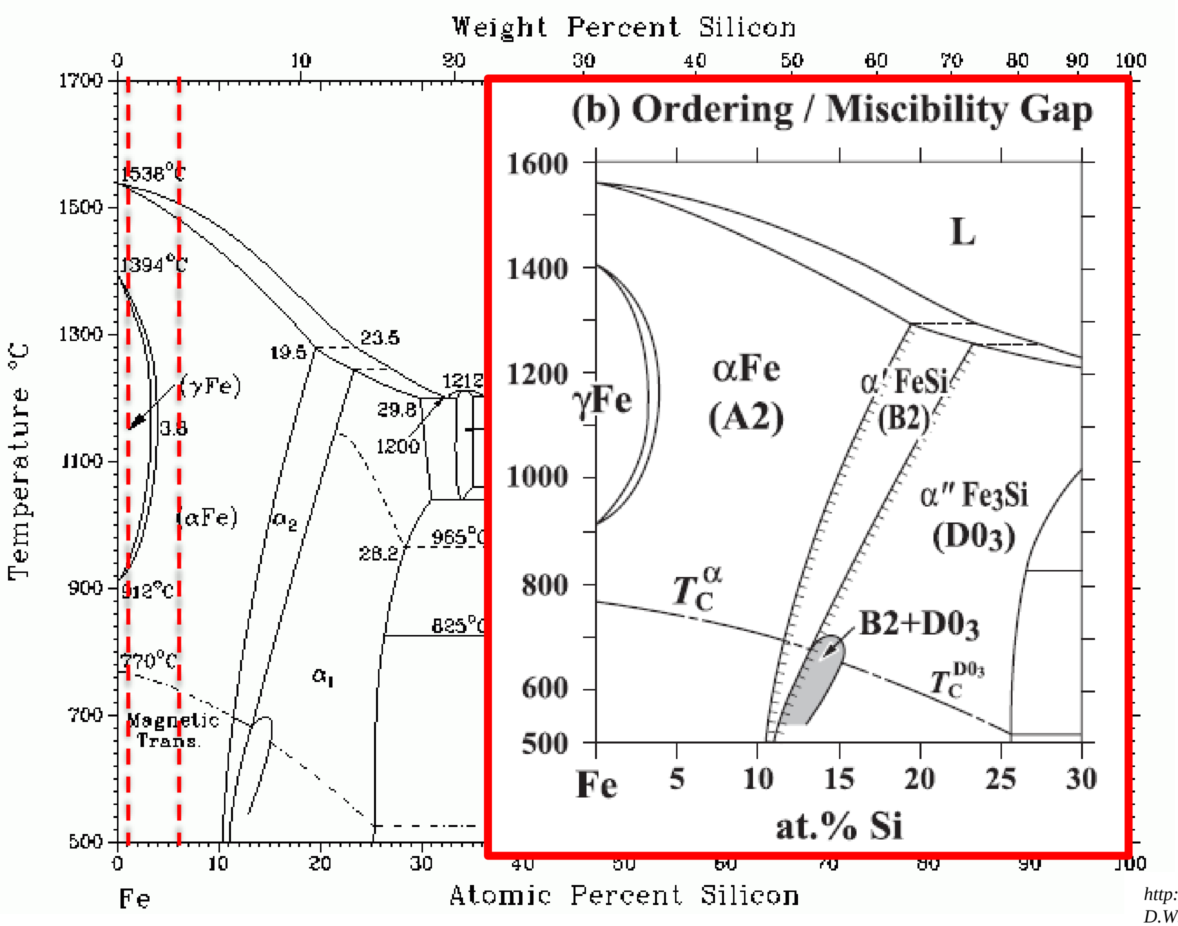
Kustas, A. B., et al., Characterization of the Fe-Co-1.5V soft ferromagnetic alloy processed by Laser Engineering Shaping (LENS), Addit Manu. (2018).

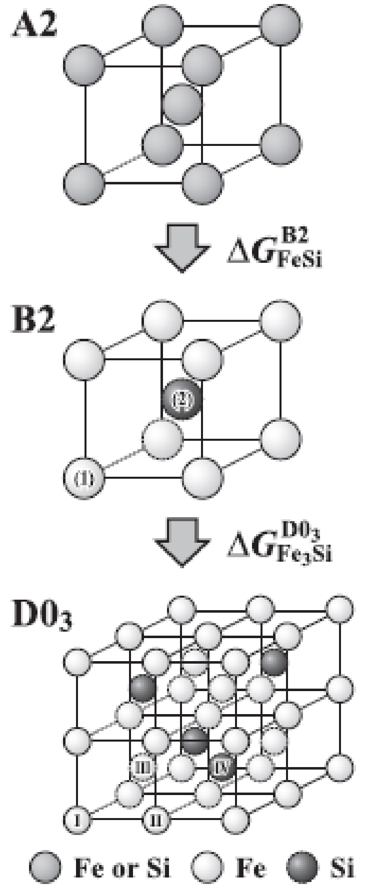
Case study II: achieving high silicon electrical steels

Silicon containing α (BCC) iron alloy (0.5 – 3.2 wt%Si – commercial range) that undergoes α-BCC→ α_2 (B_2) and/or α_1 (DO_3) transformations.

- Unworkable with increasing Si content (> 3.5 wt%Si)
- Magnetic properties improve with added Si-content until ~ 6.5 wt%Si
  - *One commercial sheet product via CVD-siliconizing, JFE Steel Corp – expensive and diffusion-limited*
- Available in bar, most commonly as sheet/foil for transformers/motors.



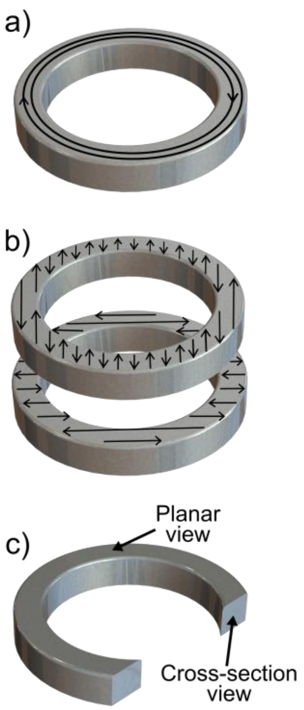


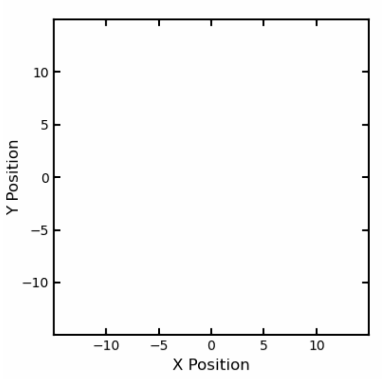


http://www.himikatus.ru/art/phase-diagr1/Fe-Si.gif
D.W. Dietrich, Vol 2, ASM Handbook, ASM International, 1990, p 761–781

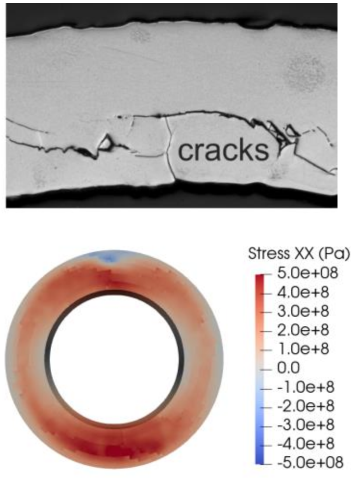
Comparable properties to conventional electrical steels

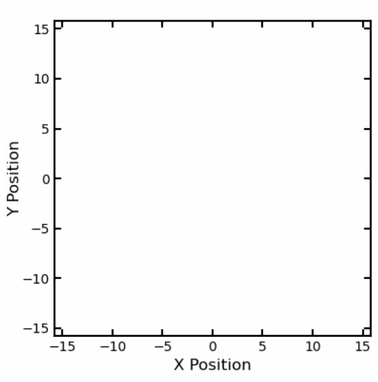
Toroid Fe-6wt.%Si parts



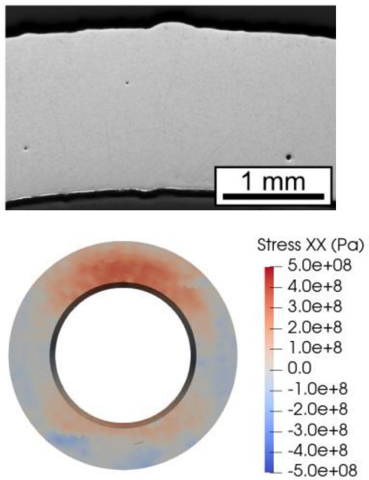


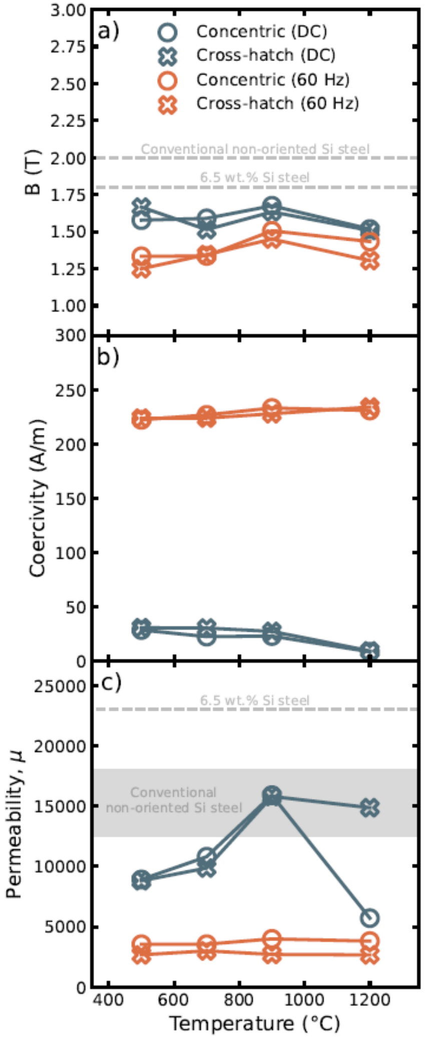
Concentric
(Cracking)





Cross-hatch
(No-cracking)





Printed bulk Fe-6wt.%Si near-net shape cylinders to extract toroid-shaped specimens for magnetic characterization. Select conditions cracked after annealing (residual stress driven).

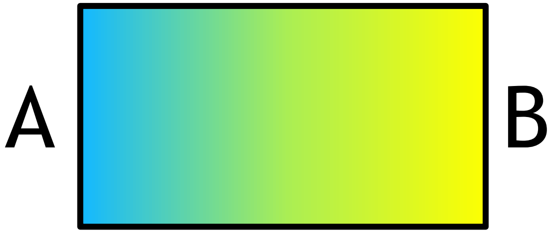
Another case where AM is enabling alloy performance, rather than limiting!

Magnetic properties are comparable to conventional electrical steels (low-Si) and CVD-siliconized Fe-6.5wt.%Si sheet (JFE steel corp.).

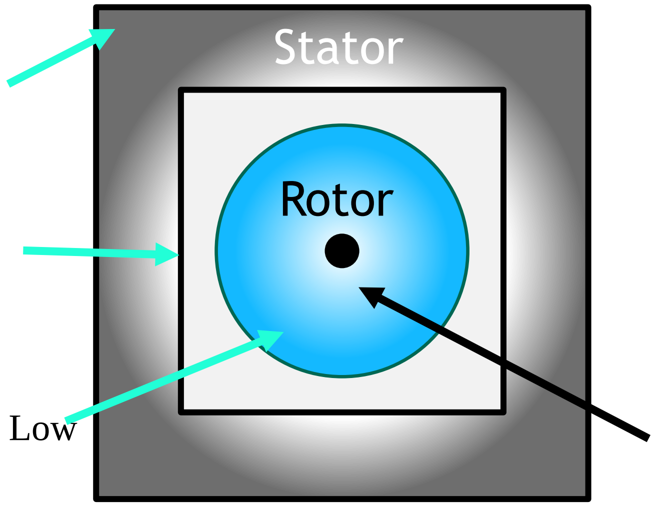
Adamczyk, J.M., Birchall, S.E., Rothermel, E.T. et al. Characterization of Fe-6Si Soft Magnetic Alloy Produced by Laser-Directed Energy Deposition Additive Manufacturing. JOM 76, 863–874 (2024). https://doi.org/10.1007/s11837-023-06293-5

Case study III: multi-material/functionally graded processing

Materials Discovery



Motor components with spatially controlled properties



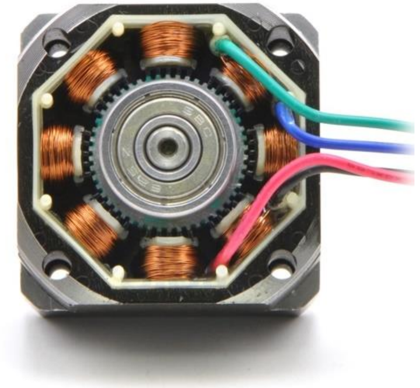
Low T_c, high B_s

High T_c, low B_s

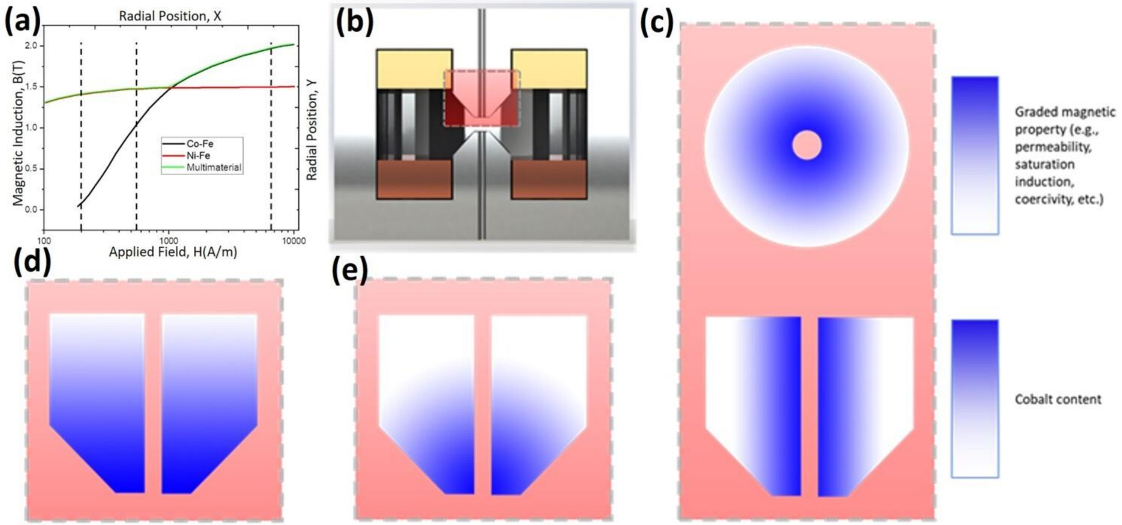
High strength, Low B_s

Low strength, High B_s

Motor internal structure



Graded pole pieces for charged particle optics



Why explore functional grading?

1. High-throughput materials discovery
2. Spatial control of structure-property relationships
3. New property combinations that are otherwise impossible to achieve

Lang, E. et al. (2024) 'Functionally graded magnetic materials: a perspective to advance charged particle optics through compositional engineering', Materials Research Letters, 12(5), pp. 336–345. doi: 10.1080/21663831.2024.2329236.

Pairing dissimilar soft magnetic alloys: Hiperco 50A and Hymu-80

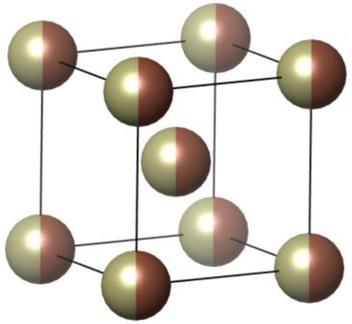
Saturation: 2.3 T

Permeability: 22,000

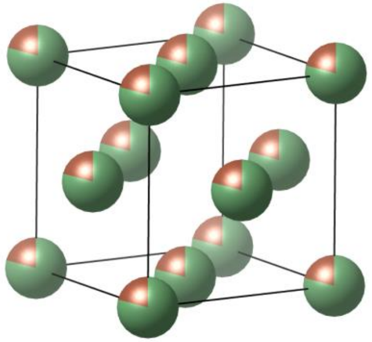
Coercivity: 30 A/m

Ductility: Very brittle

$Fe_{49}Co_{49}V_2$
Hiperco-50A



$Ni_{80}Fe_{16}Mo_4$
Hymu-80



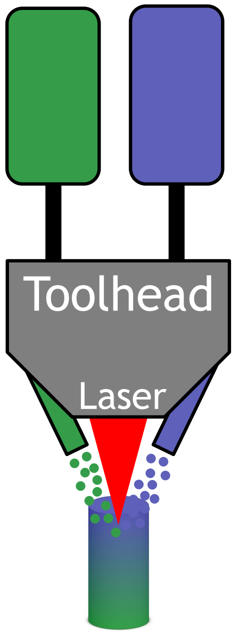
Saturation: 0.8 T

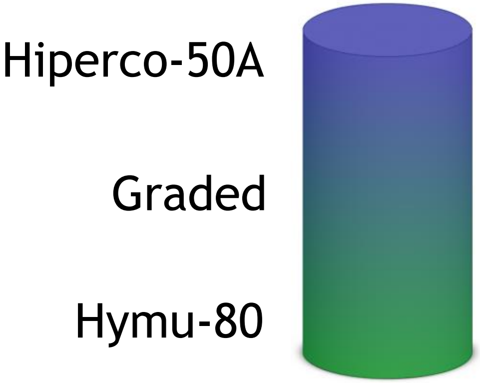
Permeability: 200,000

Coercivity: 1.6 A/m

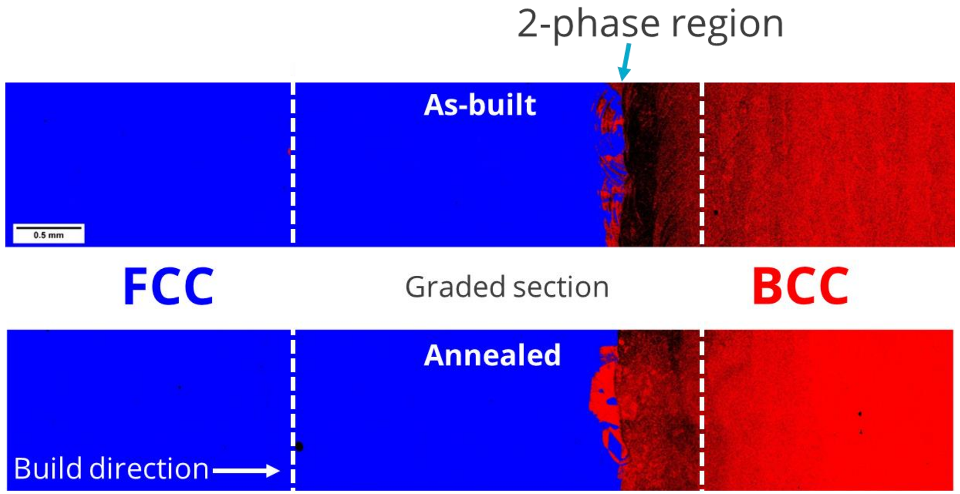
Ductility: Decent

Powder hoppers





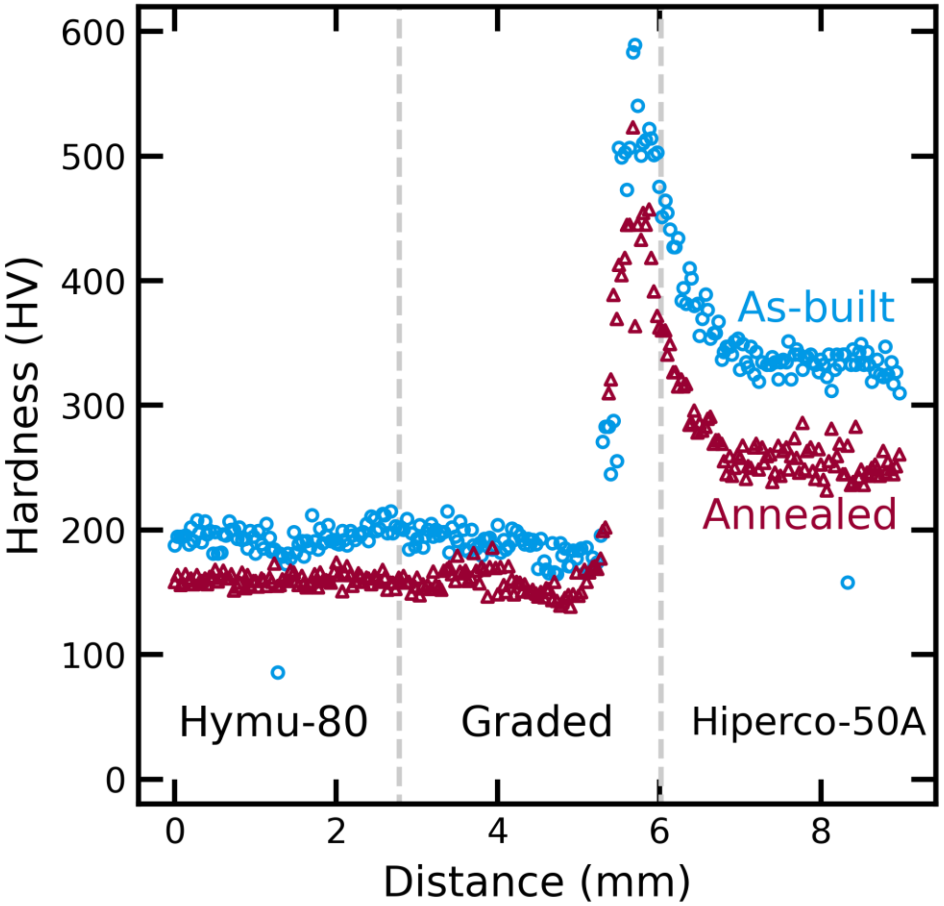
As-built cylinder

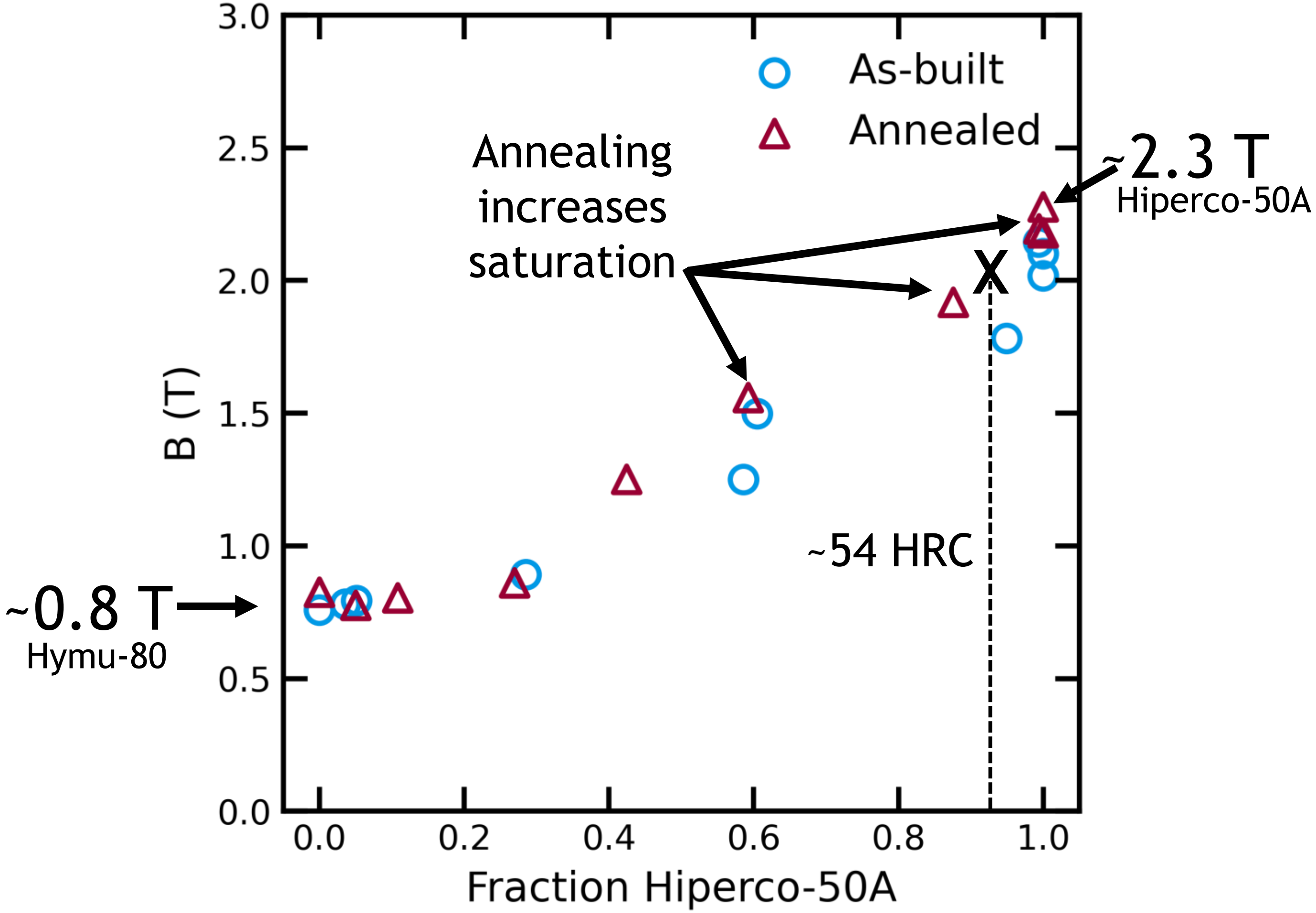


Annealing Process
788°C – 1 hour
1175°C – 5 hours

Jesse Min-Tze Adamczyk, Erin J. Barrick, Charles J. Pearce, Robert E. Delaney, Nicolas Ury, Robert Peter Dillon, Todd C. Monson, Jay D. Carroll, Donald F. Susan, Nichole R. Valdez, Eric Lang, Khalid Hattar, Ana S. Love, Hyein Choi, Andrew B. Kustas, and Samad A. Firdosy ACS Applied Engineering Materials 2024 2 (4), 818-828 DOI: 10.1021/acsaenm.3c00564

Additively enabled spatial control of mechanical and magnetic properties

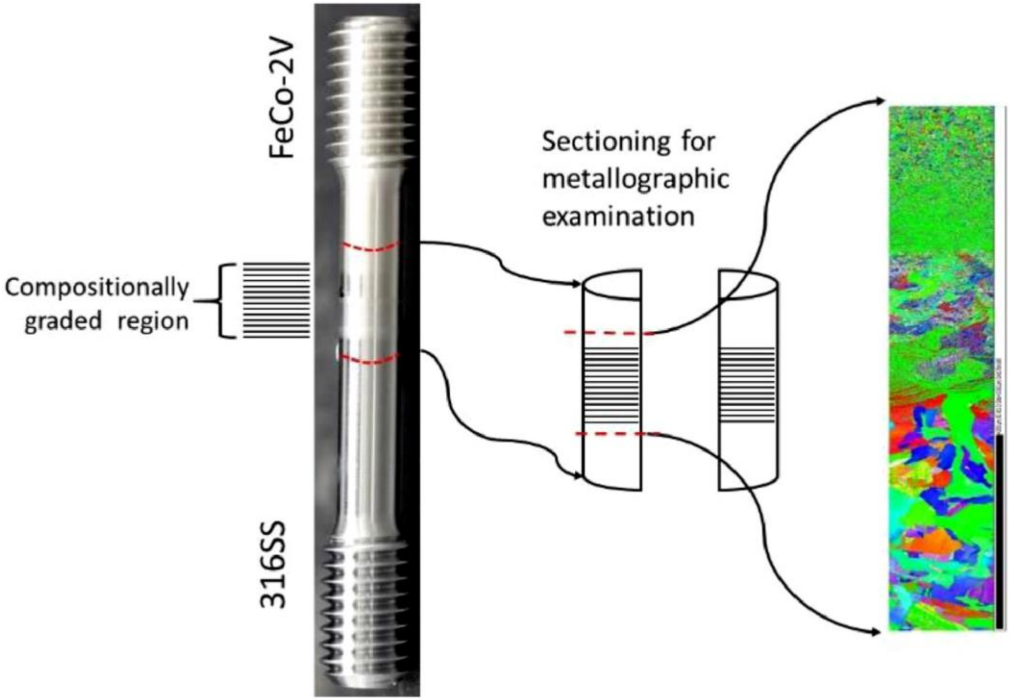


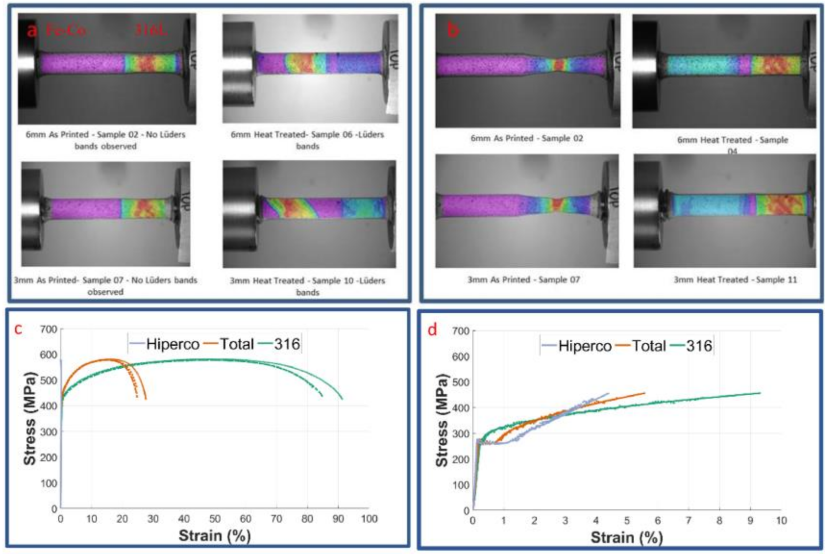


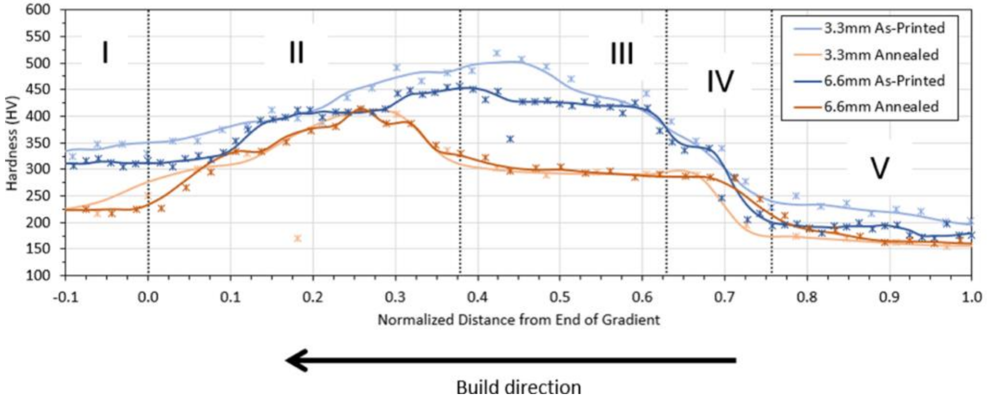
Retain >90% of the saturation of Hiperco-50A with 2x the hardness/strength

Jesse Min-Tze Adamczyk, Erin J. Barrick, Charles J. Pearce, Robert E. Delaney, Nicolas Ury, Robert Peter Dillon, Todd C. Monson, Jay D. Carroll, Donald F. Susan, Nichole R. Valdez, Eric Lang, Khalid Hattar, Ana S. Love, Hyein Choi, Andrew B. Kustas, and Samad A. Firdosy ACS Applied Engineering Materials 2024 2 (4), 818-828 DOI: 10.1021/acsaenm.3c00564

Pairing dissimilar alloys: Hiperco 50A and 304L Stainless Steel



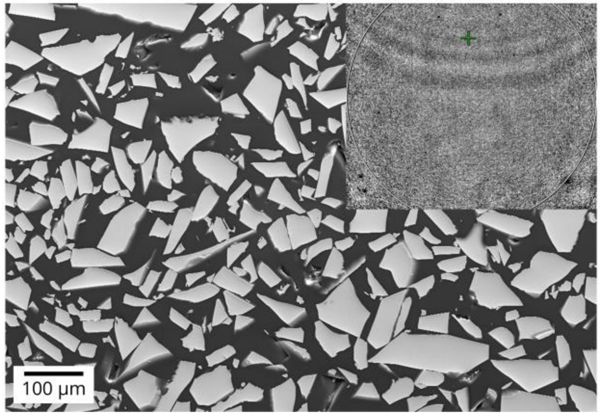


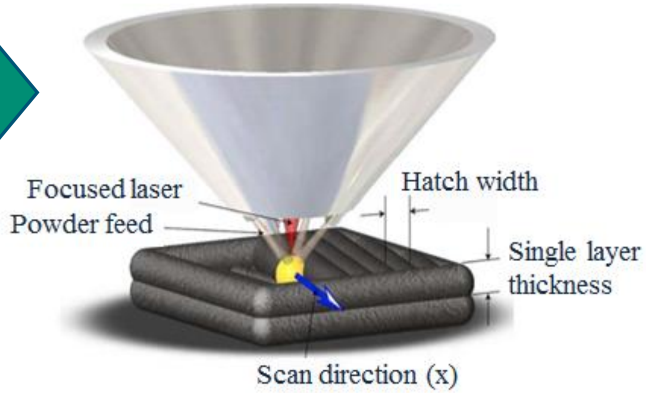


Fracture occurs in the weaker of the two materials: SS304L for as-built, Hiperco 50A for annealed. As-built material showed 20-30% “total composite” strain-to-failure, far exceeding monolithic Hiperco 50A alloy.

Samad Firdosy, Nicholas Ury, Andrew B. Kustas, Jay D. Carroll, Priya Pathare, Zachary Casias, Daniel Tung, Don Susan, N. Scott Bobbitt, Michael Chandross, J.P. Borgonia, Vilupanur A. Ravi, R. Peter Dillon, Compositionally graded joints between magnetically dissimilar alloys achieved through directed energy deposition, Scripta Materialia, 2021, 114005, https://doi.org/10.1016/j.scriptamat.2021.114005.

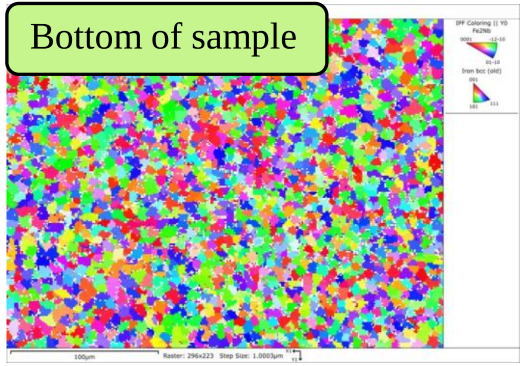
Future and ongoing work



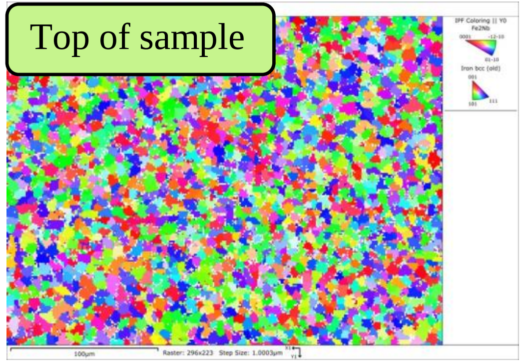


Metglas-type soft magnetic alloy: nominal Fe-8.6Si-5.6Nb-1.5B-1.3Cu composition (wt.%)

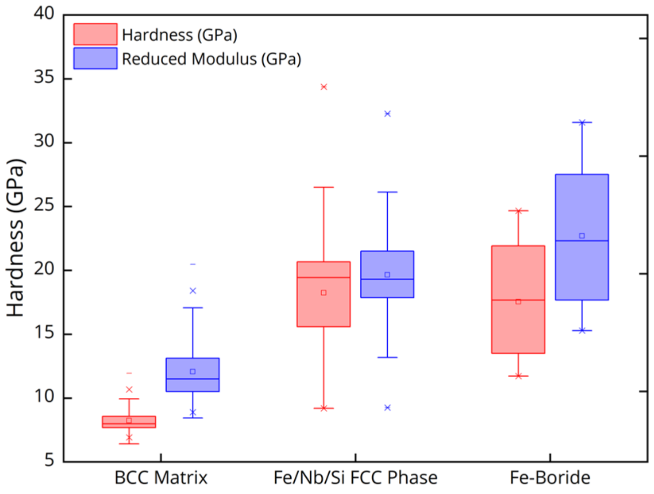
Bottom of sample



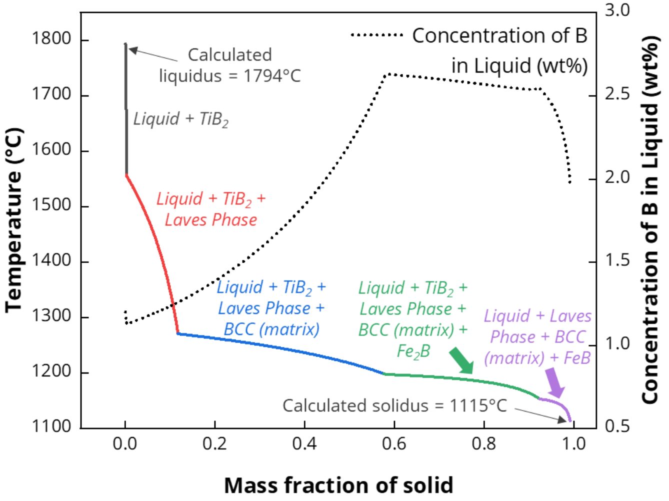
Top of sample



Can additive manufacturing enable bulk nanocrystalline magnetic structures?



Top composition (In wt %):
81% Fe, 8.2% Si, 0.2% Ti, 7.2% Nb, 1.2% Cu, 0.6% Ni, 1.2% B



Thermocalc modeling used to inform microstructure evolution as during solidification. Nanoindentation decoupling phase-specific hardness.

Conclusions

1. Additive Manufacturing is an enabling, rather than limiting, approach for producing soft magnetic alloys
    a) Especially for alloy compositions that enable higher efficiency devices but are too brittle for conventional thermomechanical processing.

2. Non-equilibrium thermal history of AM imparts unusual high strength and ductility mechanical properties
    a) Especially for FeCo alloys where disorder-order phase transformations dominate properties

3. Multi-material additive offers new opportunities for electromagnetic device design
    a) Pairing dissimilar magnetic or magnetic and non-magnetic materials
    b) Site specific control of material properties

4. Opportunities to use additive processing for unconventional compositions (metglas/nano alloys) in bulk form, as opposed to conventional melt spinning of thin ribbon

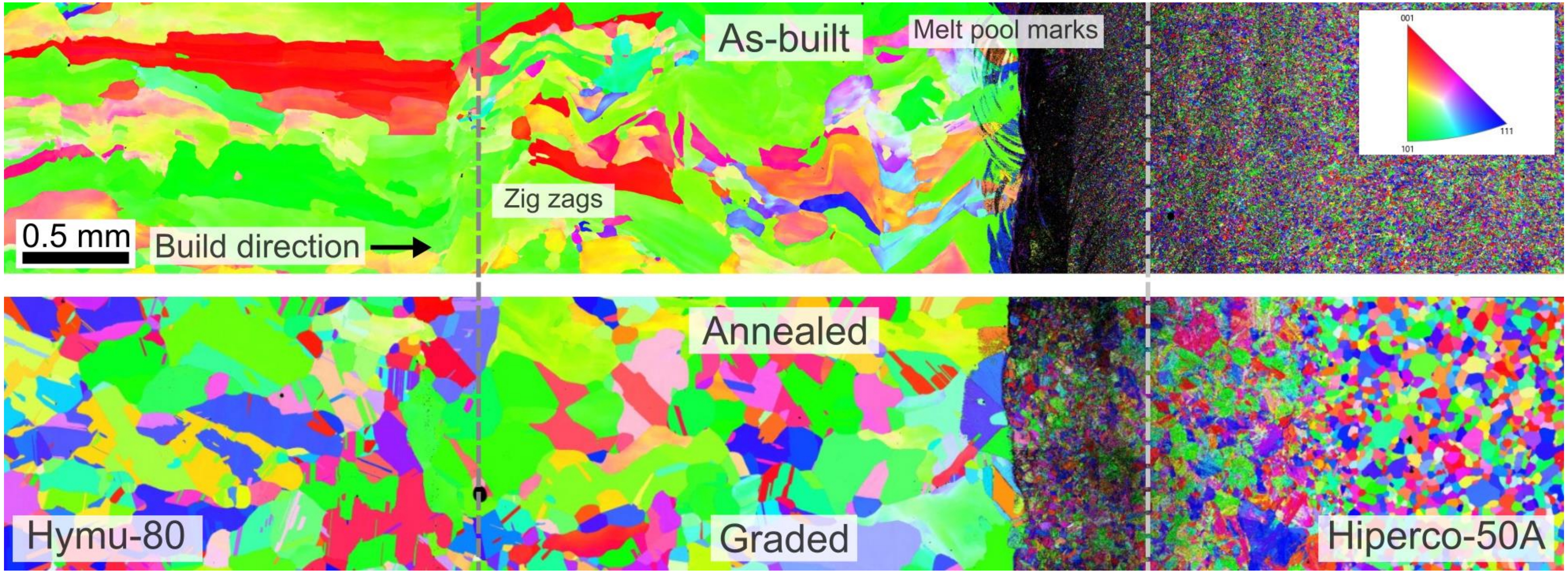
akustas@sandia.gov

Additively enabled spatial gradations

Ni-rich

FeCo-rich

Build plate



Annealing Process
788°C - 1 hour
1175°C - 5 hours

FCC

BCC

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