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Qualification Activities: Stainless Steel 316H

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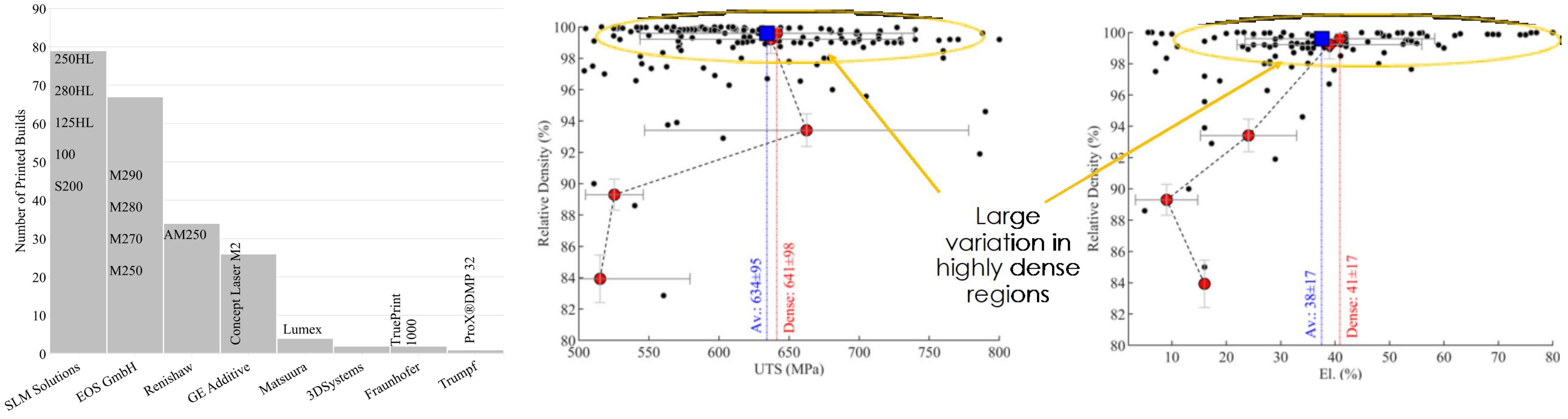
Variability: A Concern (Ex: SS 316L)

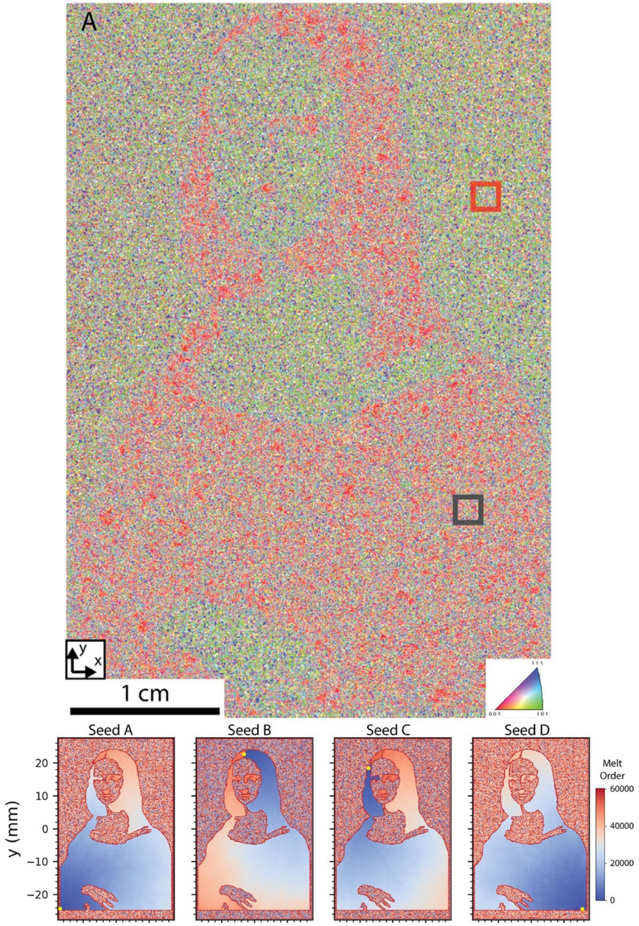


Significant variation in ultimate tensile strength: 641±98 MPa (Min: 400 MPa, Max: 1150 MPa)

Variation in elongation: 41±17%

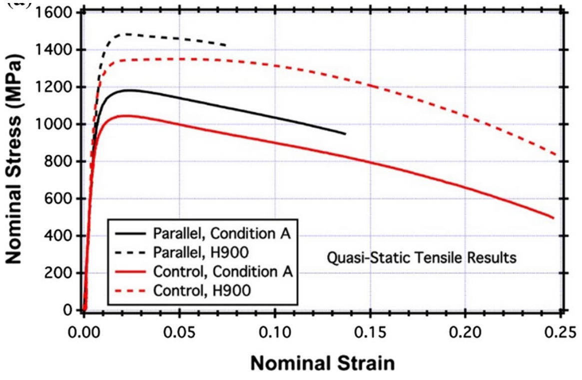
Volumetric energy density variation: 20-650 J/mm^3

Variability: Turning a Liability into an Asset

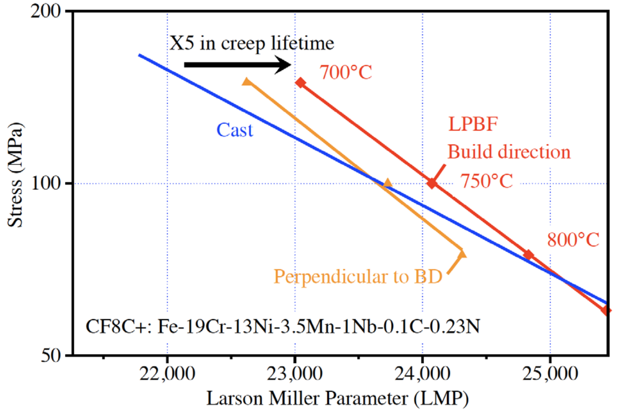


Microstructure control

Plotkowski et al. AM, 2021

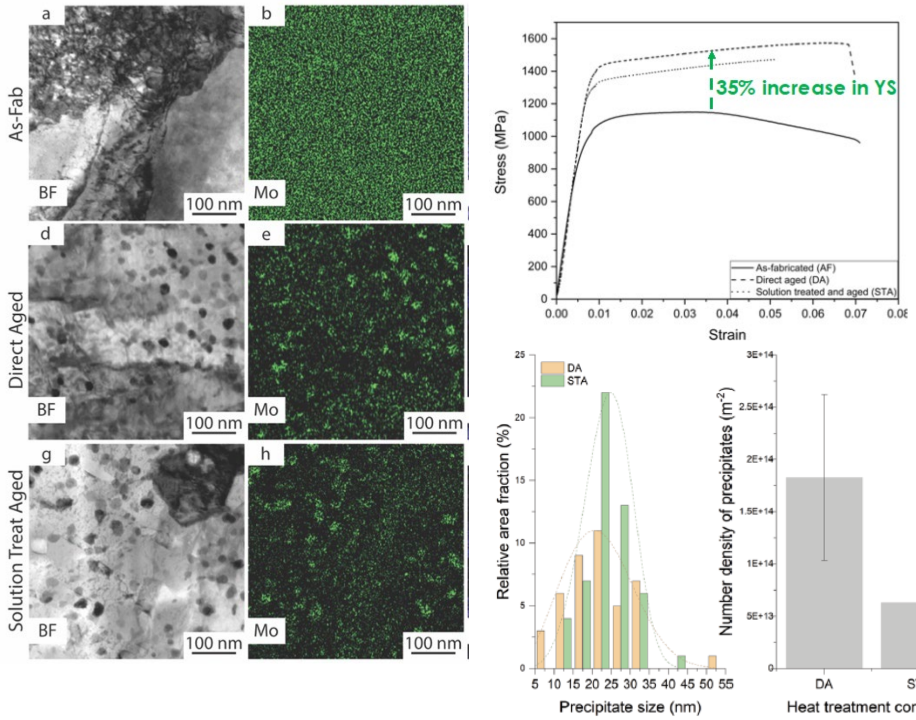


Hagdadi et al. J. Mat. Sci., 2021



Courtesy, S. Dryependt, ORNL

Superior properties compared to conventional



Nandwana et al. JOM, 2020

Post processing to achieve high number density of strengthening precipitates

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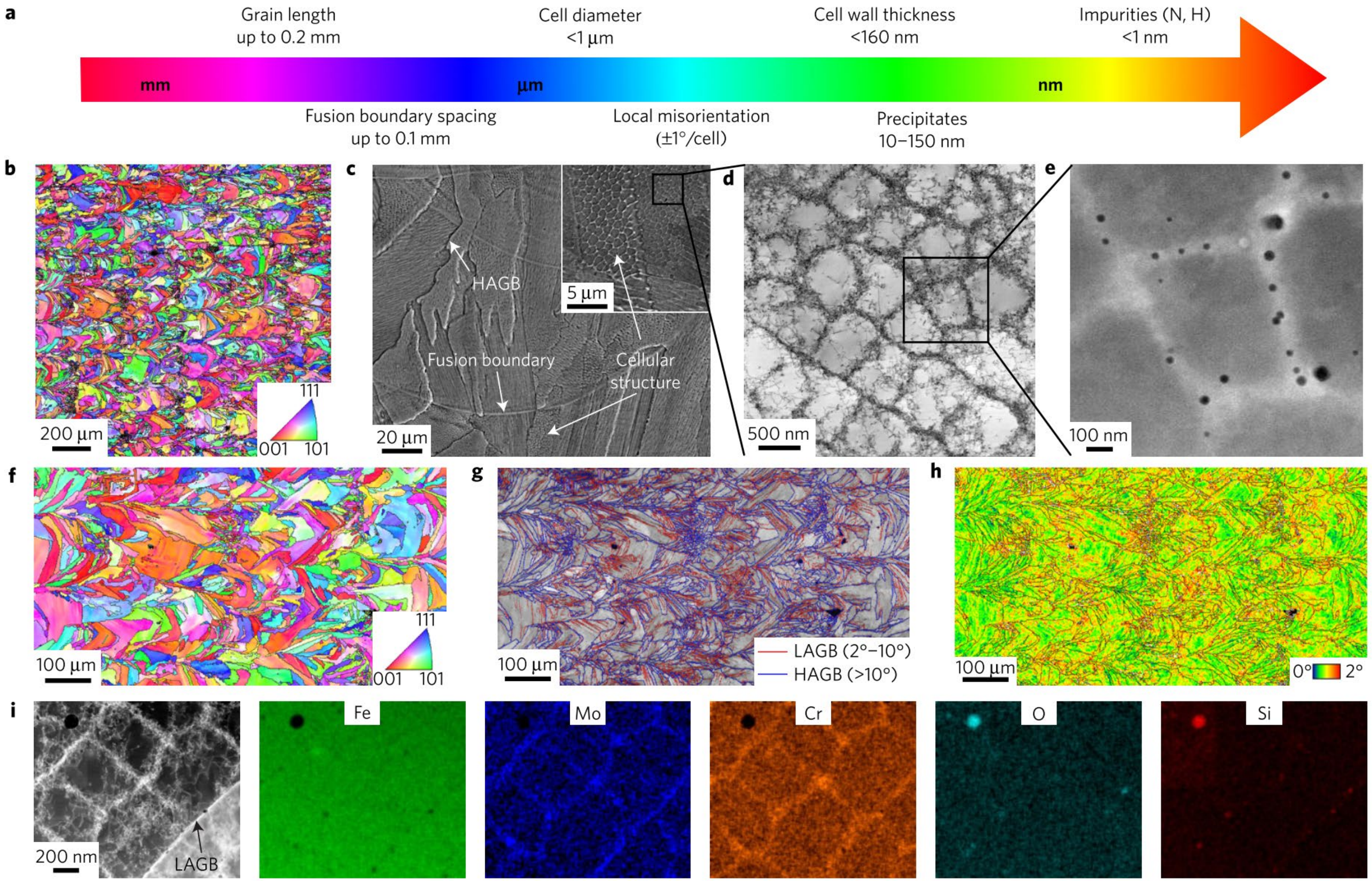
Variability Can Arise at Any Length Scale



Wang et al. Nature Materials, 2018

- 316SS has microstructural features that span nm – mm length scales
- The absence of variability at a mm length-scale or in mechanical properties does not necessarily mean the absence of heterogeneity
- Effects of these features on long-term performance of the material can be significant

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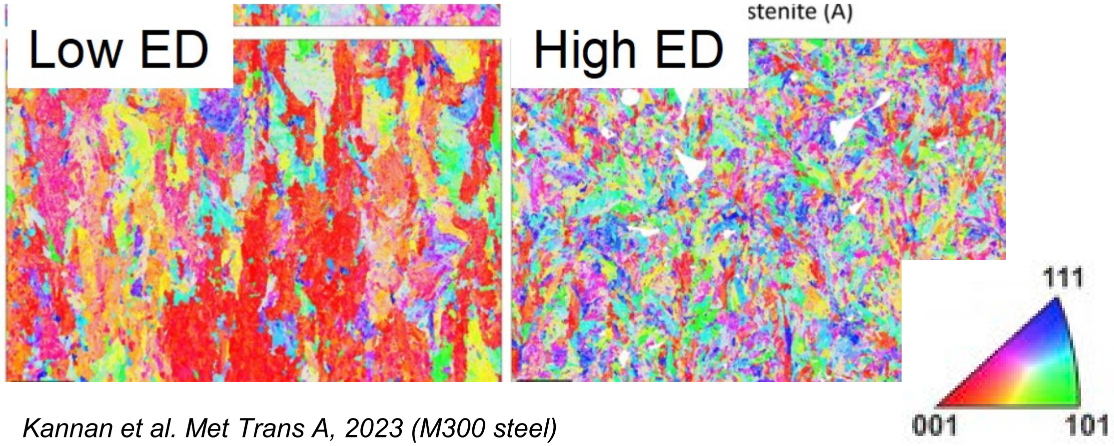
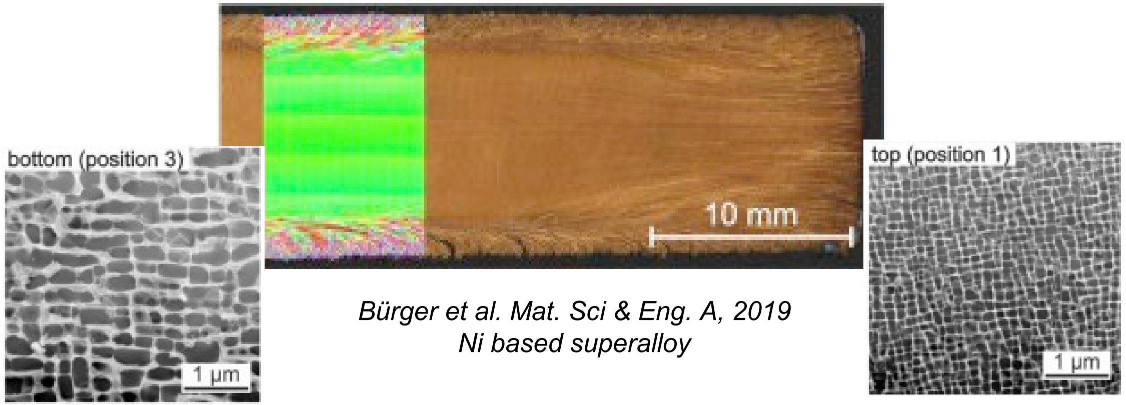
Sources of Variability



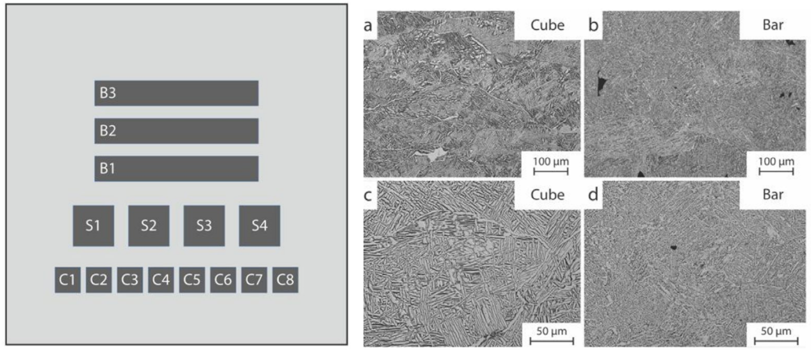
Kannan et al. Met Trans A, 2023 (M300 steel)

Process Variables



Bürger et al. Mat. Sci & Eng. A, 2019
Ni based superalloy

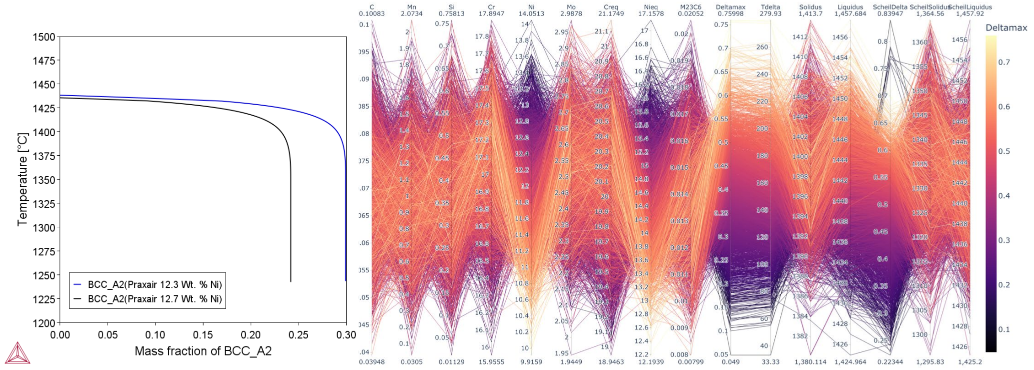
Spatial Variation Within a Build



Nandwana et al. Mat. Today Comm., 2020 (Ti64)

Geometry Effects

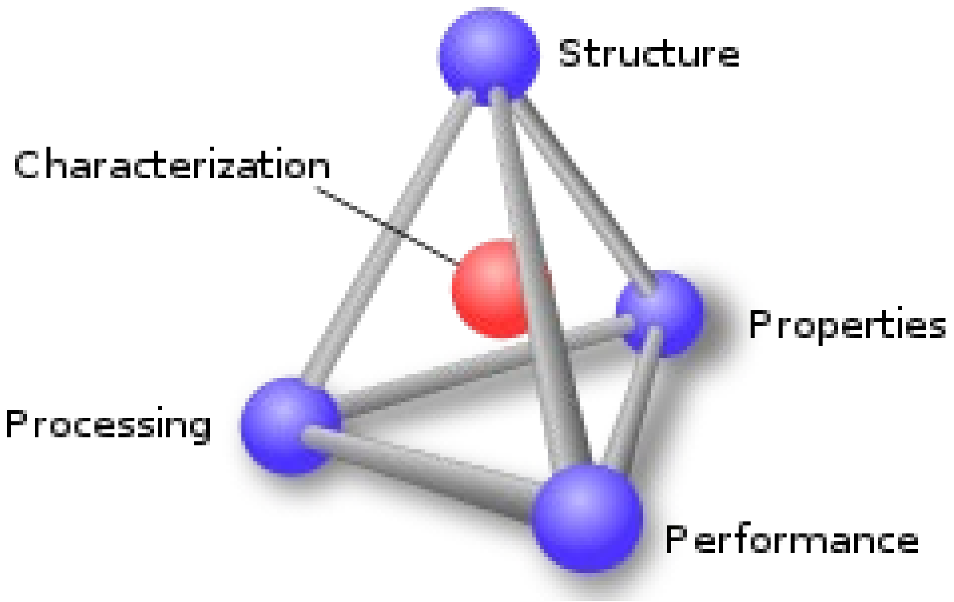
Machine to Machine

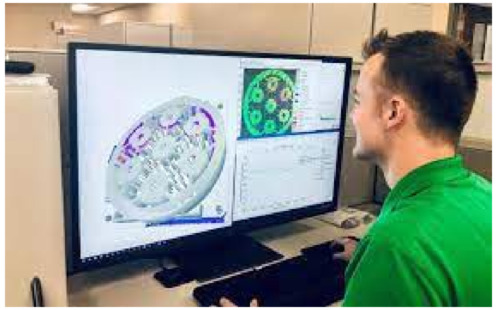


Kannan et al. IMMI, 2022 (SS316L)

Feedstock Chemistry

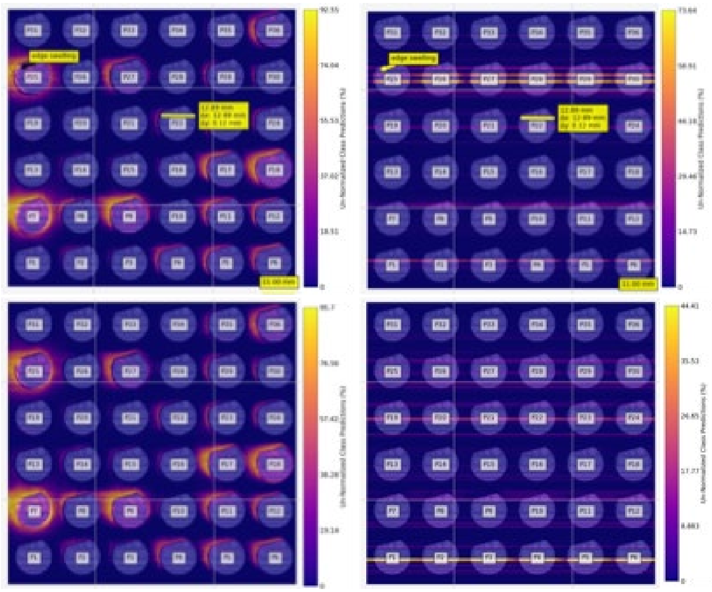
Approach to Qualification





Soot

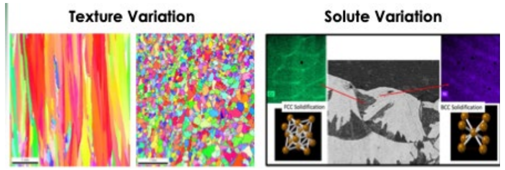
Streaking



Back to basics → But with a twist → In-situ process monitoring

Approach to Qualification: Multi-Lab Efforts

Machine-to-machine variability
Geographic effects



Process parameters
Spatial variation
Geometry effects

Process Development & Understanding

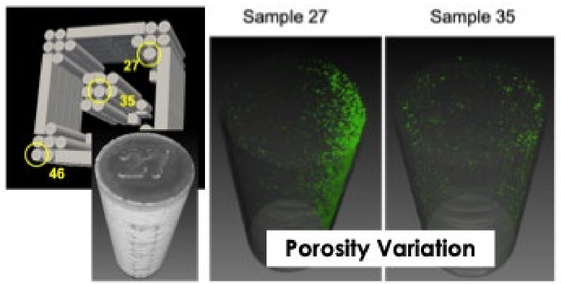
Round Robin Testing

Alloy Chem. Variations

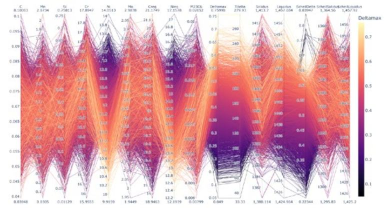
In-situ Sensing & Implementation

Modeling

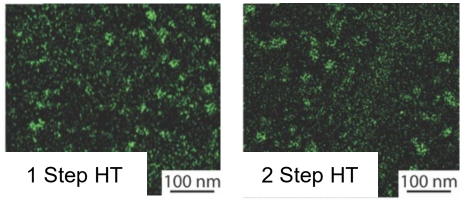
Post-Processing (hot isostatic pressing, heat treatments)



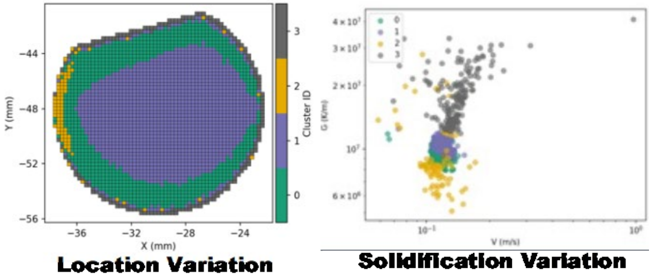
Defect detection
Quality assurance



Feedstock variability



Aid Precipitation
Enable Phase Selection
Reduce Variability

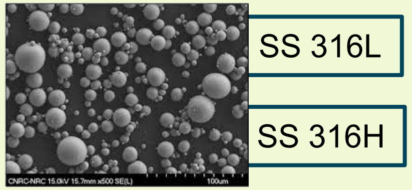


Process modeling
Microstructure modeling
Thermo-kinetic modeling

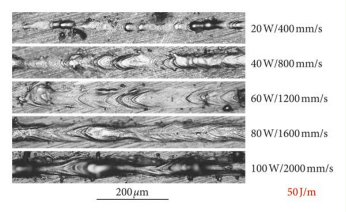
Tracking the Origins of Variability

MDDC

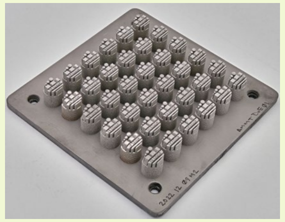
Feedstock



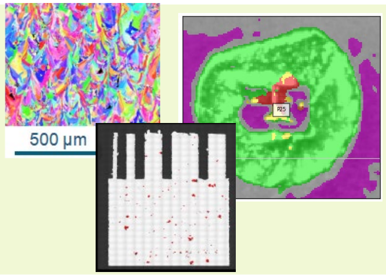
Process Variables



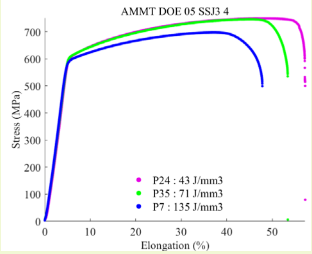
Geometry



Defects & Microstructure

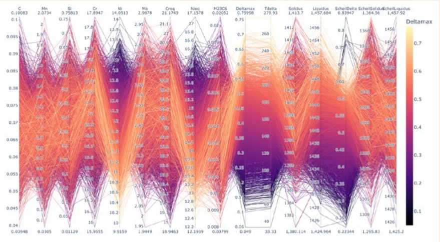


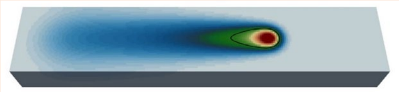
Performance

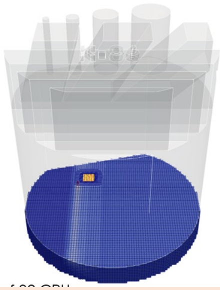


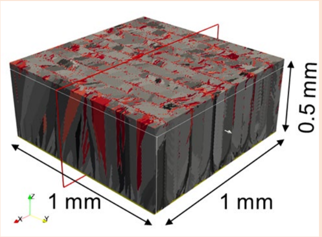
Experiment

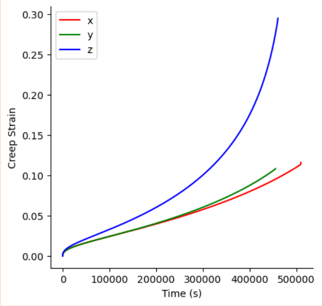
Modeling





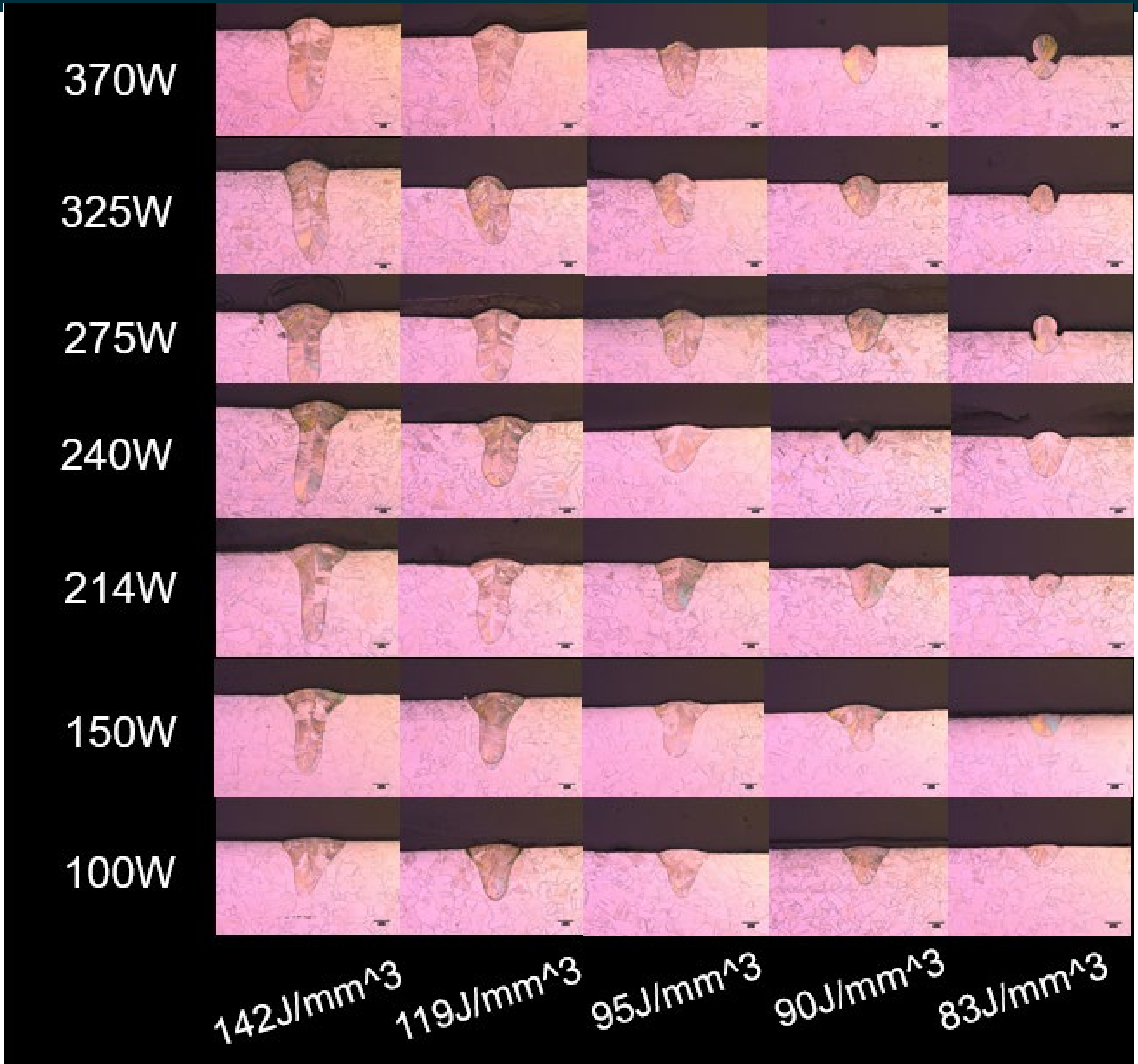


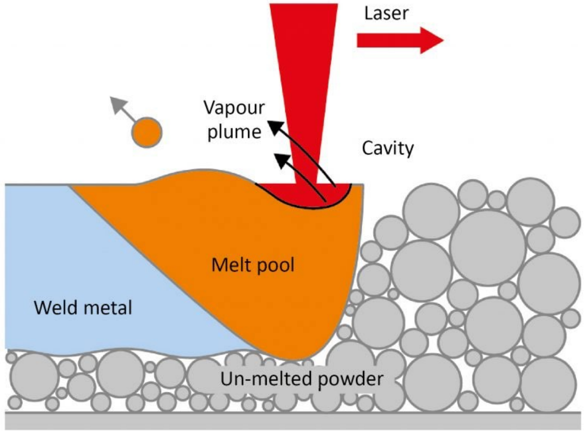




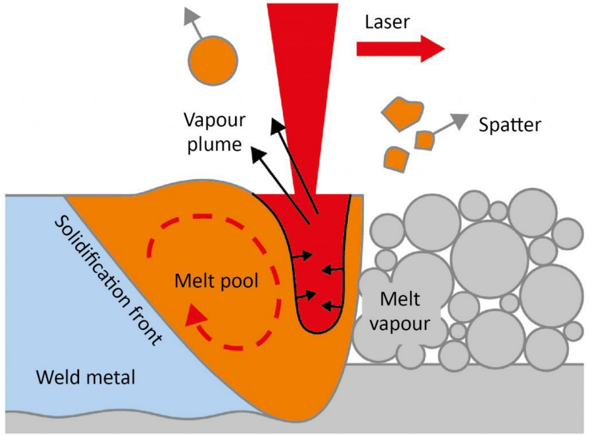
Implement on multiple machines across DOE labs

Building A Foundation: Single Track Melts

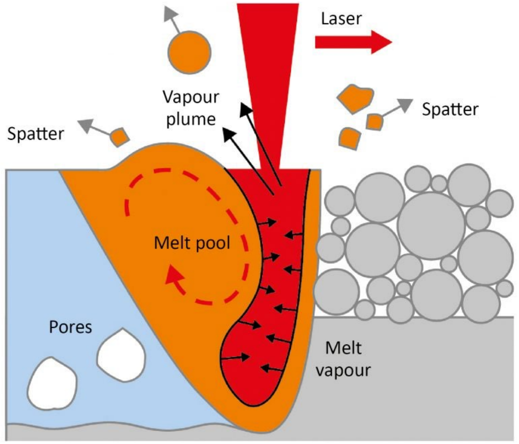




Insufficient Melting



Appropriate Melting



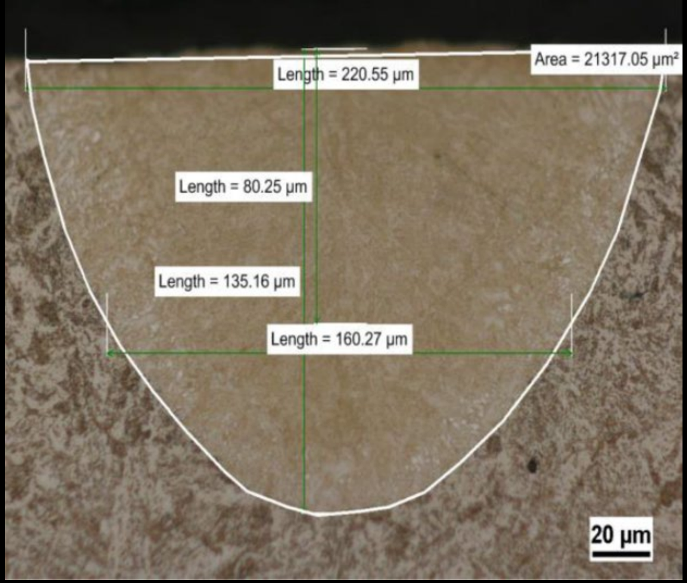
Keyhole Formation

Initial identification of processability

Input for melt pool model calibration

Alloy Effects on Processability

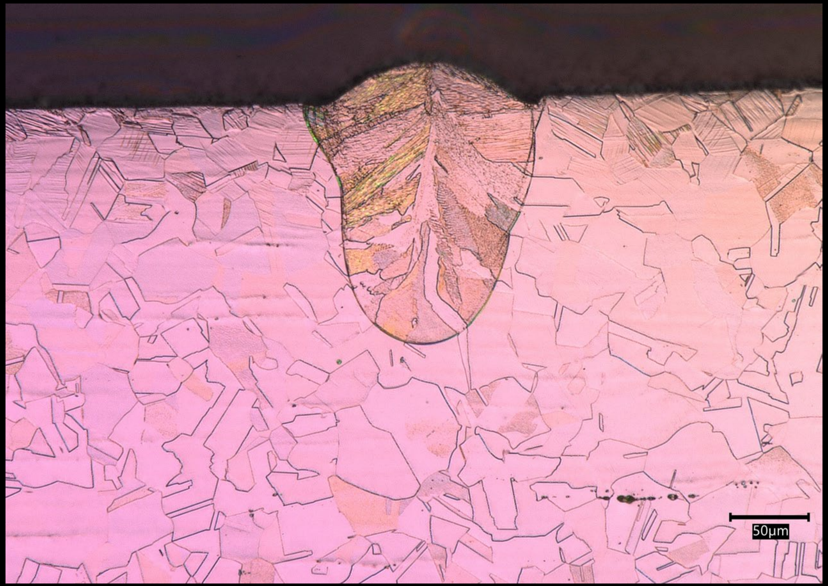
Optimal Parameters for 316L



214.2W
928mm/s
57.70J/mm^3

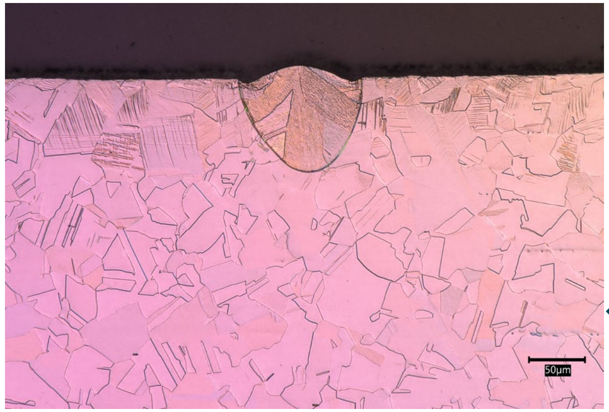
Carbon Content:
0.02%

Possible Optimal Parameters for 316H



275W
688mm/s
95J/mm^3

Carbon Content:
0.047%

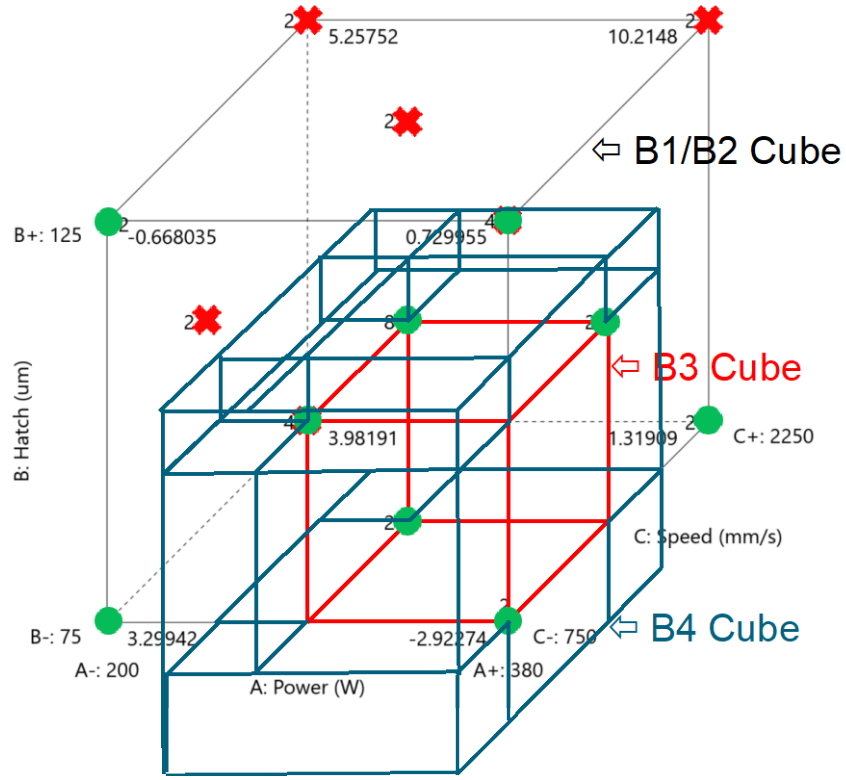


316H @ Optimal Parameters for 316L

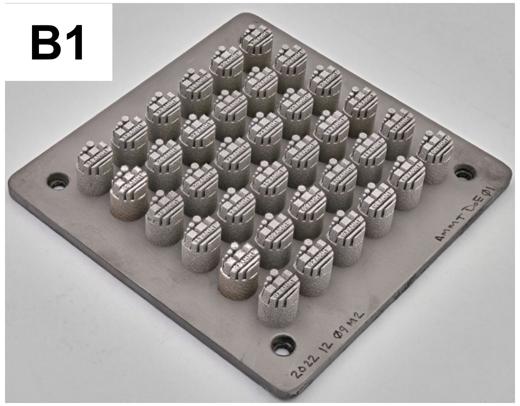
The increase in C content reduces the weldability and ductility of the material

Weld	316L	316H
Width (µm)	220	153
Depth (µm)	135	193
Area (µm^2)	21317	18924

Addressing AM Variability in LPBF: Process



Central composite design of experiments used to explore the process parameter space by varying **Power, Velocity, and Hatch Spacing on a Concept Laser M2**

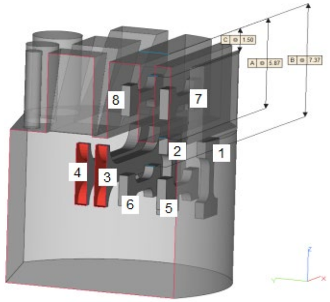


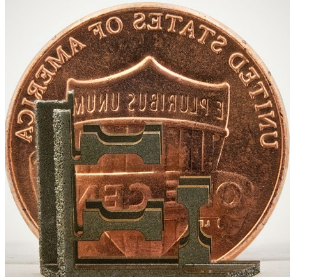
Power: 200 – 380 W
Hatch: 75 – 125 μm
Speed: 750 – 2250 mm/s

Power: 290 – 380 W
Hatch: 75 – 100 μm
Speed: 750 – 1500 mm/s

B4

Power: 250 – 380 W
Hatch: 60 – 110 μm
Speed: 400 – 1800 mm/s





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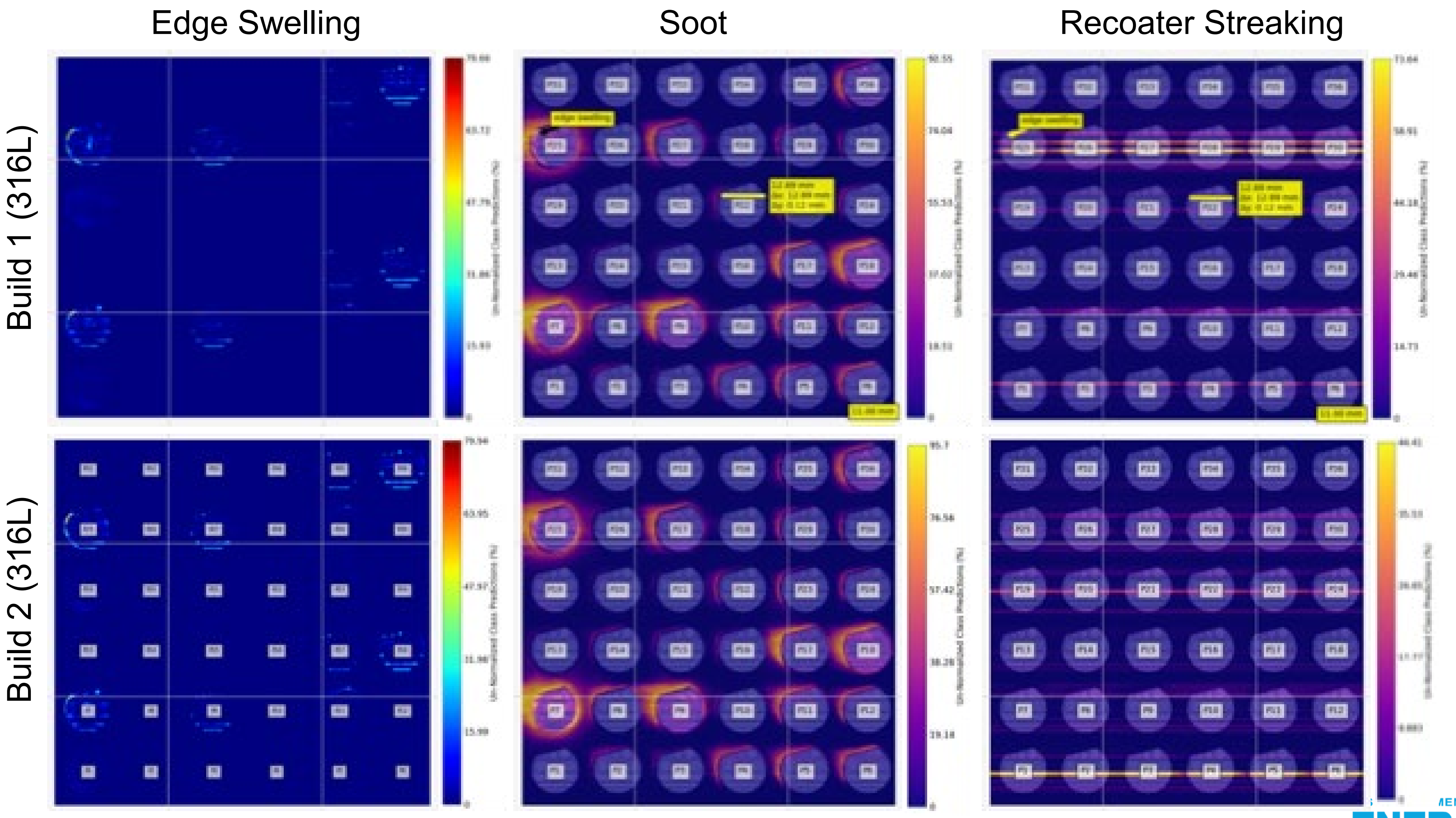
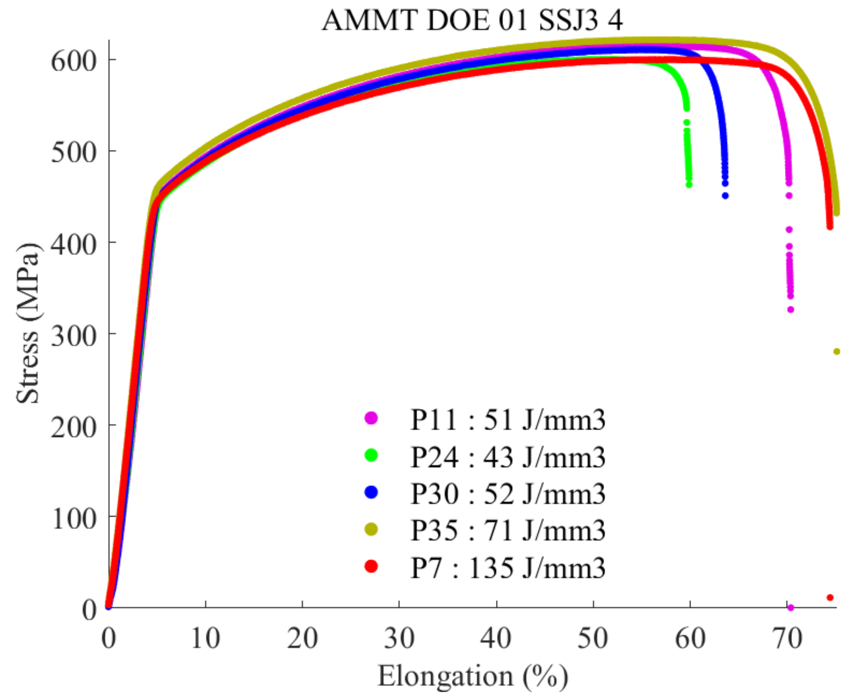
Addressing AM Variability in LPBF: Build-to-Build

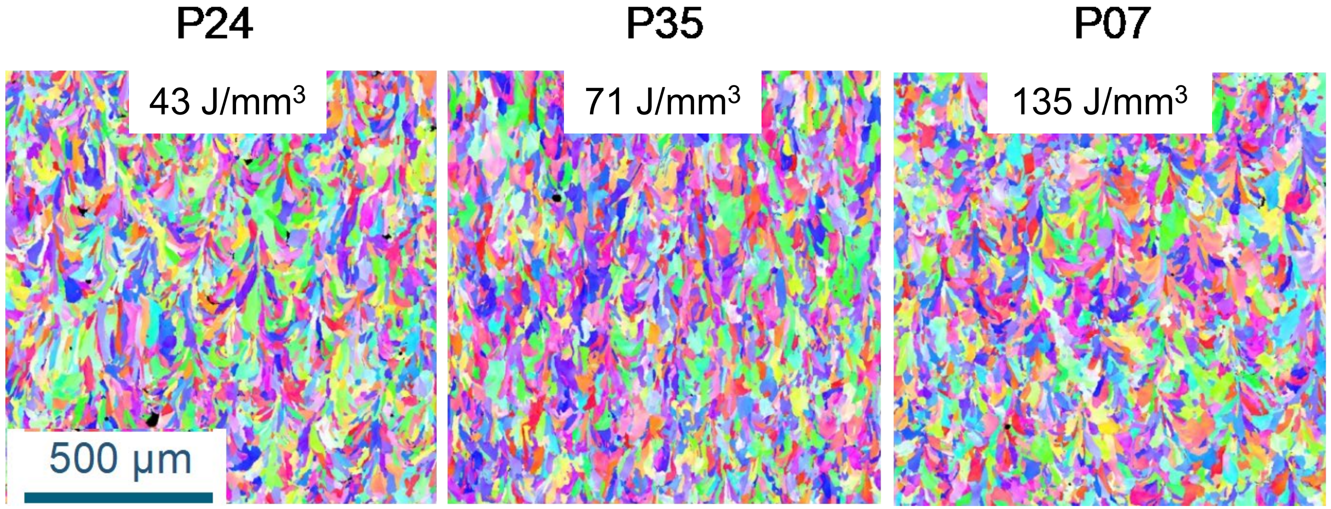


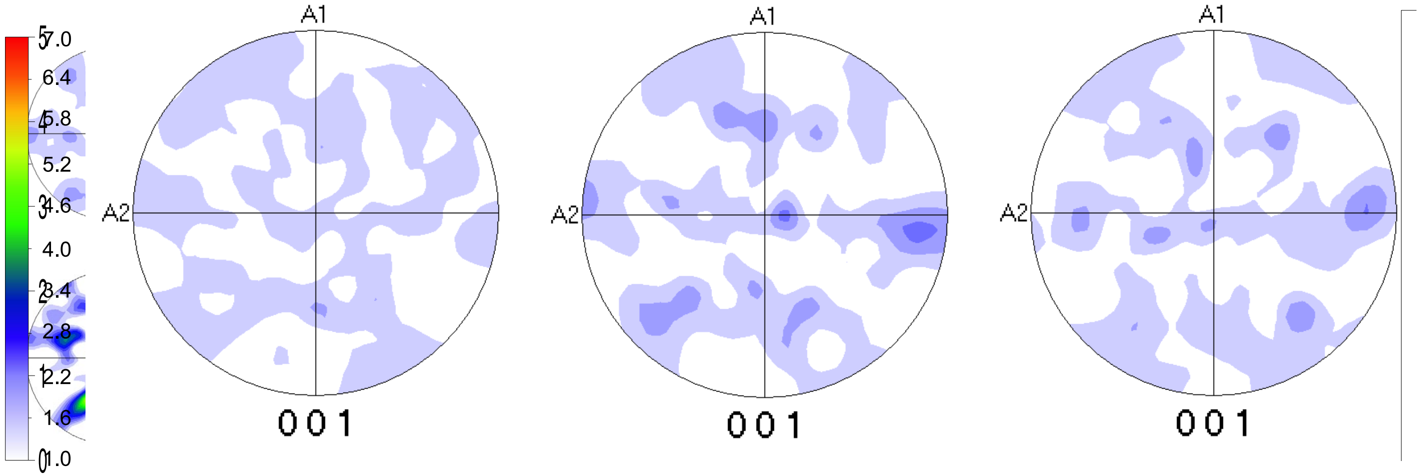
Identical builds conducted on two different days

In-situ signals consistent between the builds

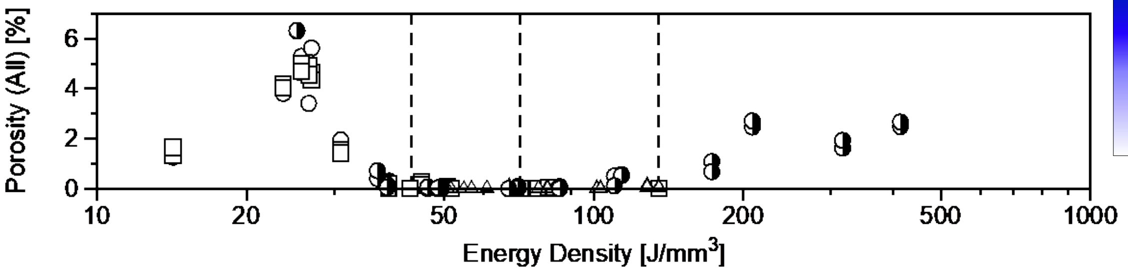
Does Energy Density Impact Microstructure & Strength?







No noticeable change in tensile strength and microstructure



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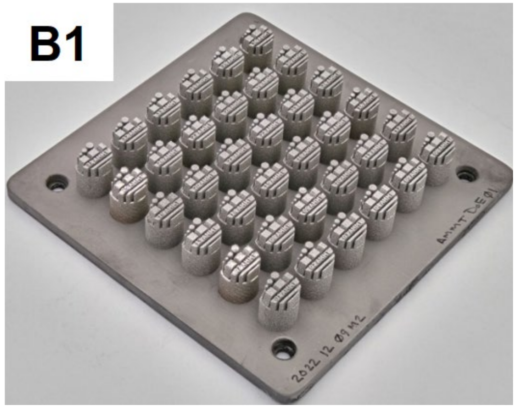
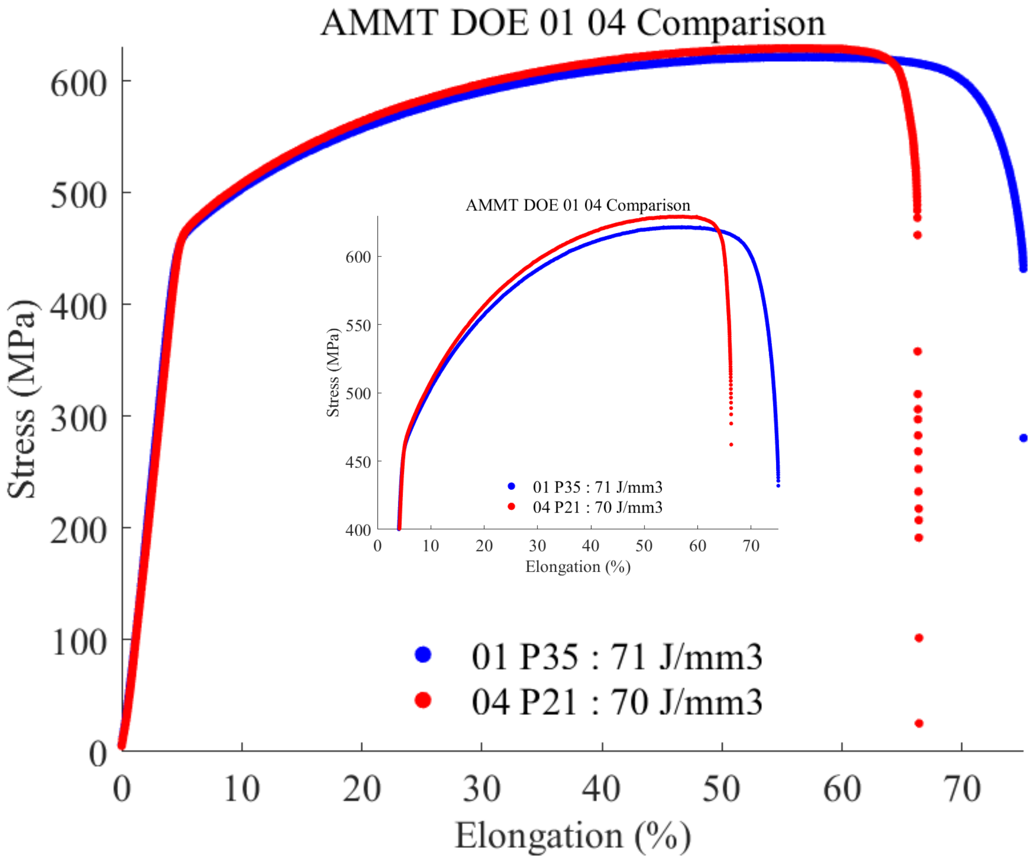
How About Same Energy Density (71J/mm^3) With Different Process Variables?



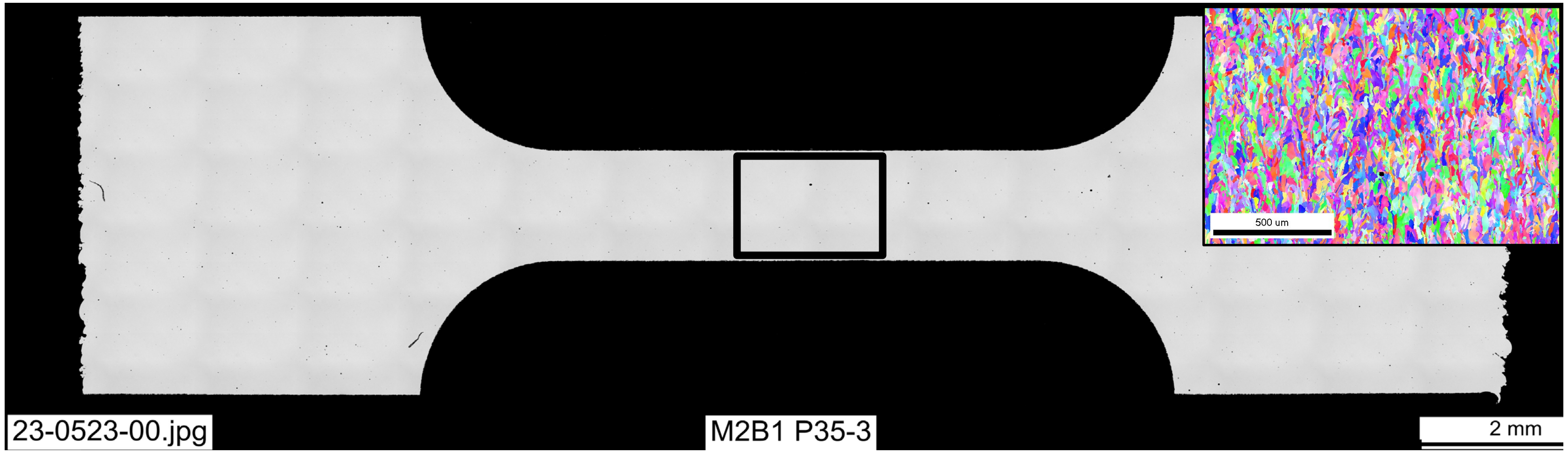
B1-P35: 71J/mm^3
P=200W
V=750mm/s
Hatch=75μm

B4-P21: 70J/mm^3
P=380W
V=1800mm/s
Hatch=60μm



Similar energy density, despite the change in individual parameters results in **same yield strength** and insignificant differences in UTS

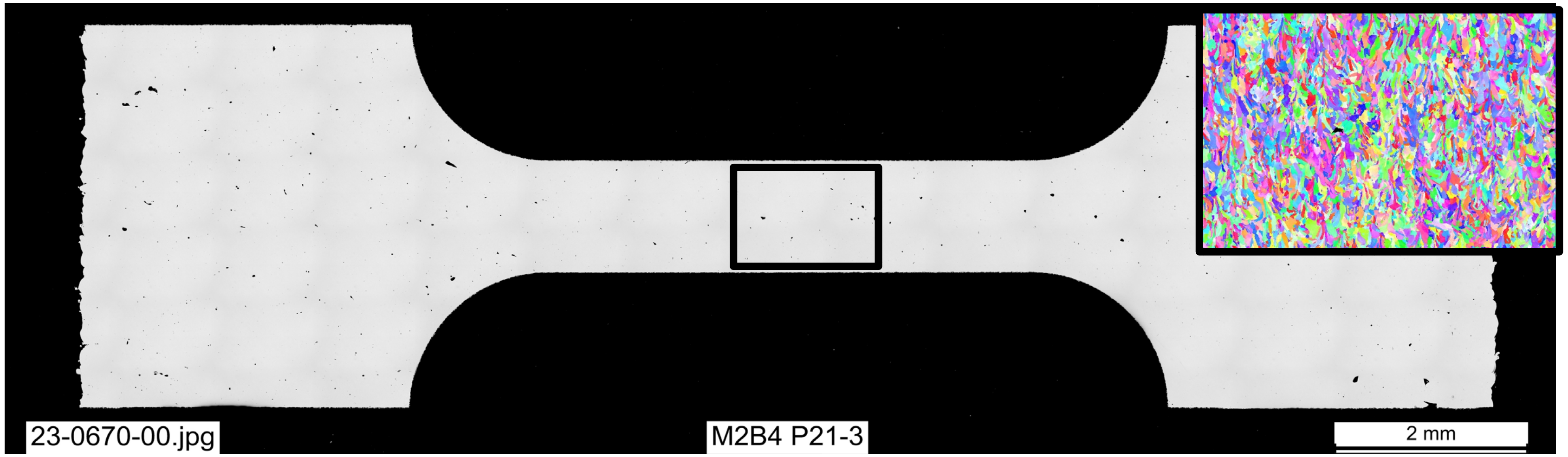
How About Same Energy Density ($71 J/mm^3$) With Different Process Variables?



B1-P35: $71 J/mm^3$
P=200W
V=750mm/s
Hatch=75μm

Higher beam speed results in **higher porosity in B4-P21** despite having the same energy density

Texture is similar



B4-P21: $71 J/mm^3$
P=380W
V=1800mm/s
Hatch=60μm

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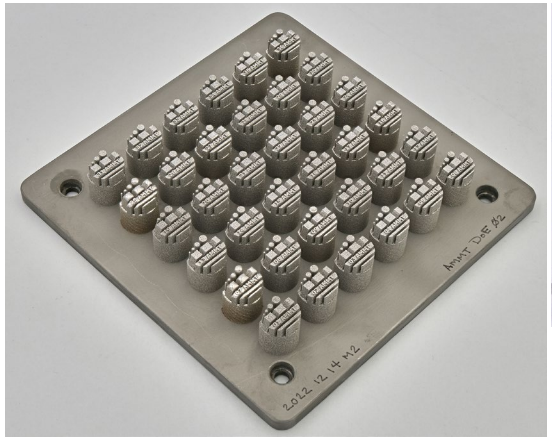
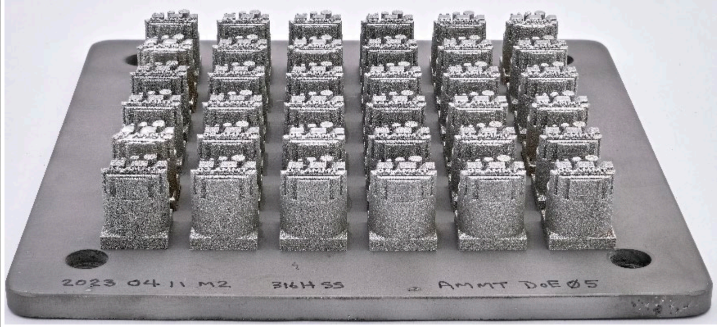
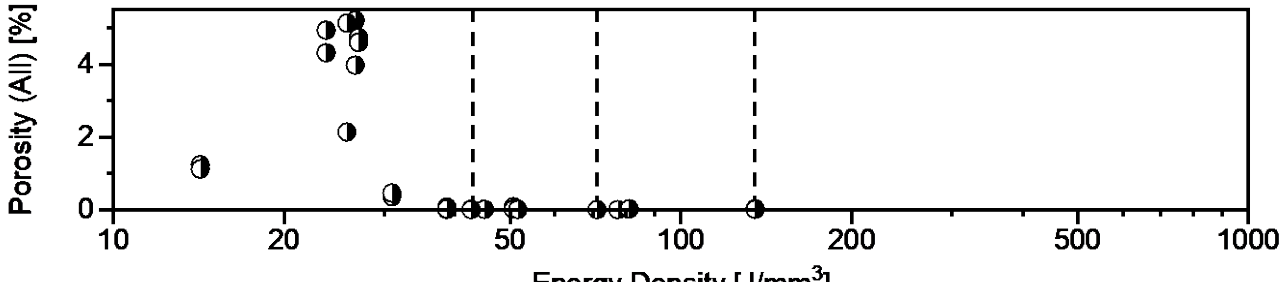
Shifting Gears: Do the Findings Translate to SS316H

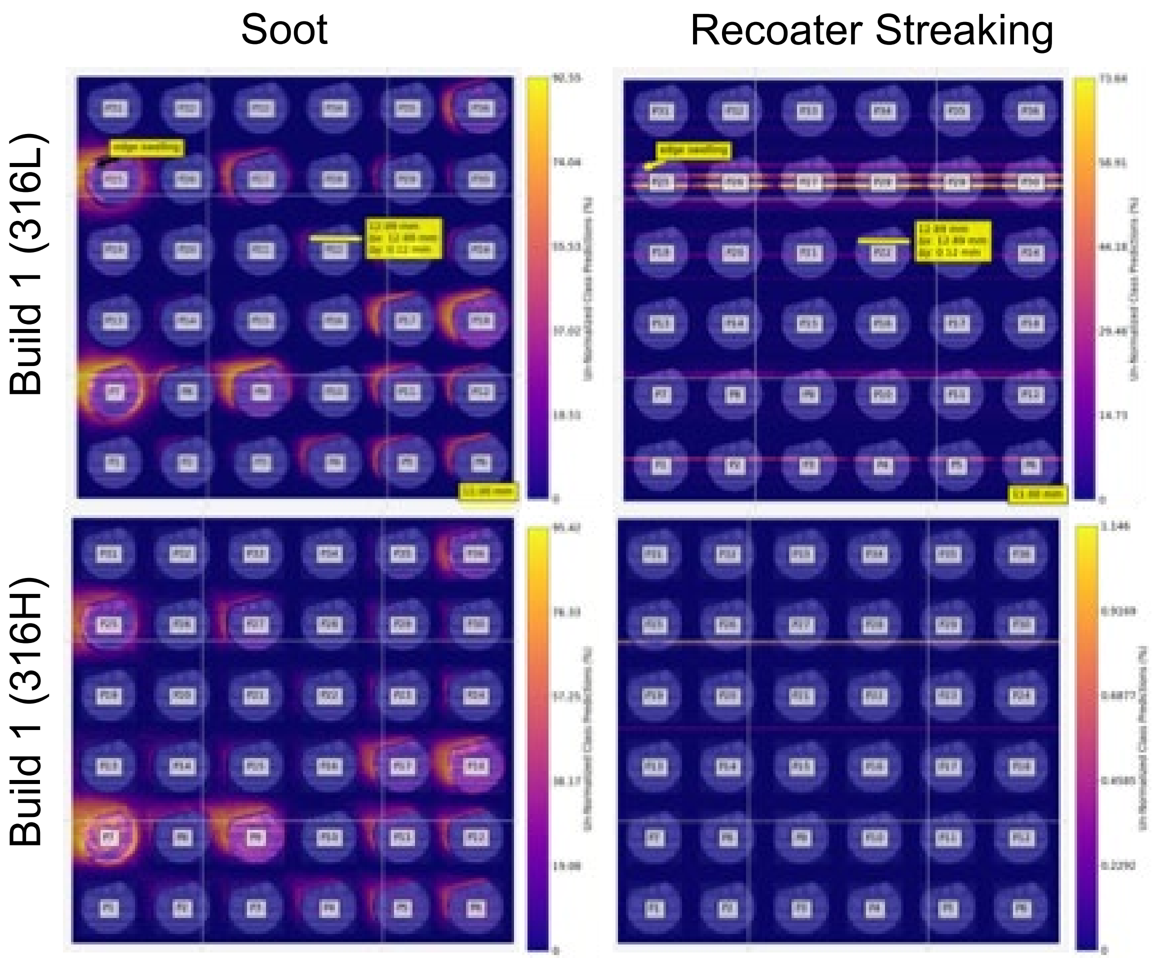




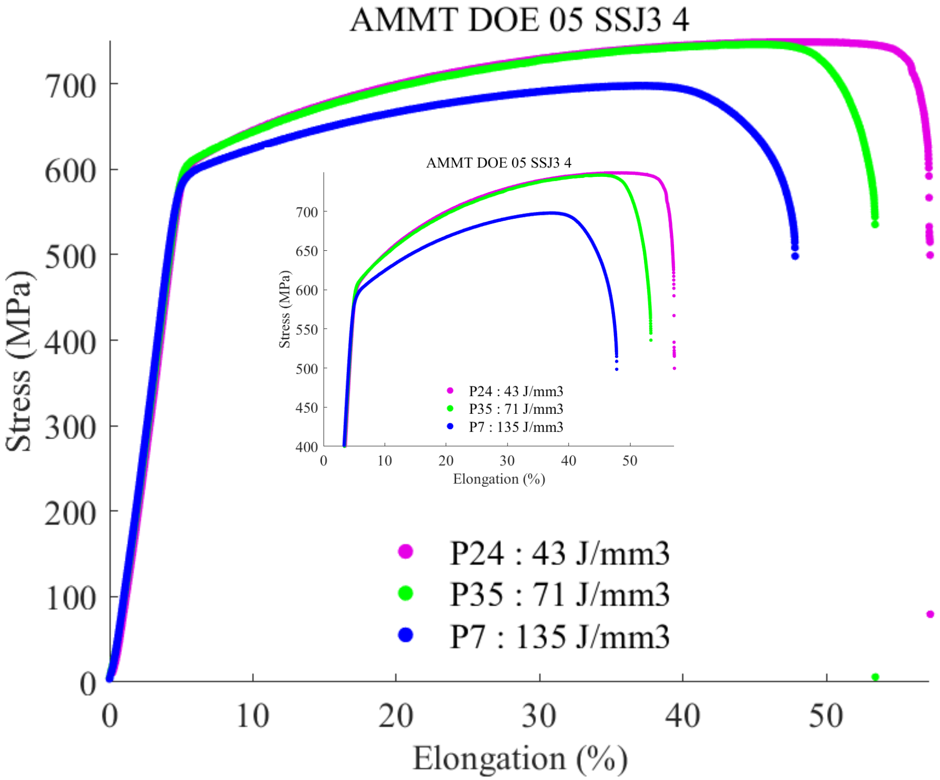
Visually noticeable – Build surface is qualitatively rougher in SS316H compared to 316L when processed with the exact same parameters

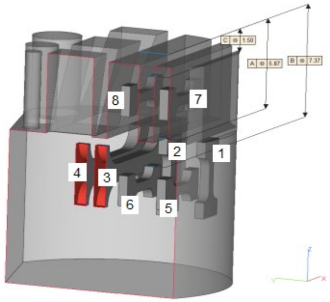
In-situ process monitoring shows similar trends despite the change in powder chemistry, increase in carbon (0.08 wt.%)

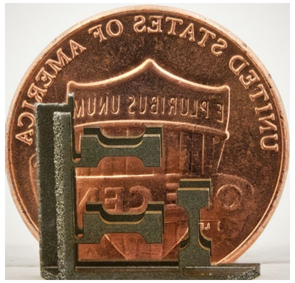




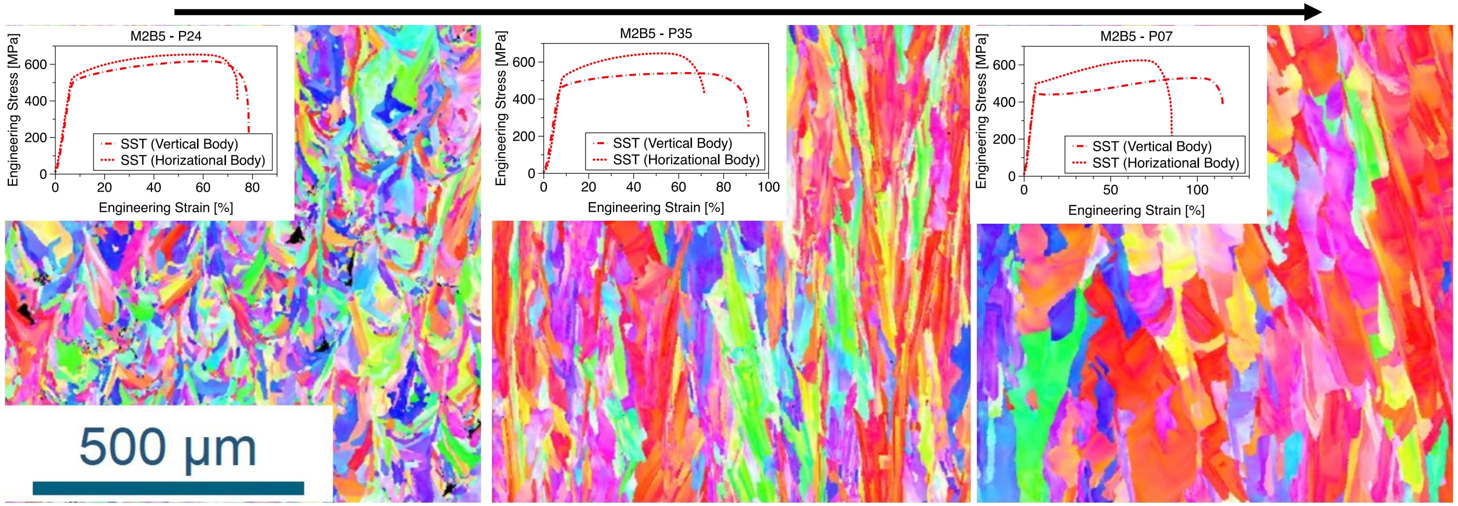
SS316H: What About Variability?







Increasing Energy Density

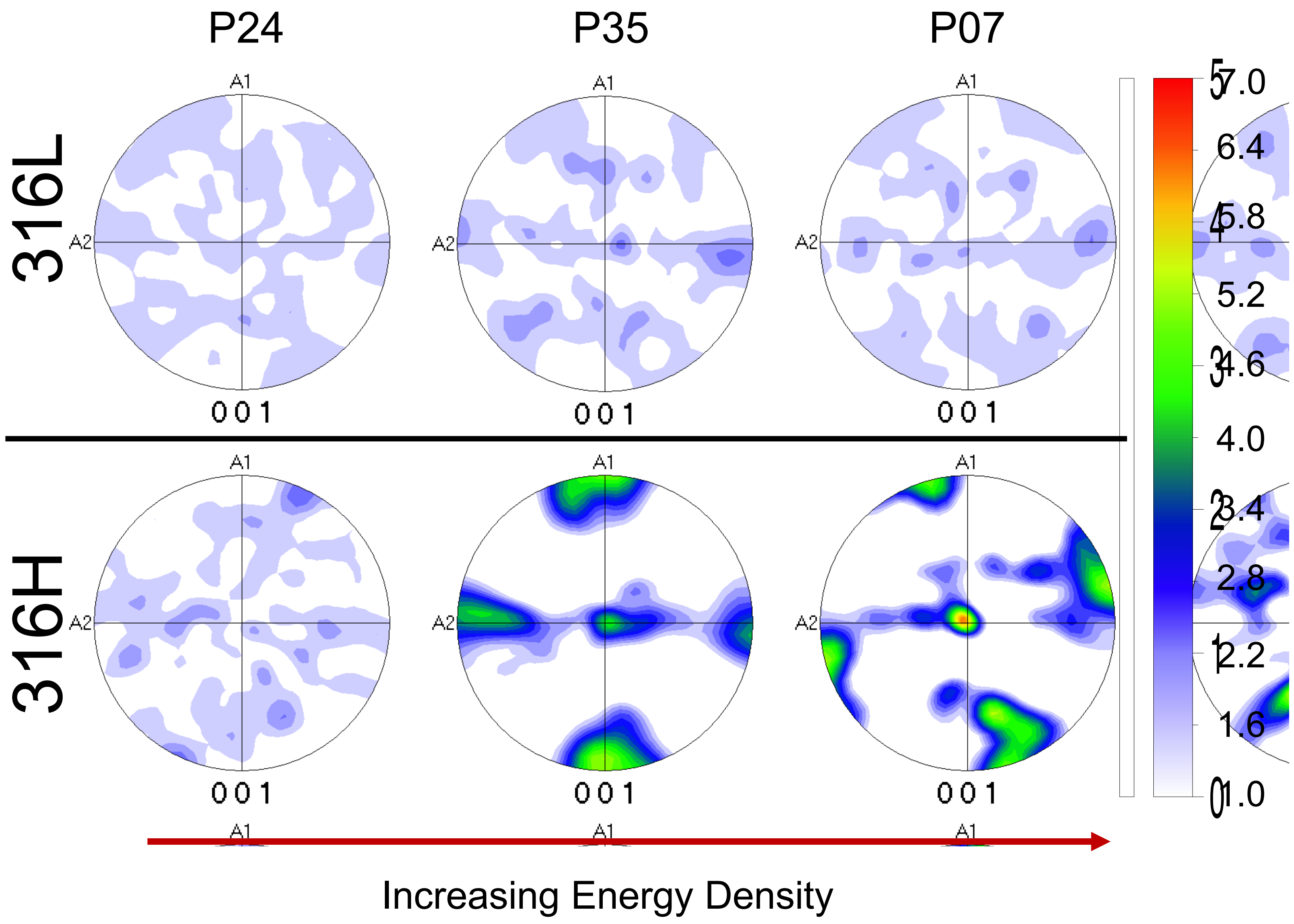


Despite microstructure change, the bulk tensile properties are similar for energy density values of 43J/mm^3 and 71J/mm^3

Increasing the energy density to 135J/mm^3 results in a drop in both UTS and elongation, even though the YS is similar

Anisotropy evident in SS-T samples

Composition Matters: 316L vs. 316H



Energy density has a weak, if any, **effect on SS316L**

316H, on the other hand is **more sensitive to the heat input**, indicating a difference in solidification behavior and subsequent texture evolution

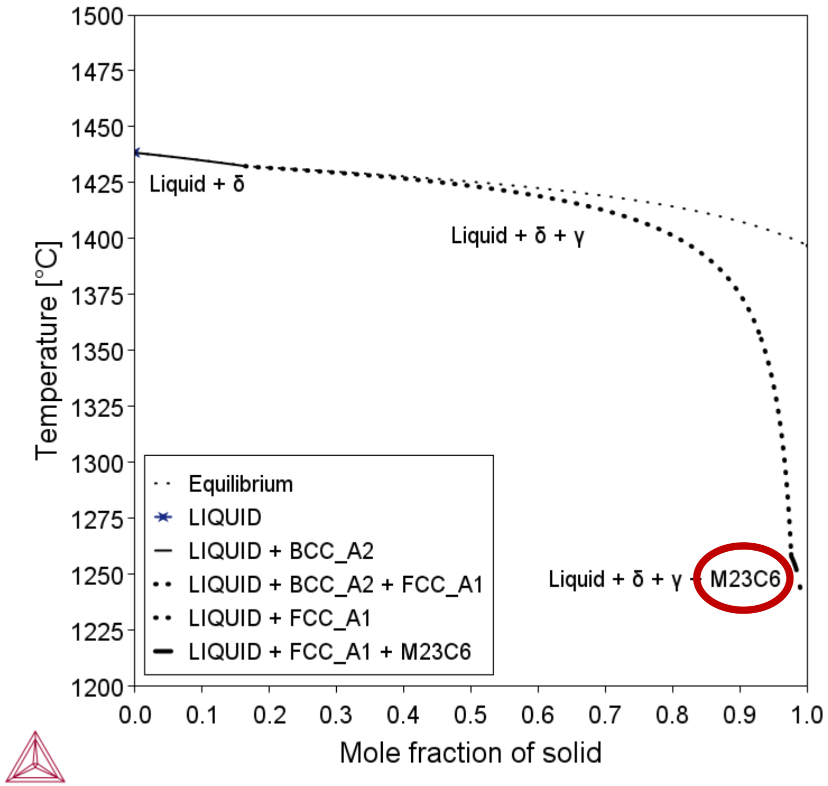
Feedstock Associated Variability: SS316H

All three powders are within spec. for SS316H

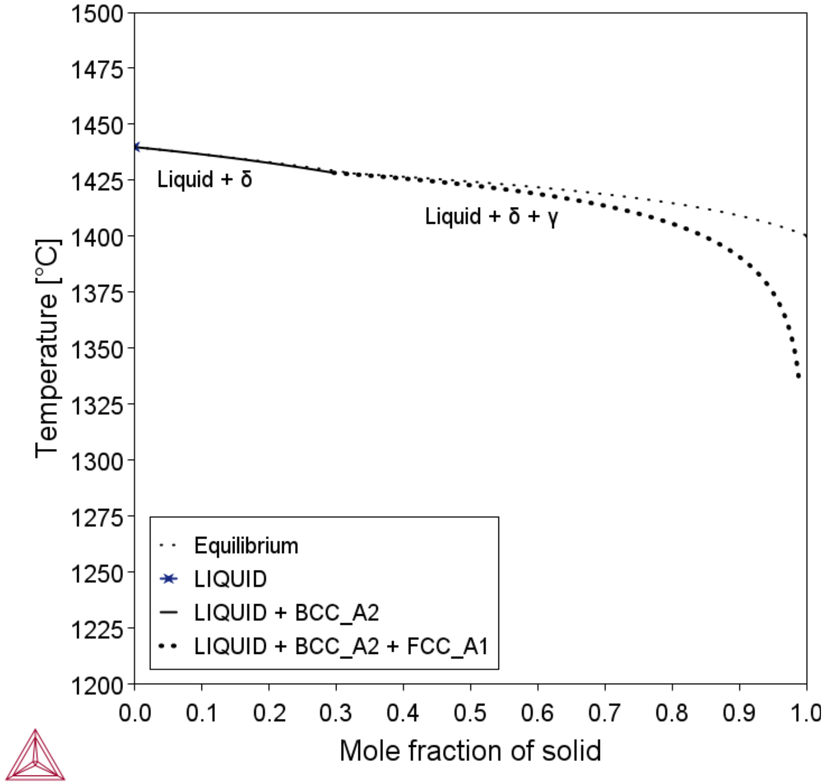
	Powder 1	Powder 2	Powder 3	Spec.
Carbon	0.08	0.06	0.04	0.04-0.10
Oxygen	0.03	0.03	0.03	0-NS
Nitrogen	0.01	0.01	0.05	0-NS
Chromium	17.0	16.8	16.4	16-18
Nickel	12.3	12.1	10.0	10-14
Manganese	1.05	1.13	1.0	0-2
Molybdenum	2.3	2.5	2.1	2-3
Silicon	0.07	0.48	0.4	0-1
Phosphorous	<0.005	<0.005	0.02	0-0.045
Sulfur	0.0	0.00	<0.005	0-0.03
Iron	Bal.	Bal	Bal	Bal

Compositions in wt.%

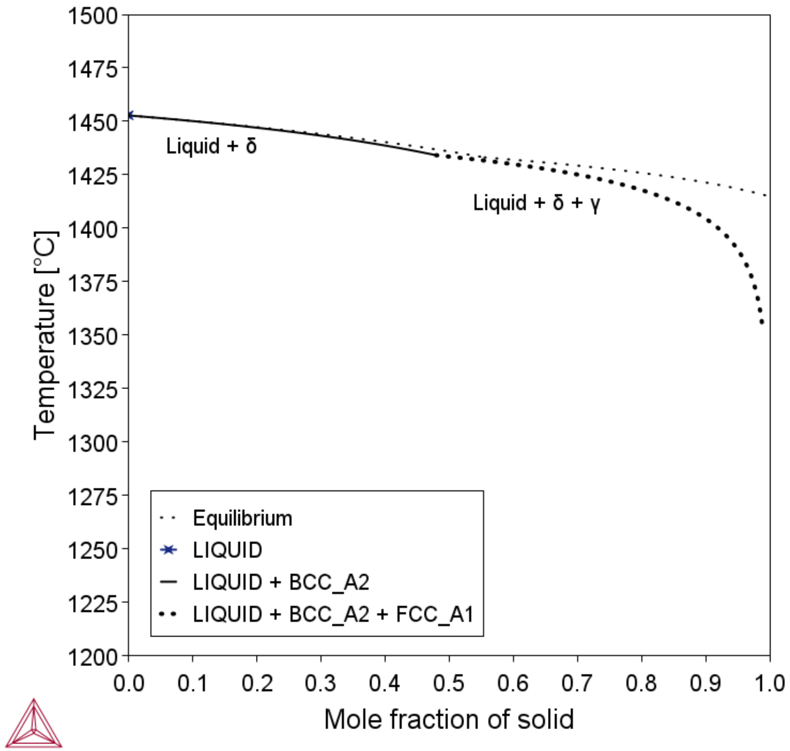
How About Solidification?



Powder 1
0.08 wt.%C



Powder 2
0.06 wt.%C



Powder 3
0.04 wt.%C

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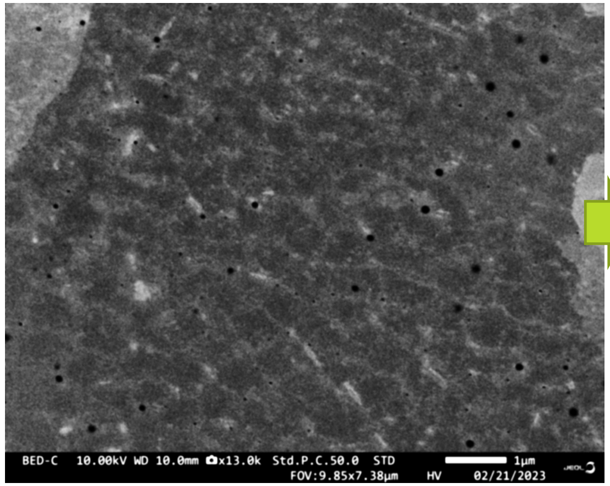
Synthetic Data to Expand the Composition Space

1 million synthetic compositions, all within SS316H spec to identify compositions with highest $M_{23}C_6$ on a regular laptop within 1 hour

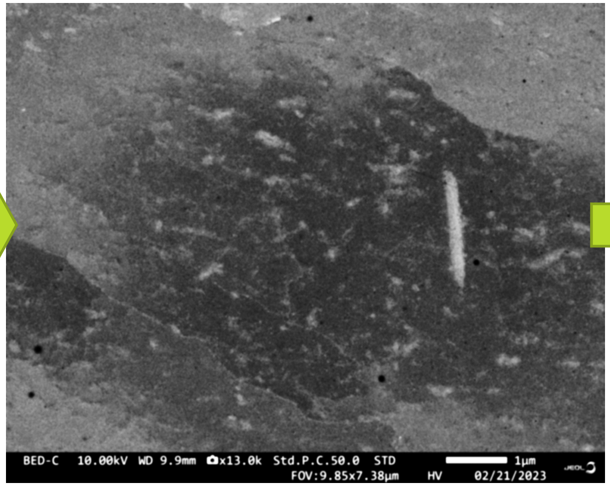
Approach based on Kannan & Nandwana, Scripta Mat. 2023

Post-Processing: Long Term Aging Needed for SS316H

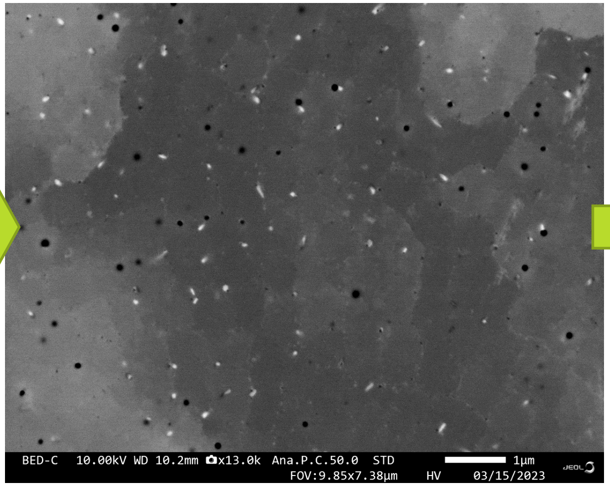
As-built



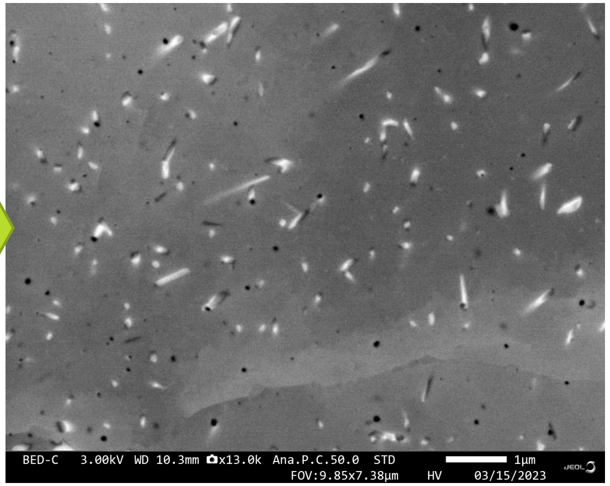
650°C-100h



650°C-500h



750°C-500h

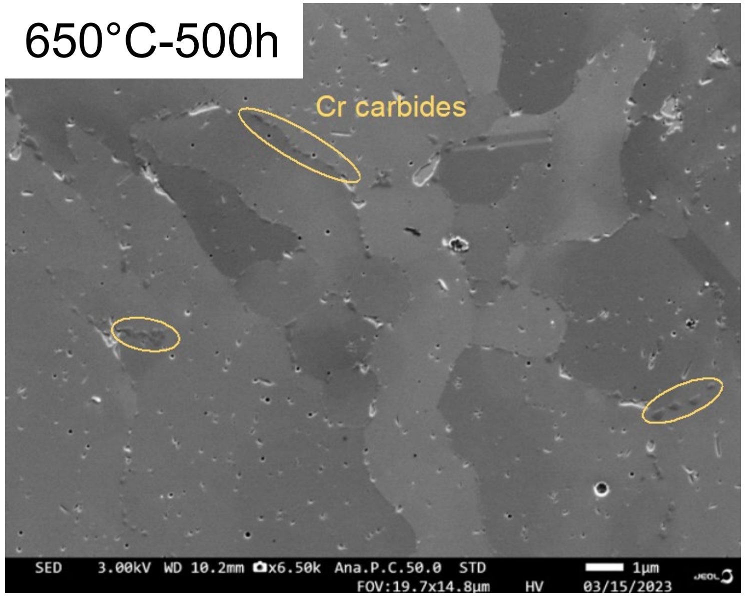


As-fabricated microstructure free of carbides

Long term aging results in Cr-rich grain boundary carbides and Mo-Si rich phases

Characterization ongoing to identify the precipitates and their origin

650°C-500h



Summary

- ➢ Variability is a challenge in AM
- ➢ However, it can be a tool to control the microstructure and properties
- ➢ Team is well-positioned to track, understand and mitigate the sources of variability
- ➢ A microstructure and performance-based qualification approach is more agile
- ➢ **Industry partnerships critical to address component relevant (geometric) sources of variability**

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