

How AM Parts Fail: Influence of Build Orientation and Post Machining

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Motivation

Electro-discharge machining (EDM) of as-printed material:

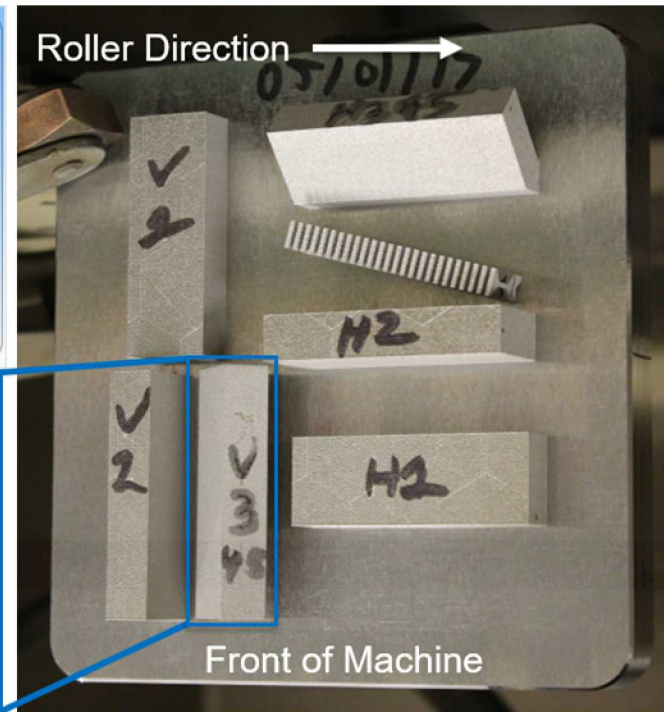
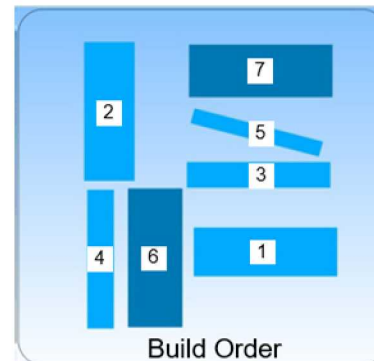
- Reduces surface microcracks
- Reduces surface roughness
- Increases strength



What are the failure mechanisms of AM as-printed and EDM mechanical properties in various orientations?

Machine Parameters:

100 W Laser Power
1400 mm/s laser mark speed
30 μm layer thickness
0 laser defocus
50 μm hatch spacing
Hexagon pattern



*V and H denote orientation in XY on plate

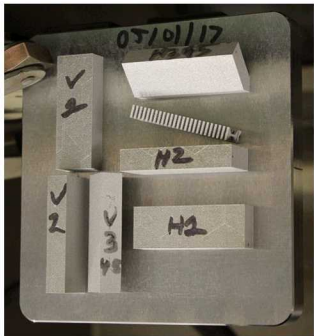
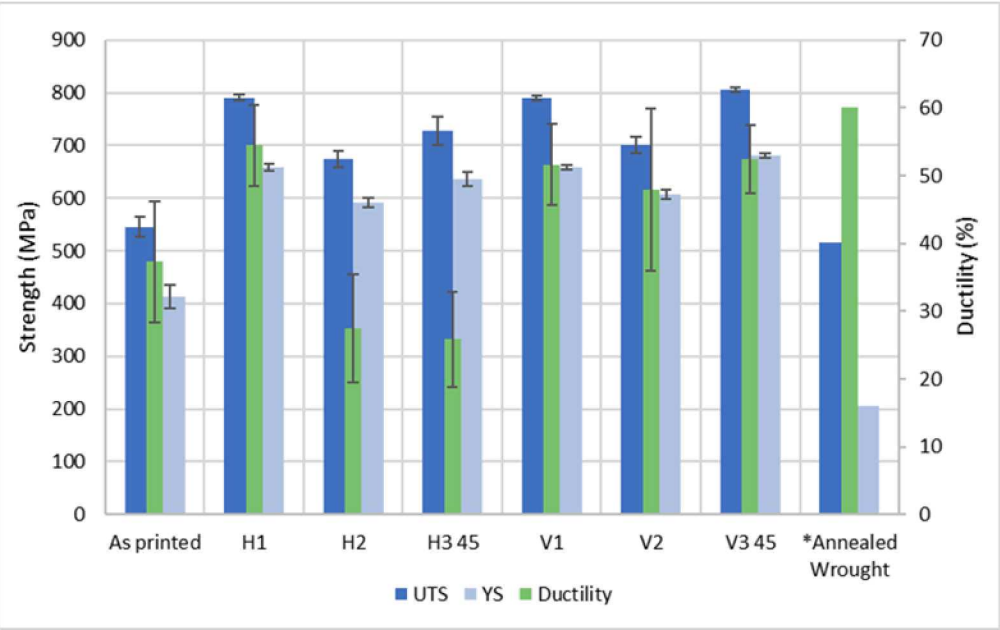
Mechanical Properties

- UTS highest: V3-45, H1, V1
- Yield highest: V3-45, V1, H1
- Ductility highest: H1, V3-45, V1
lowest: H2, H3-45
- As-printed lowest properties

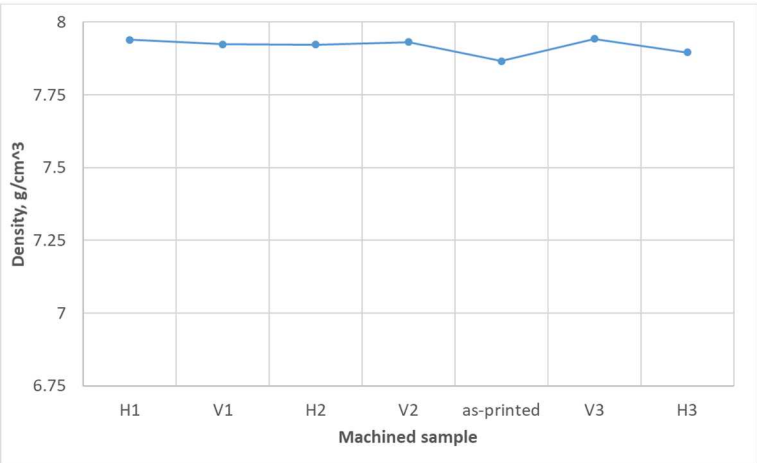
Why bad performance for as-printed?

Why ductility so low for H2 & H3-45?

Why horizontal better than vertical?



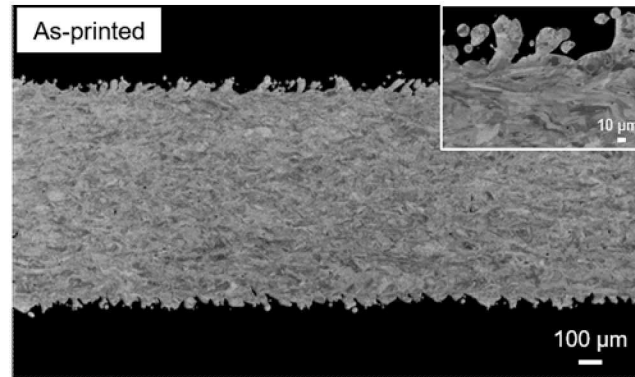
build plate
orientation in the
ProX 200



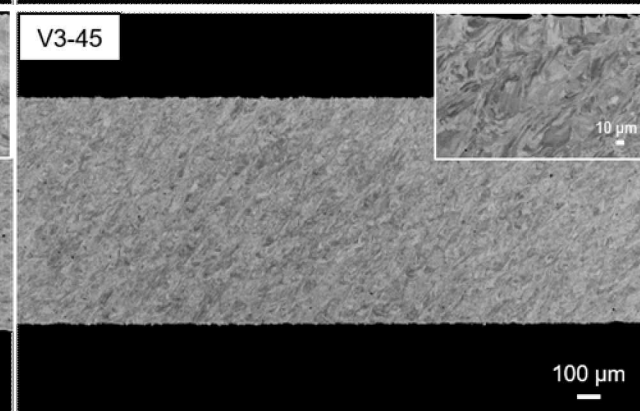
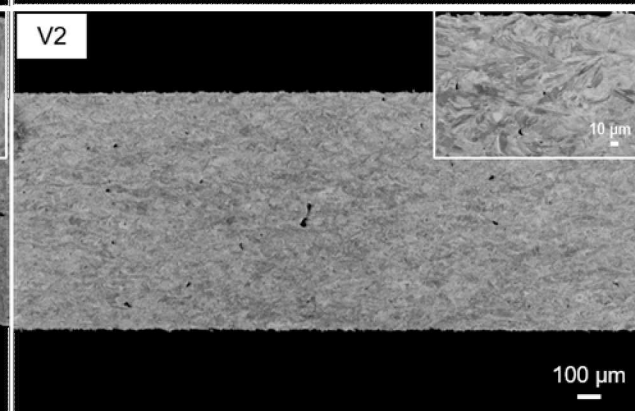
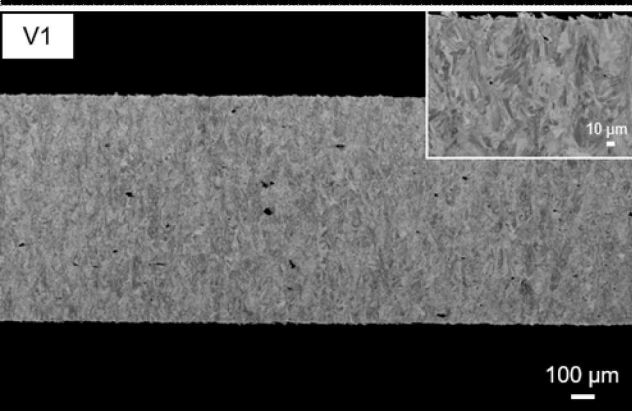
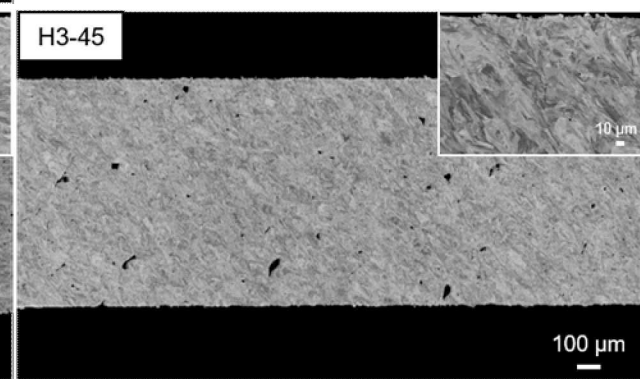
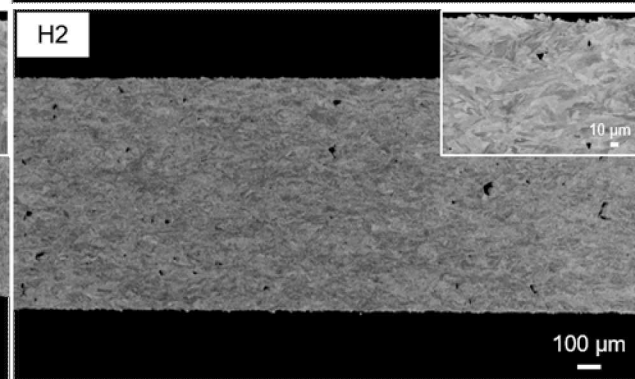
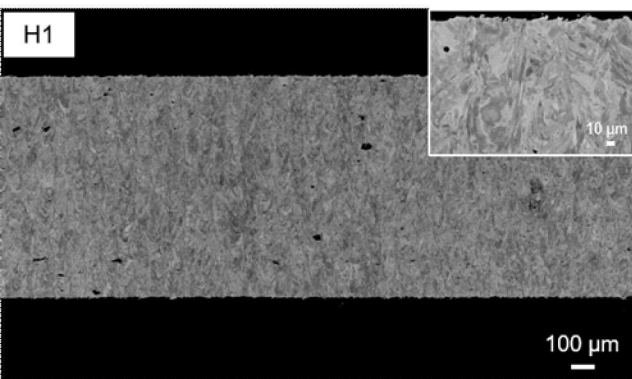
Sample	UTS	Yield	Ductility
As printed	546 (19)	414 (22)	37 (9)
H1	791 (5)	658 (6)	54 (6)
H2	674 (16)	592 (9)	28 (8)
H3 - 45	728 (27)	636 (13)	26 (7)
V1	790 (5)	659 (4)	52 (6)
V2	701 (15)	607 (9)	48 (12)
V3 - 45	806 (4)	682 (5)	52 (5)
Literature, ASM	515	205	60

Roughness

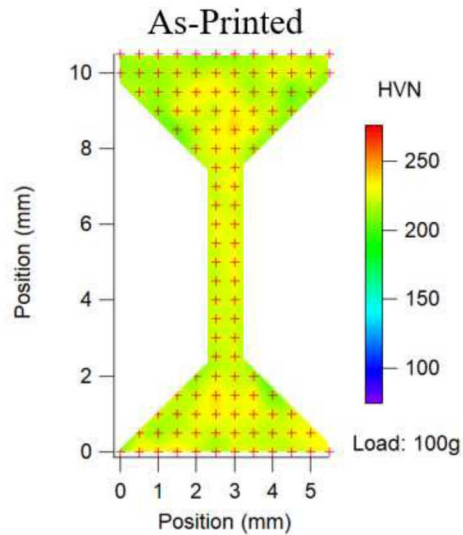
Sample	Sa (μm)	stdev (μm)
As printed	15.0	1.4
H1	6.5	0.7
H2	5.5	0.7
H3	9.0	0.0
V1	3.0	0.0
V2	6.0	1.4
V3	4.0	0.0



- As-printed surface layer $\sim 60 \mu\text{m}$ thick
- EDMed surface is $\sim 5\text{-}10 \mu\text{m}$ thick

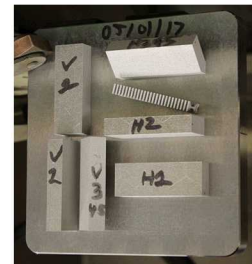
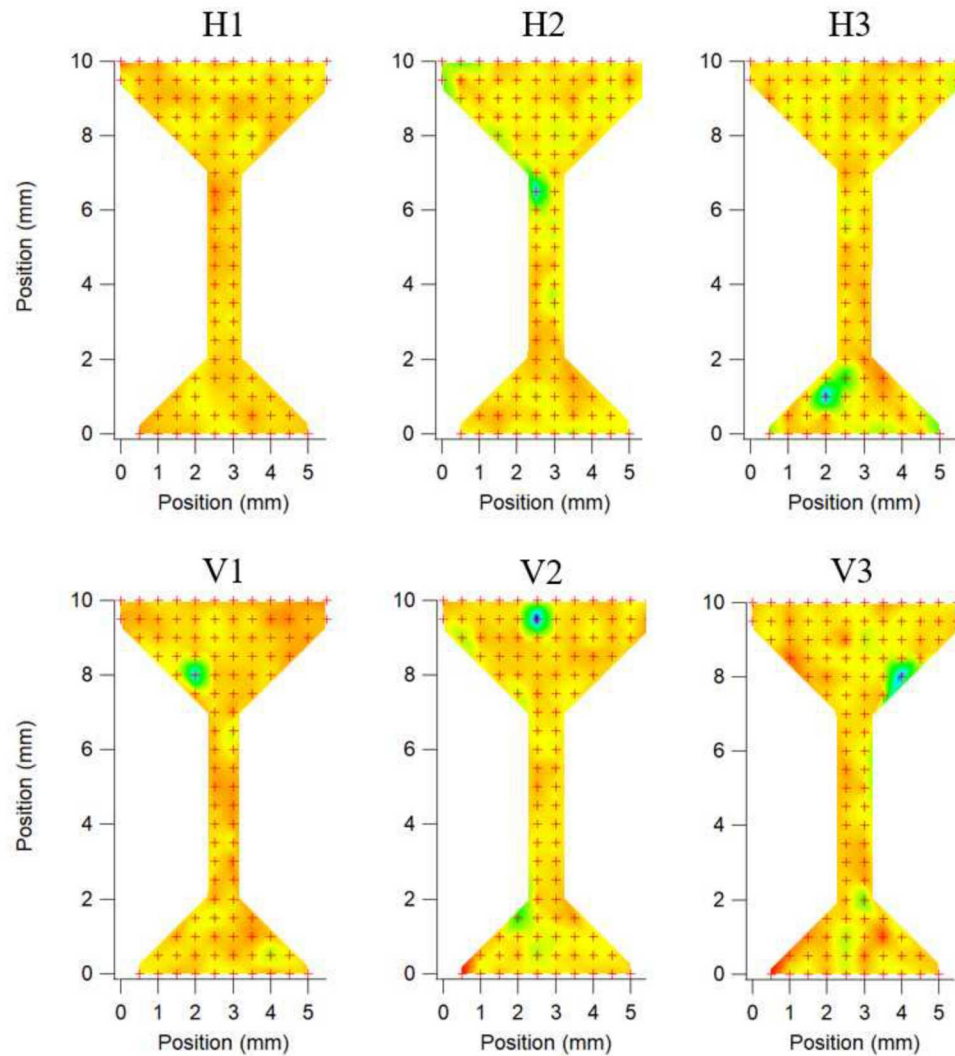


Vickers Hardness



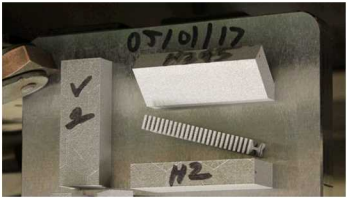
- Lower hardness for as-printed tensile samples

Keep this in mind for witness coupons and part size



	As-Printed	H1	H2	H3-45	V1	V2	V3-45
Average	222.6	237.5	232.2	232.9	237.9	234.5	235.6
Max	239	263	252	253	255	273	272
Min	202	220	123	102	118	83.9	108
St.Dev.	7.9	7.0	14.4	16.8	14.2	17.5	16.1

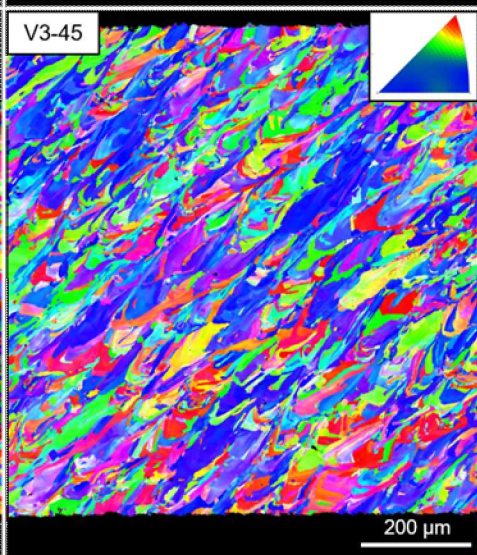
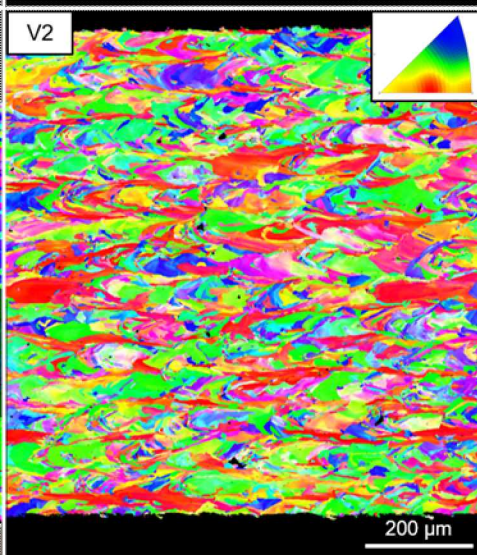
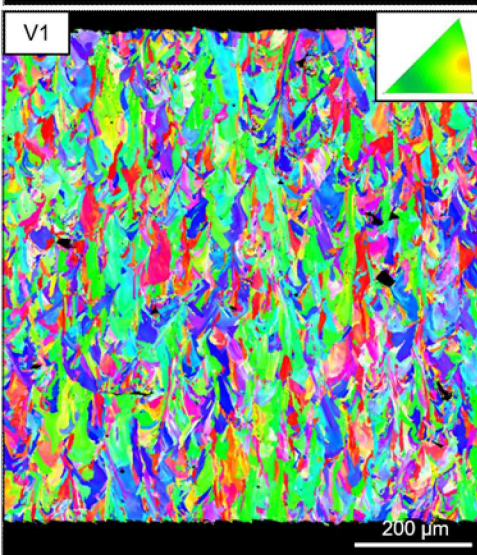
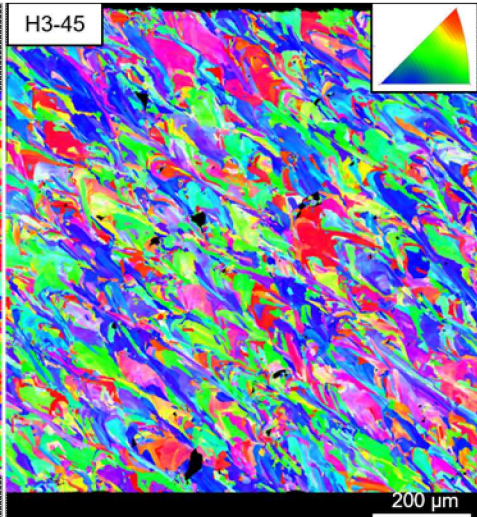
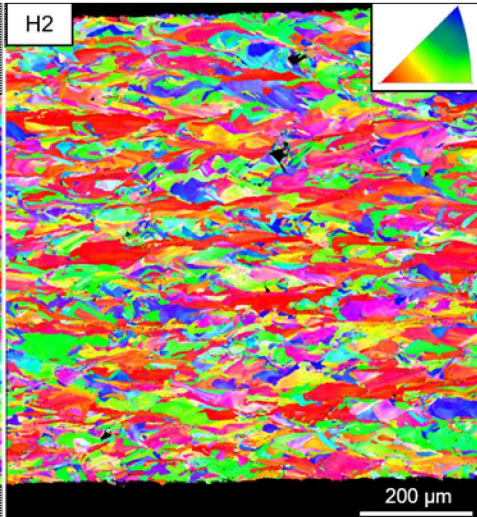
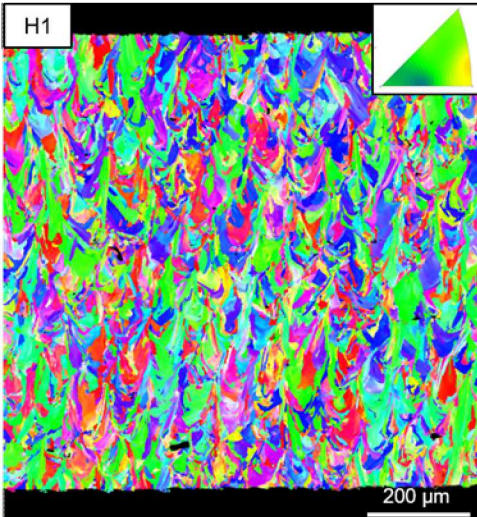
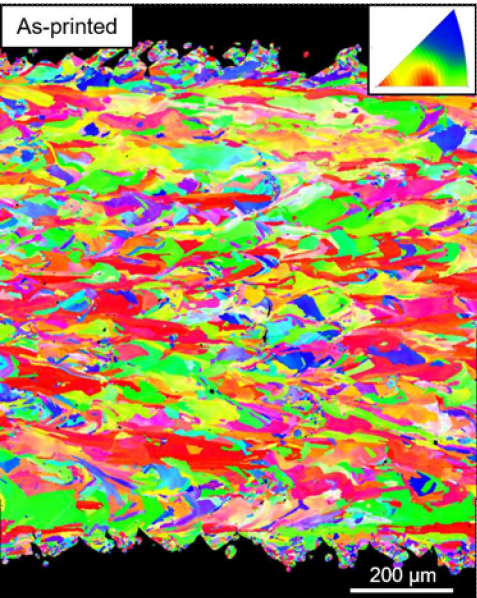
EBSD



- Grains oriented in build direction

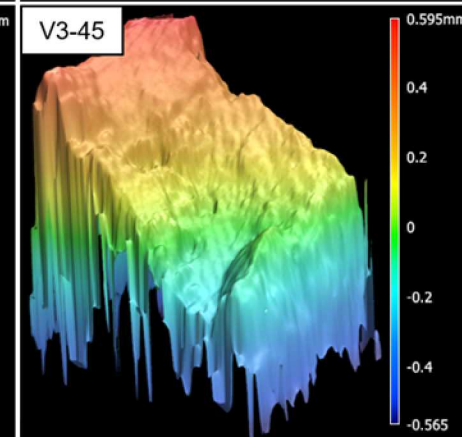
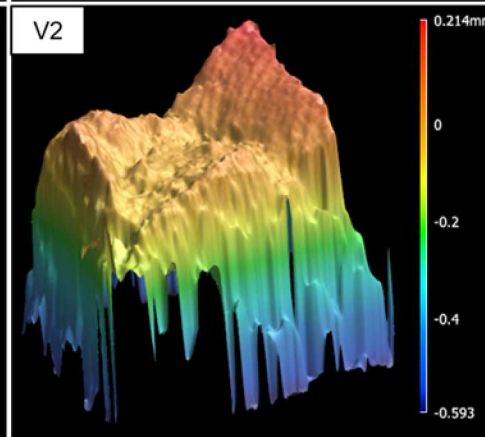
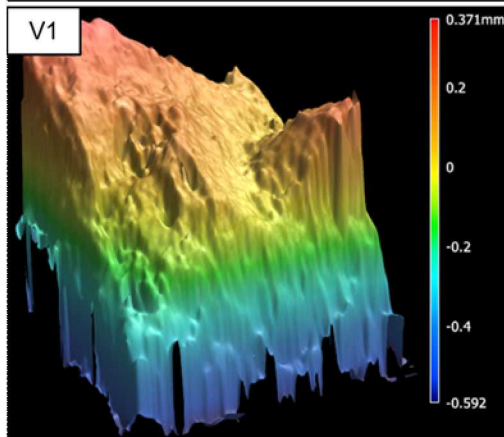
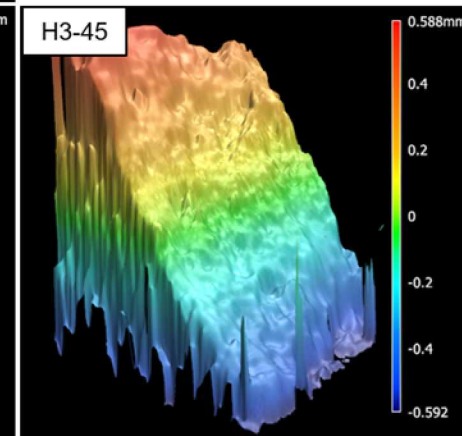
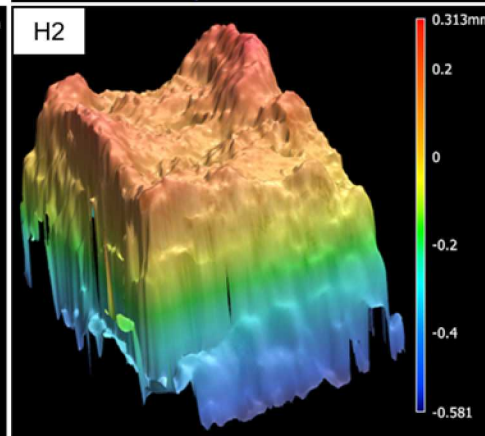
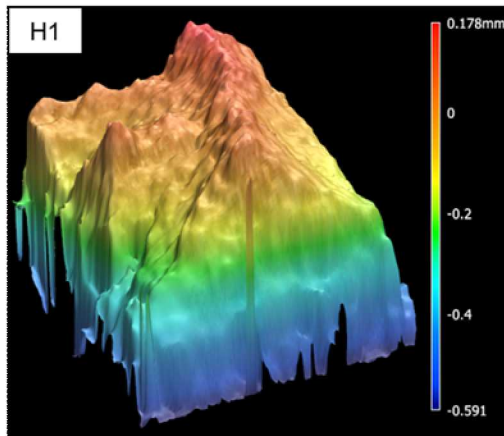
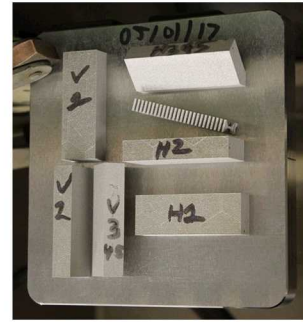
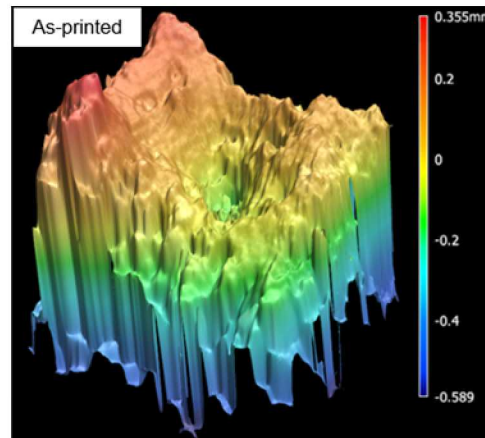
Keep this in mind for design of part thickness

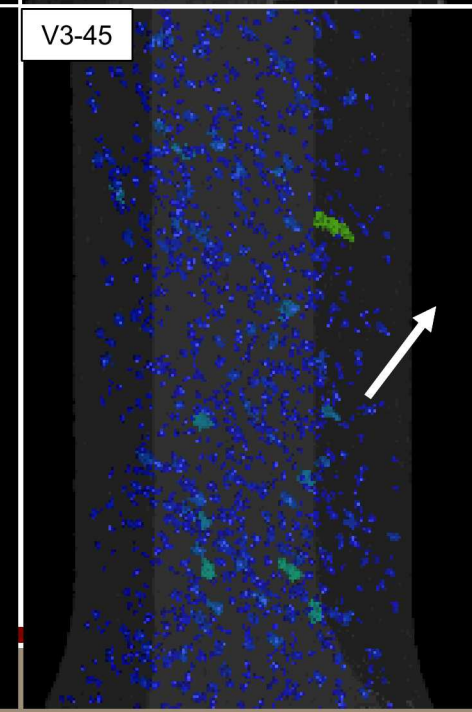
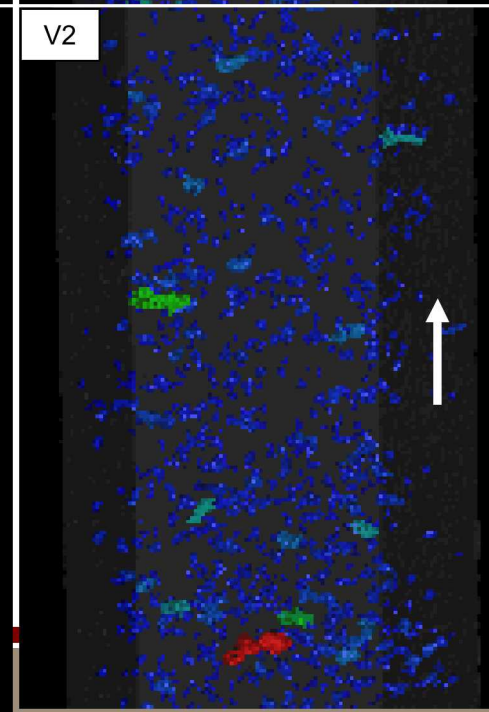
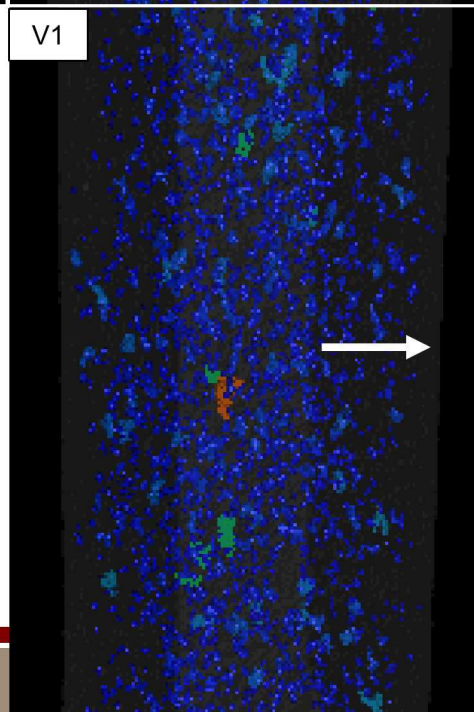
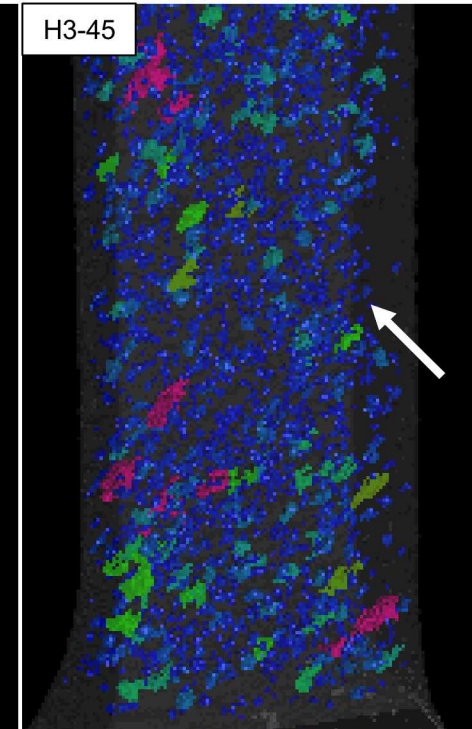
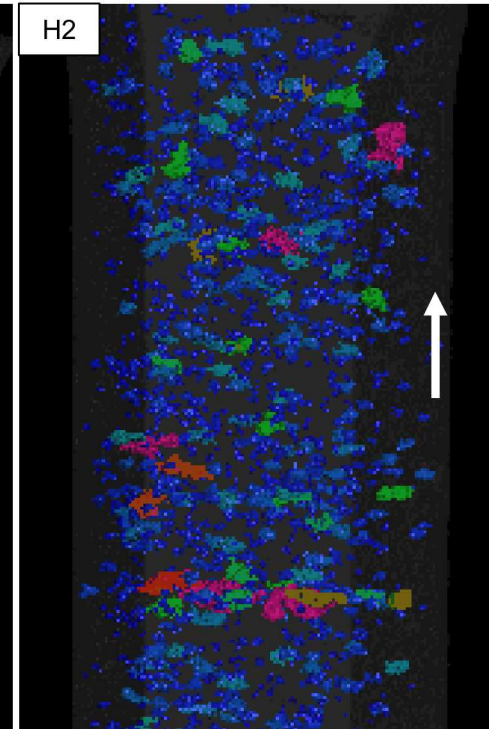
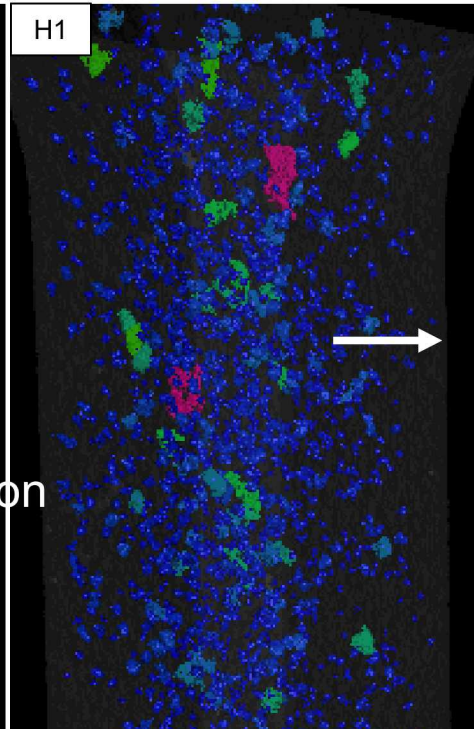
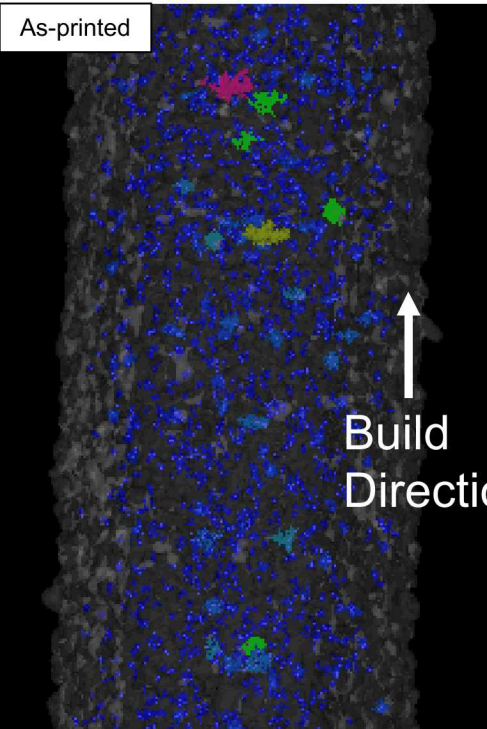
Sample	UTS (MPa)	YS (MPa)	Ductility (%)	Grain Size (um)	Aspect Ratio
As printed	546 (19)	414 (22)	37 (9)	10.7 (10.3)	3.4 (2.4)
H1	791 (5)	658 (6)	54 (6)	9.8 (7.7)	3.4 (2.2)
H2	674 (16)	592 (9)	28 (8)	10.2 (8.6)	3.5 (2.3)
H3 - 45	728 (27)	636 (13)	26 (7)	10.4 (8.9)	3.5 (2.2)
V1	790 (5)	659 (4)	52 (6)	10.0 (8.3)	3.7 (2.5)
V2	701 (15)	607 (9)	48 (12)	10.8 (9.1)	3.7 (2.5)
V3 - 45	806 (4)	682 (5)	52 (5)	10.4 (8.9)	3.5 (2.2)

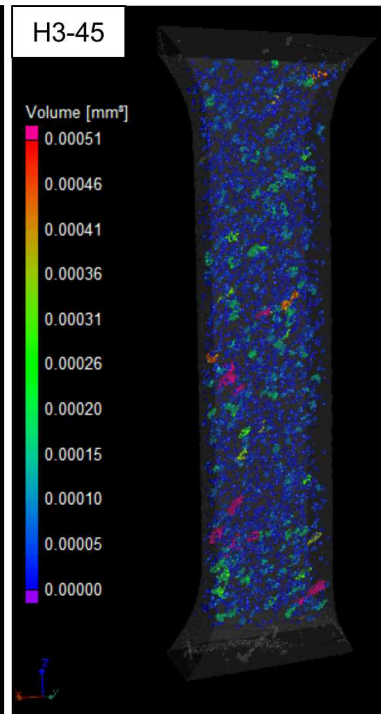
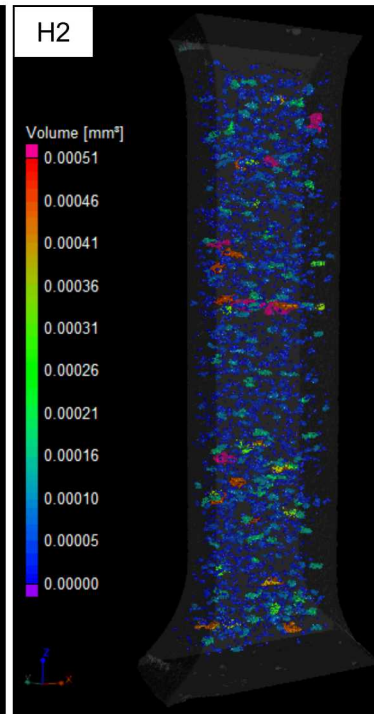
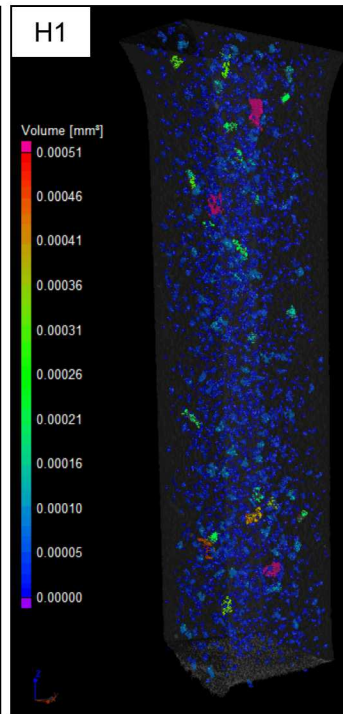
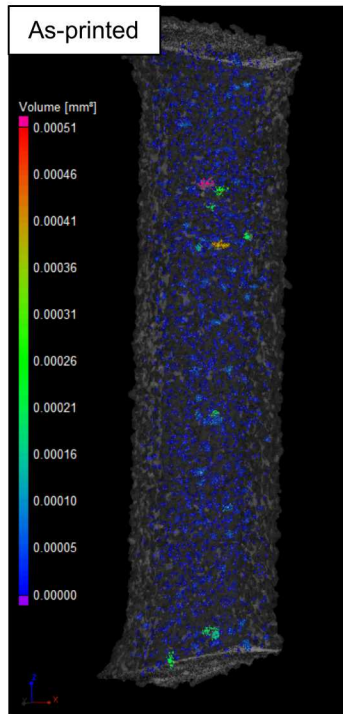
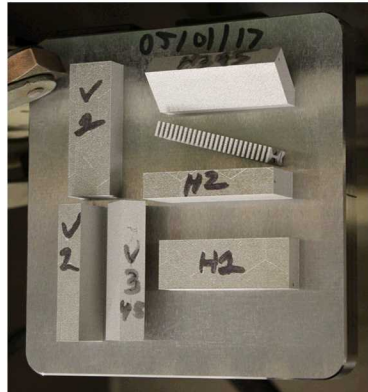
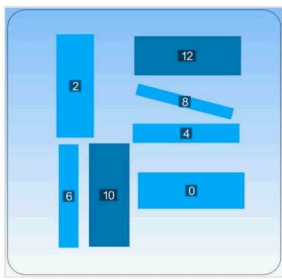


Fractography

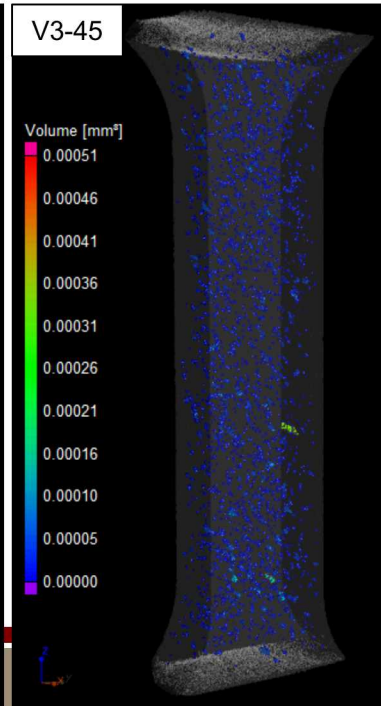
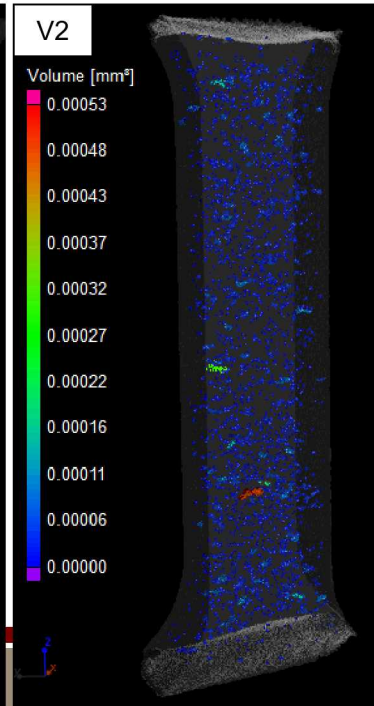
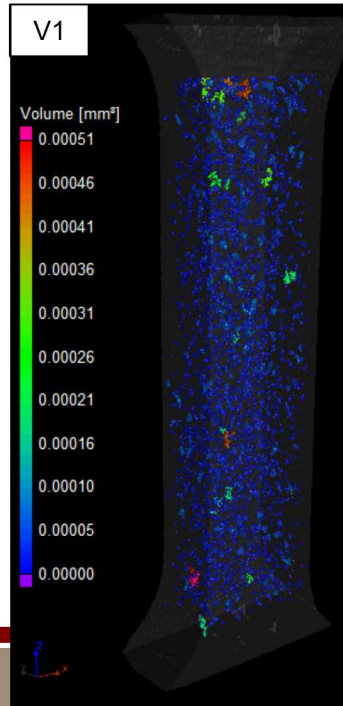
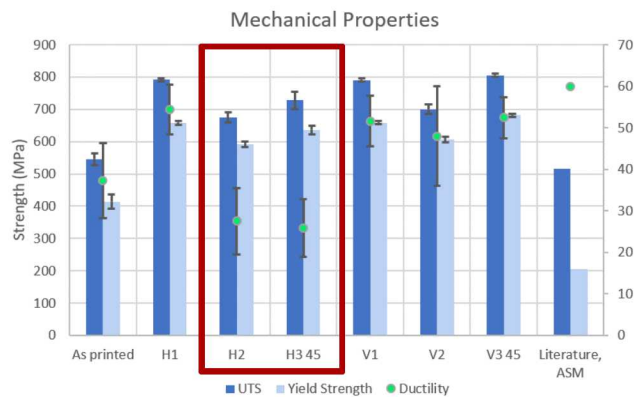
- Primarily ductile fracture
- More of a shear-like failure for parts built at 45°
- H3-45 has sharper shear plane



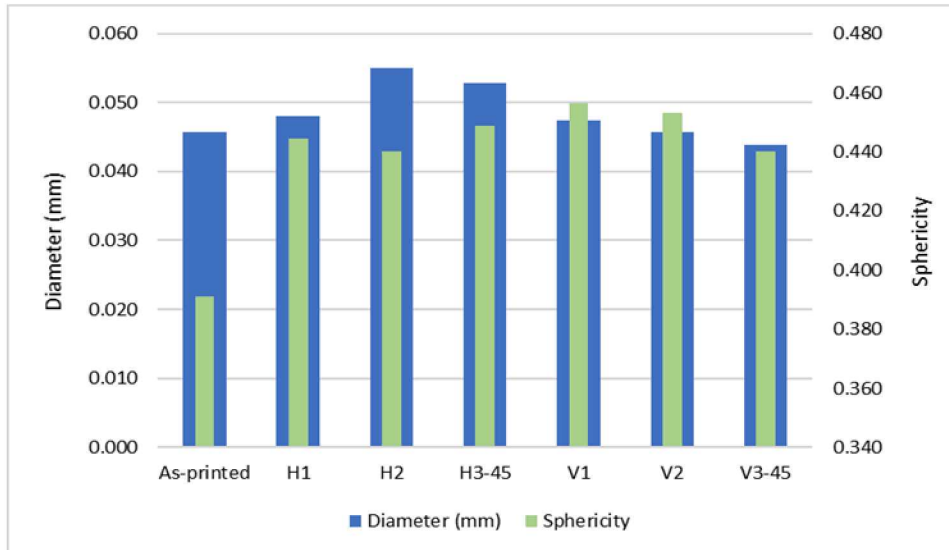
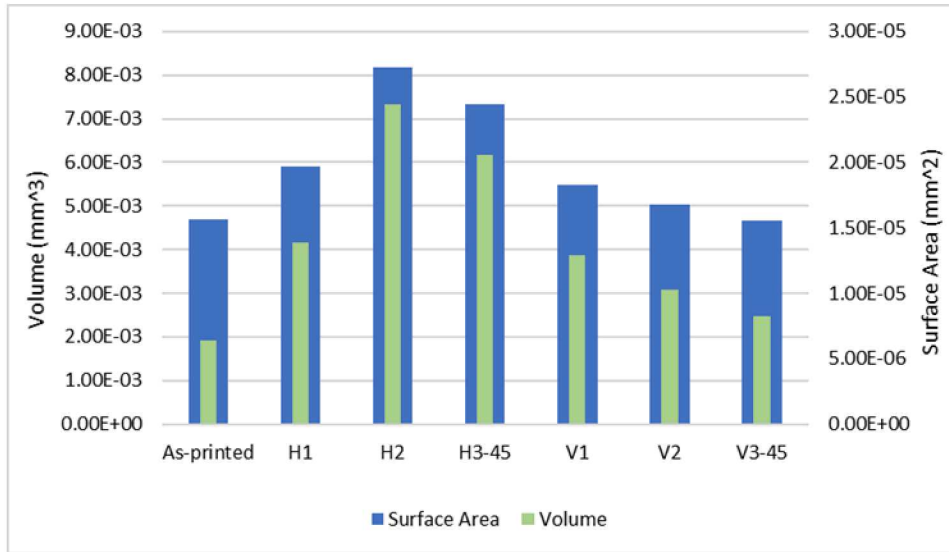




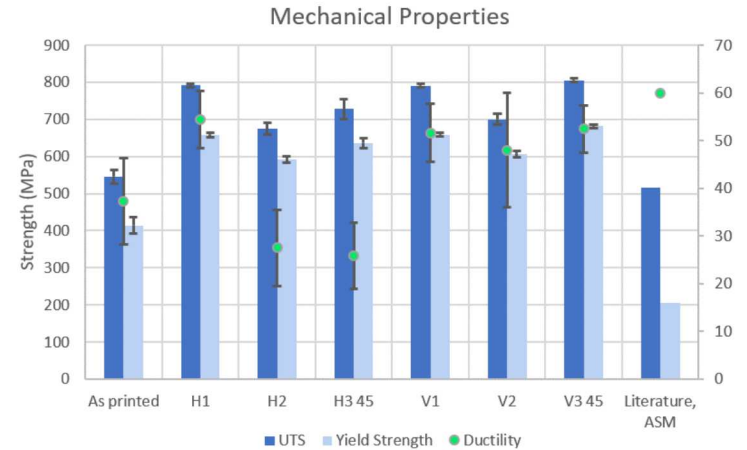
- Pores oriented perpendicular to build direction
- Higher concentration of large pores in H1, H2, and H3-45
- H1 pores oriented parallel to tensile axis



Porosity



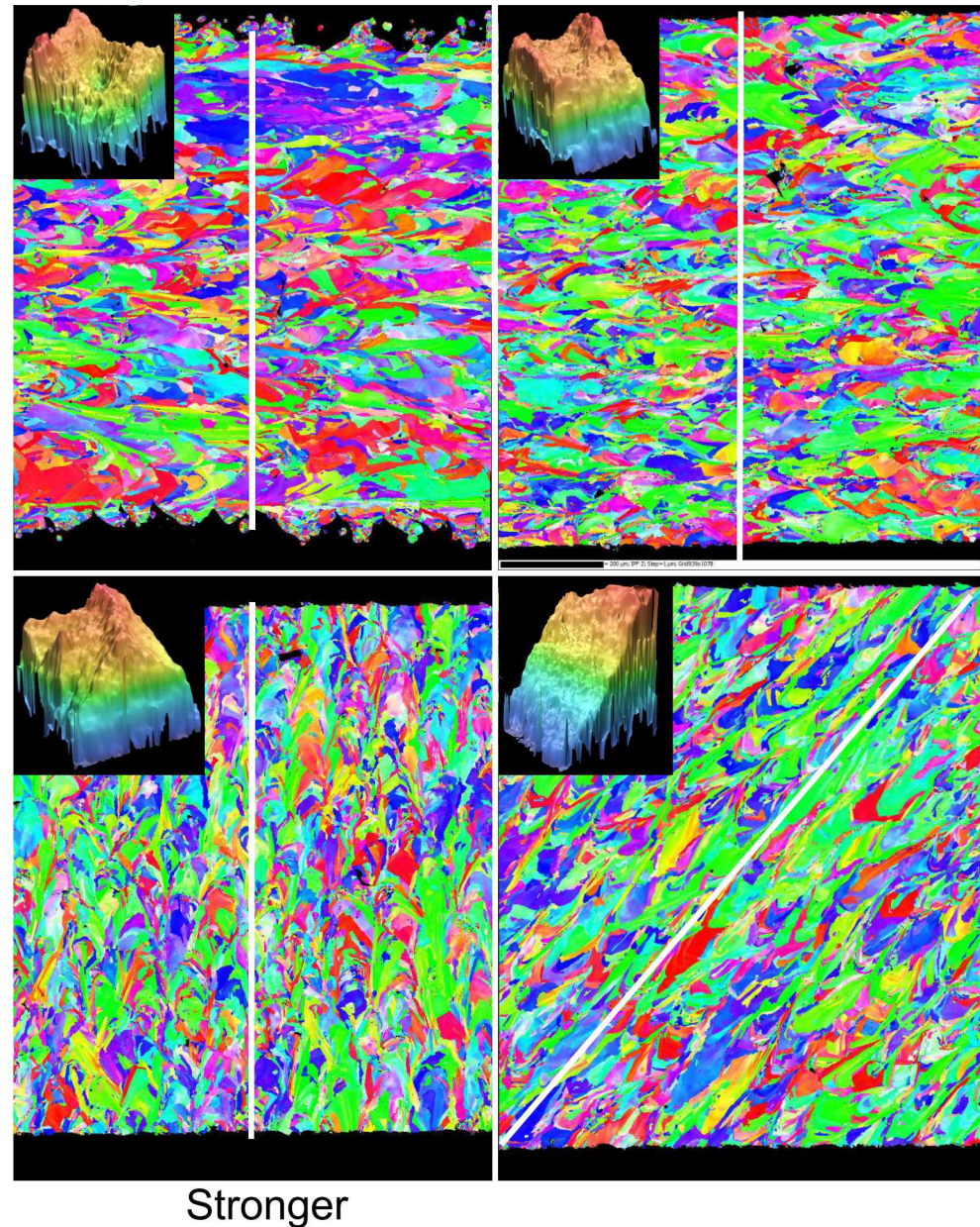
Measurement	As-printed	H1	H2	H3-45	V1	V2	V3-45
# of pores	2459	3191	3129	4381	3178	2488	2515



- Ductility influence influenced by larger average pore diameter, volume, surface area,

Conclusions

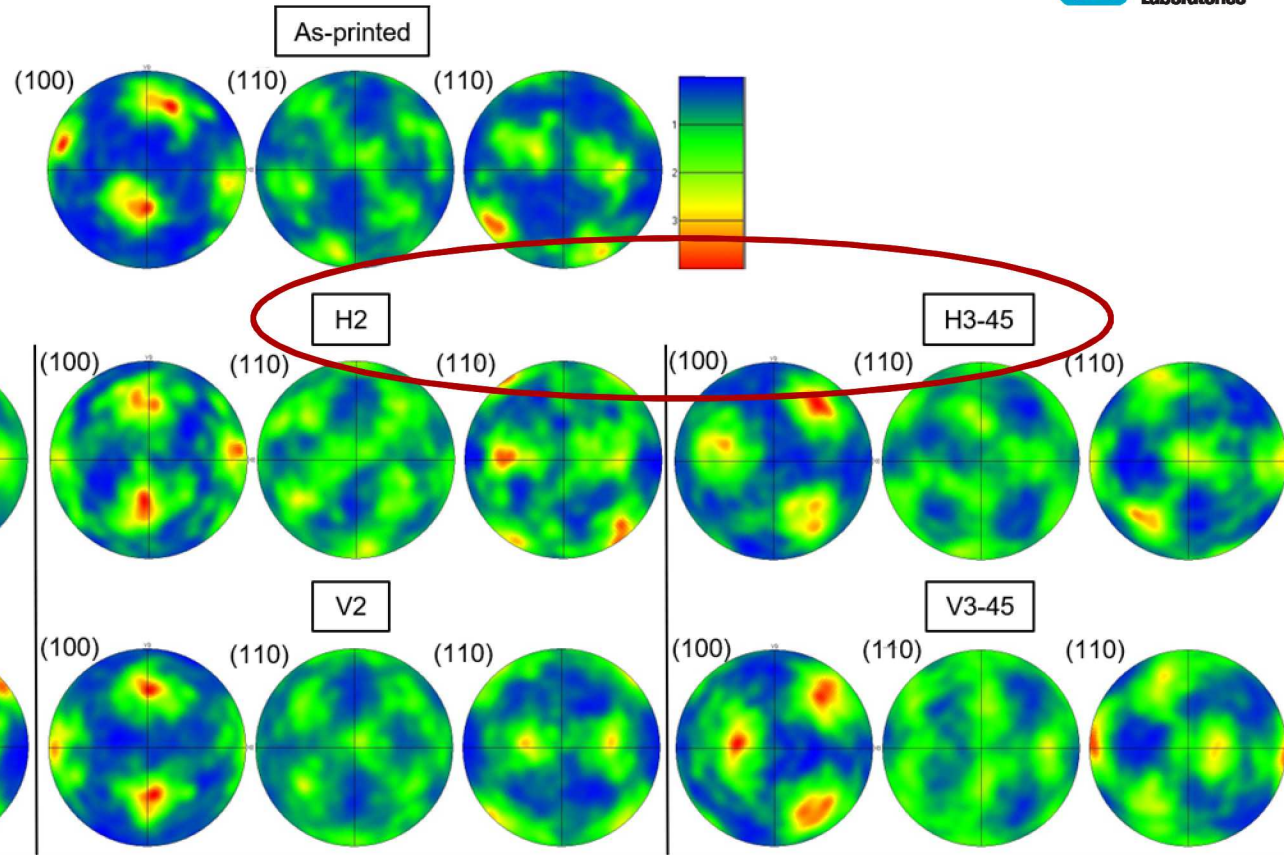
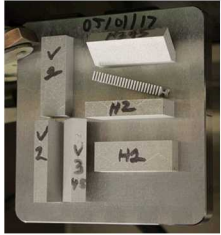
- Large surface roughness and slower cooling rates of as-printed parts limit AM mechanical properties
- Generally, AM parts built to be post-machined have higher mech. properties
- Horizontal-built grains act as better barriers to crack growth than vertical-built grains – higher UTS and YS
- Orientations built at 45° fail at a 45°
- Build orientation influences microstructure, and properties, but build direction doesn't
- Even with similar densities, parts with higher concentrations of large pores lower ductility – easier to grow/coalesce
- Higher amount of porosity is believed to be caused from spatter/condensate, influenced by gas flow direction, order of build on plate, and part spacing



Acknowledgements

- Joe Michael
- David Moore
- Andrew Lentfer
- John Miers
- Sara Dickens
- Christina Profazi
- Celedonio Jaramillo
- Andrew Kustas

Z-Plane Pole Figure



- H2, and V2 have similar textures
- H3-45 and V3-45 have similar textures
- V1 and As-printed are slightly rotated compared to H2 and V2
- H1 is very different
- Still doesn't explain why H2 and H3-45 have such reduced ductility

Fractography

- 45° orientations fracture at that angle
- Out of page build direction $\otimes$

