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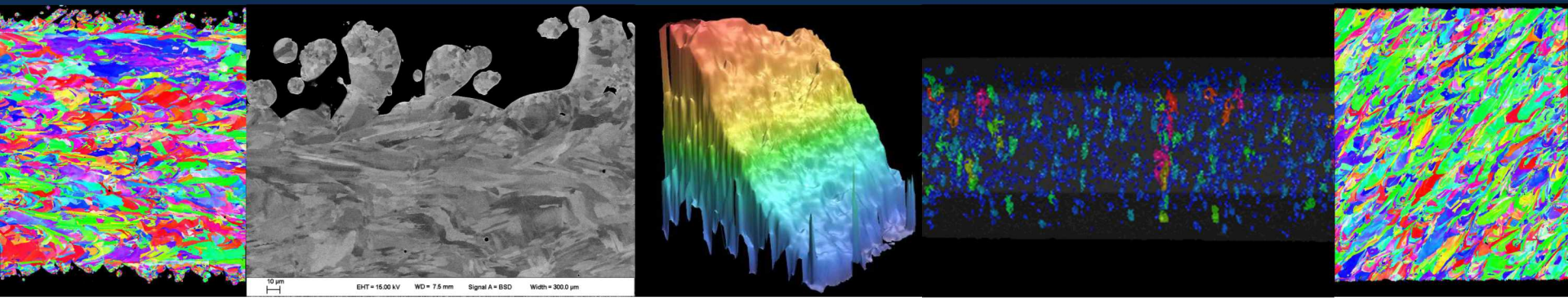

How AM Parts Fail: Influence of Build Orientation and Post Machining

Michael Heiden, David Saiz, Dan Tung, Bradley Jared

Sandia National Laboratories, Albuquerque, NM

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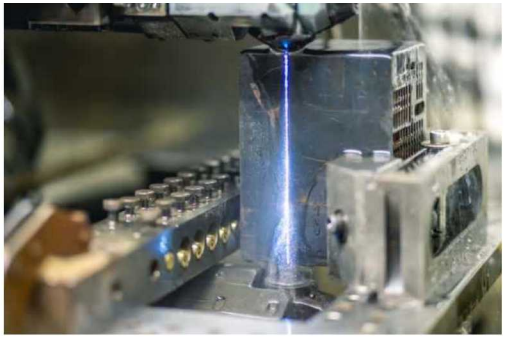
Motivation

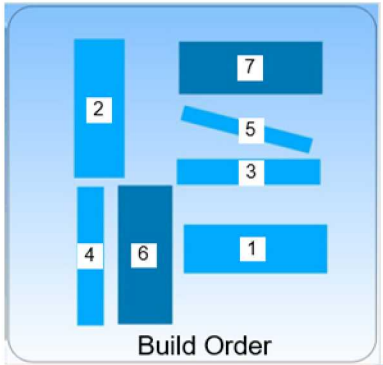
Sandia National Laboratories

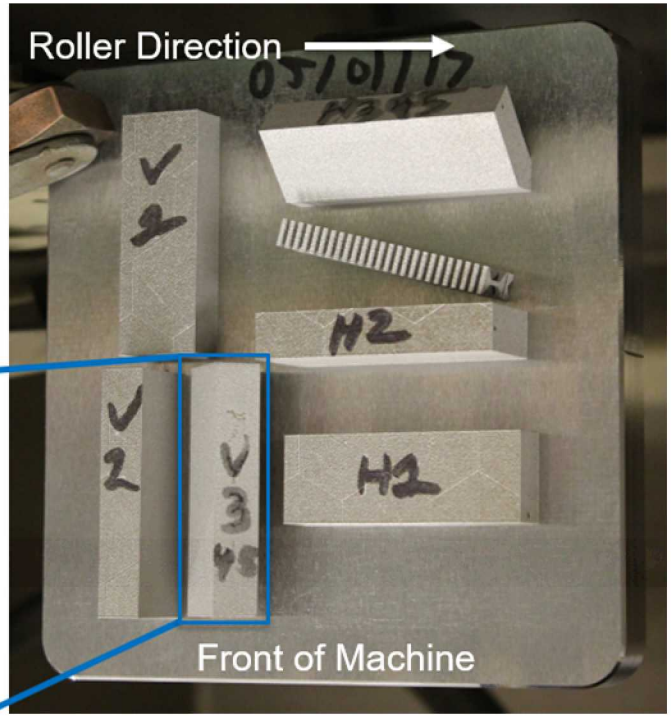
Electro-discharge machining (EDM) of as-printed material:

- 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

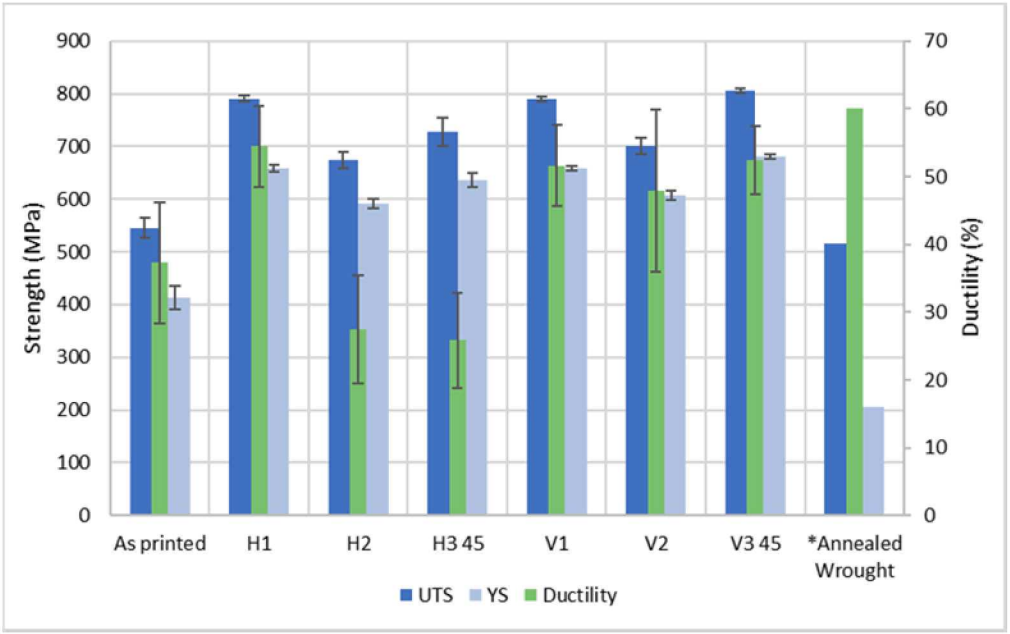
Mechanical Properties

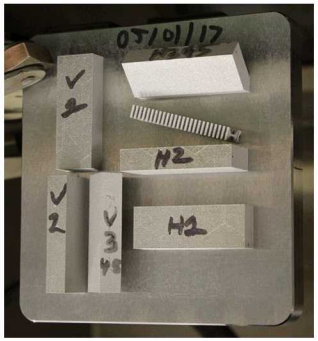
- UTS highest: V3-45, H1, V1
- Yield highest: V3-45, V1, H1
- Ductility highest: H1, V3-45, V1
  lowest: H2, H3-45
- As-printed lowest properties

Why lower performance for as-printed?

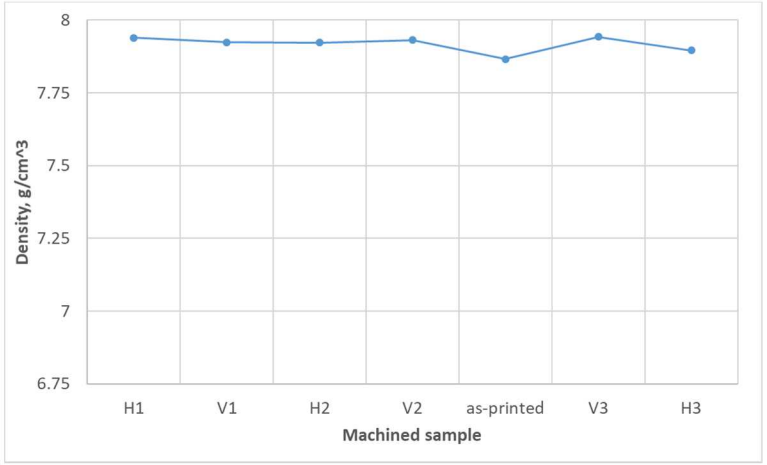
Why ductility so low for H2 & H3-45?

Why horizontal better than vertical?





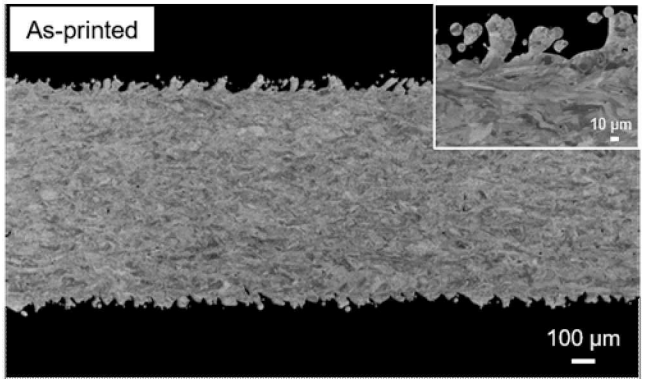
build plate orientation in the ProX 200



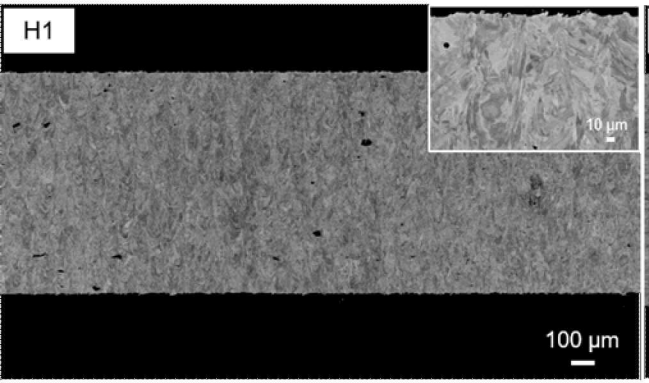
Sample	UTS	Yield	Ductility
As printed	546 (19)	414 (22)	37 (9)
H1	791 (5)	658 (6)	54 (6)
H2	674 (16)	592 (9)	28 (8)
H3 - 45	728 (27)	636 (13)	26 (7)
V1	790 (5)	659 (4)	52 (6)
V2	701 (15)	607 (9)	48 (12)
V3 - 45	806 (4)	682 (5)	52 (5)
Literature, ASM	515	205	60

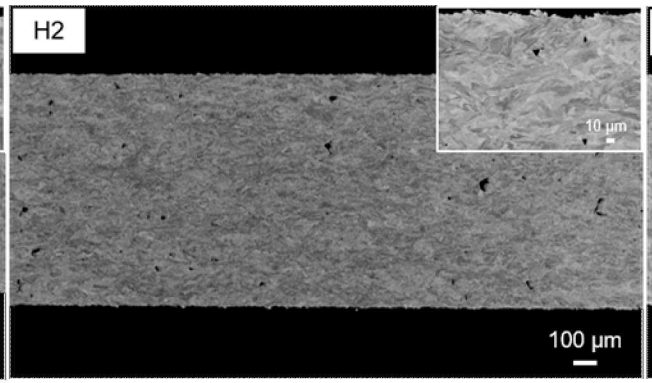
Roughness

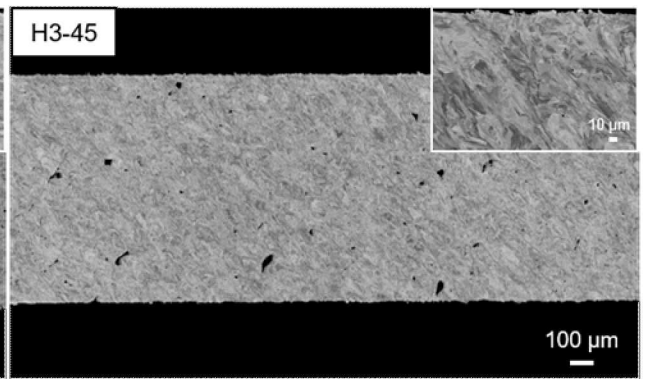
Sample	Sa (µm)	stdev (µm)
As printed	15.0	1.4
H1	6.5	0.7
H2	5.5	0.7
H3	9.0	0.0
V1	3.0	0.0
V2	6.0	1.4
V3	4.0	0.0

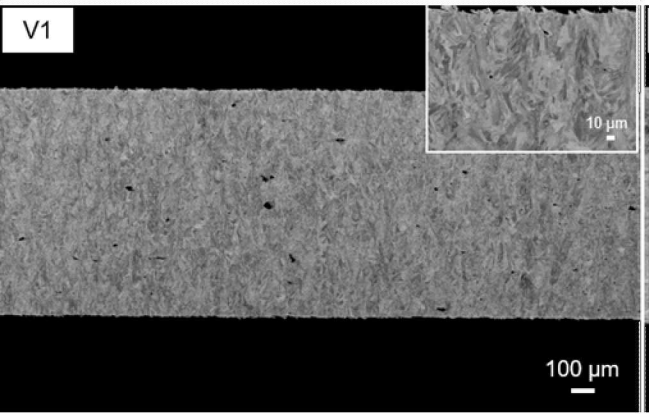


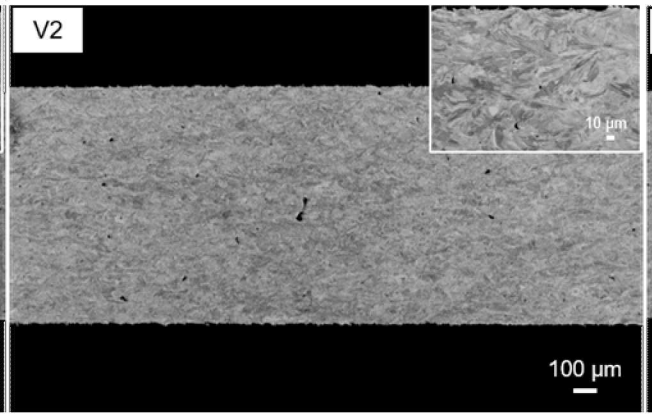
- As-printed surface layer ~ 60 µm thick
- EDMed surface is ~ 5-10 µm thick

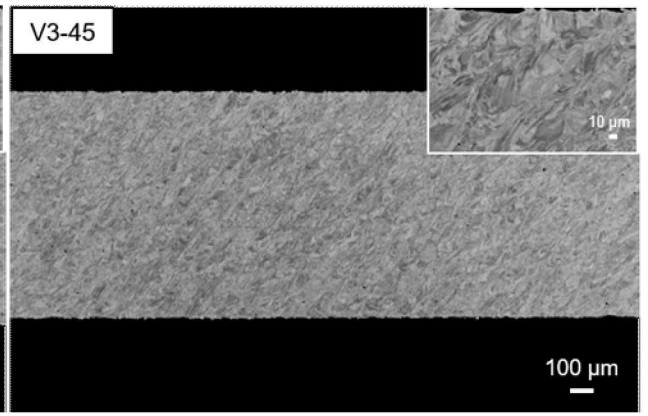




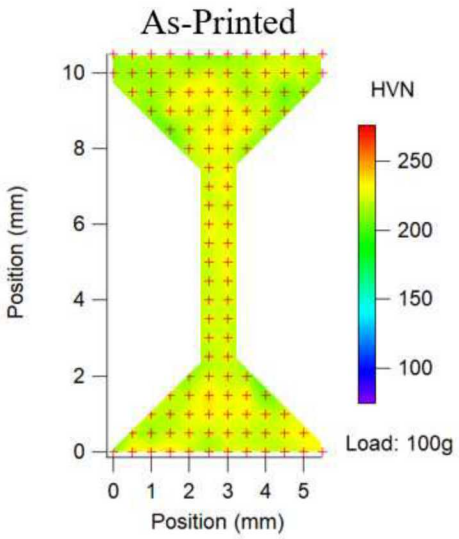


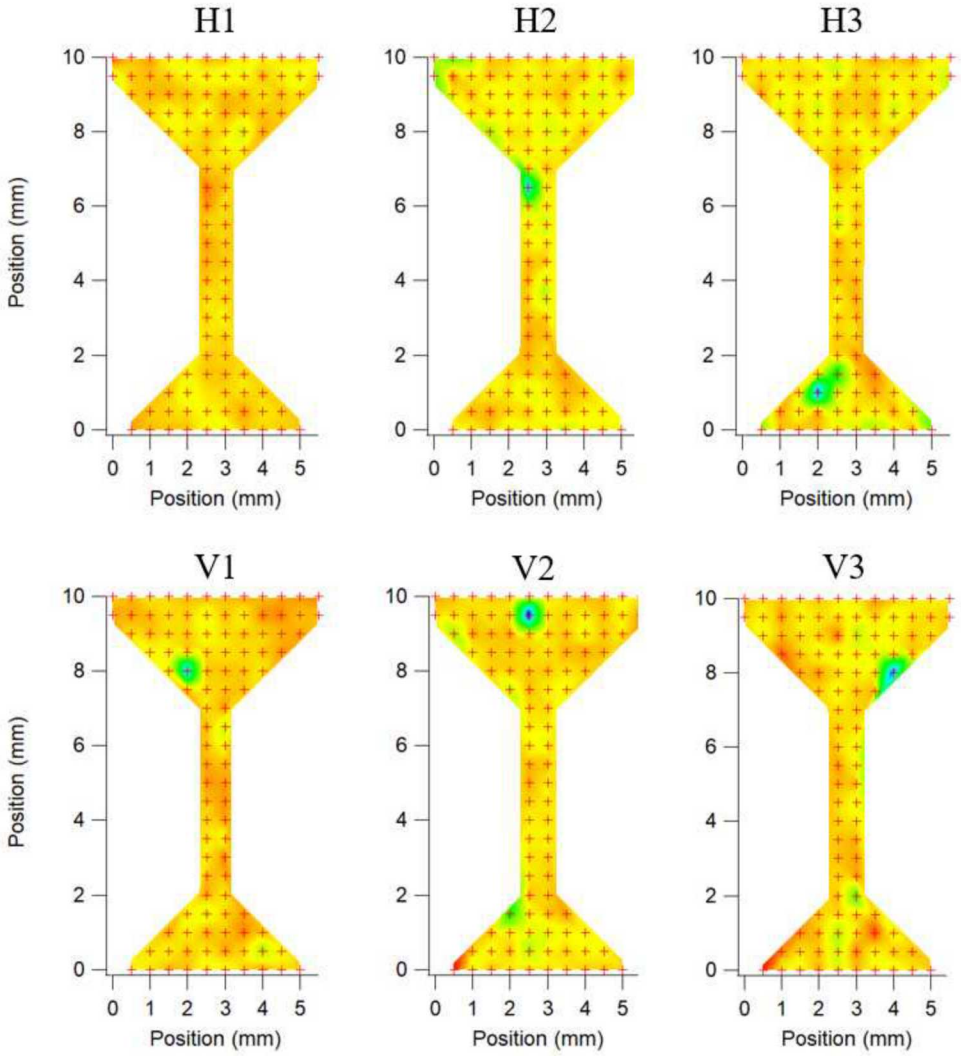


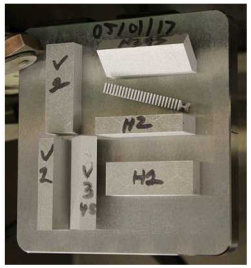




Vickers Hardness







- Lower hardness for as-printed tensile samples

Keep this in mind for witness coupons and part size

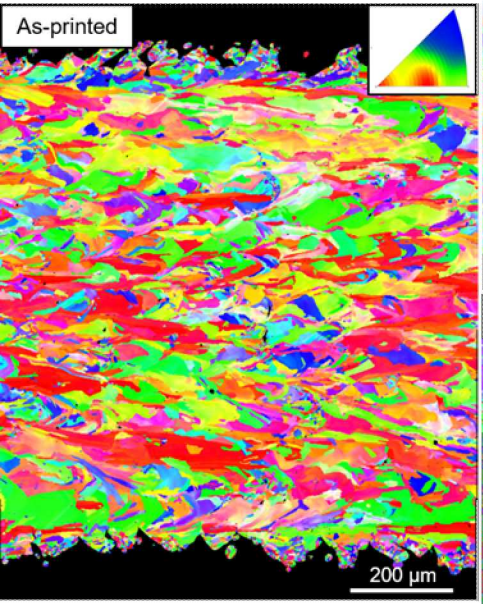
	As-Printed	H1	H2	H3-45	V1	V2	V3-45
Average	222.6	237.5	232.2	232.9	237.9	234.5	235.6
Max	239	263	252	253	255	273	272
Min	202	220	123	102	118	83.9	108
St.Dev.	7.9	7.0	14.4	16.8	14.2	17.5	16.1

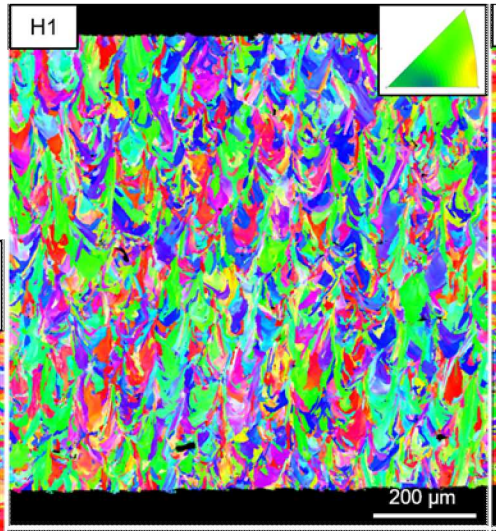
EBSD

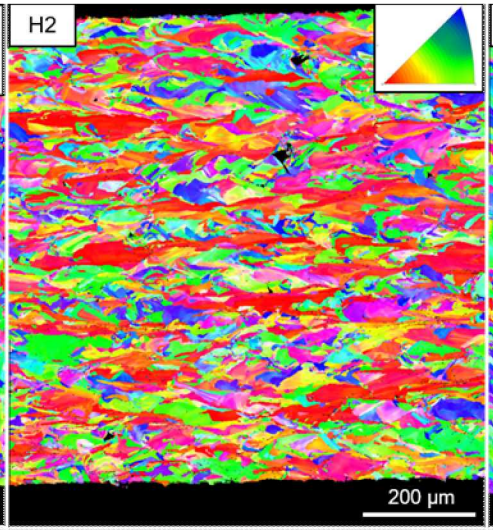
- Grains oriented in build direction

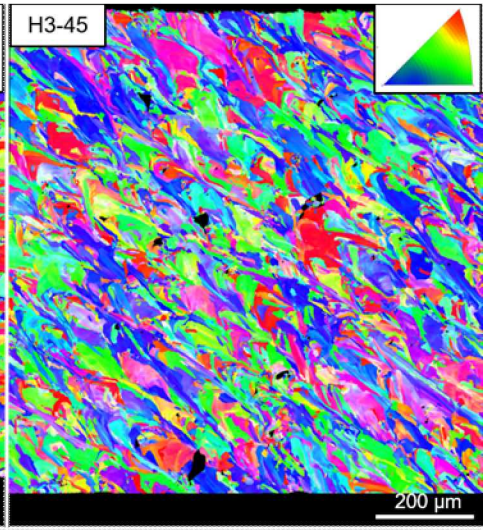
Keep this in mind for design of part thickness

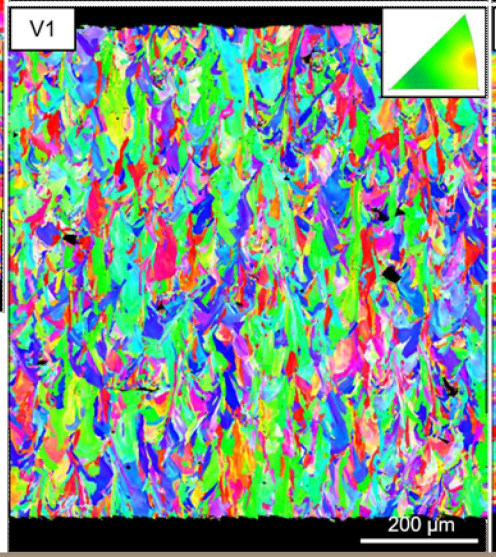
Sample	UTS (MPa)	YS (MPa)	Ductility (%)	Grain Size (um)	Aspect Ratio
As printed	546 (19)	414 (22)	37 (9)	13.1 (11.1)	3.4 (2.4)
H1	791 (5)	658 (6)	54 (6)	9.8 (7.7)	3.4 (2.2)
H2	674 (16)	592 (9)	28 (8)	10.2 (8.6)	3.5 (2.3)
H3 - 45	728 (27)	636 (13)	26 (7)	10.4 (8.9)	3.5 (2.2)
V1	790 (5)	659 (4)	52 (6)	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)

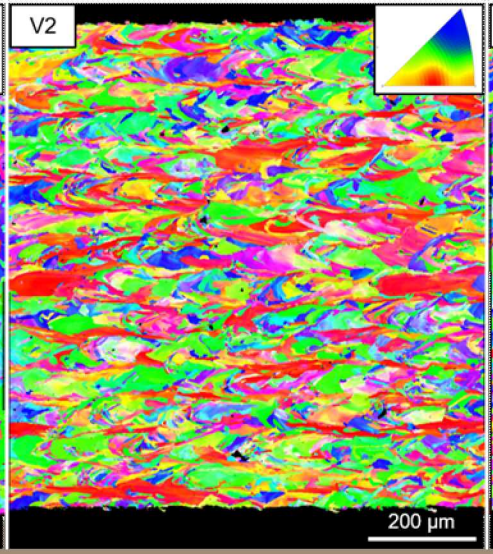


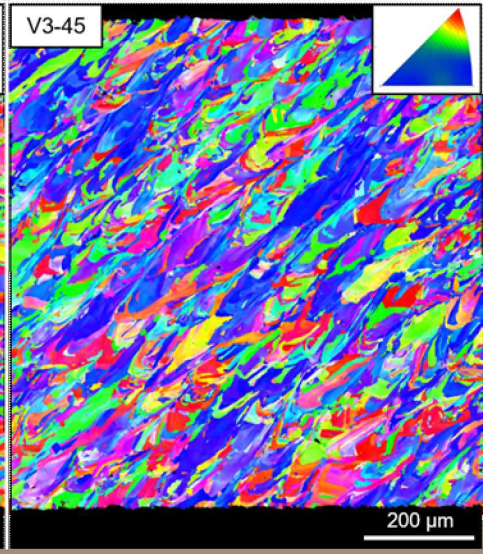






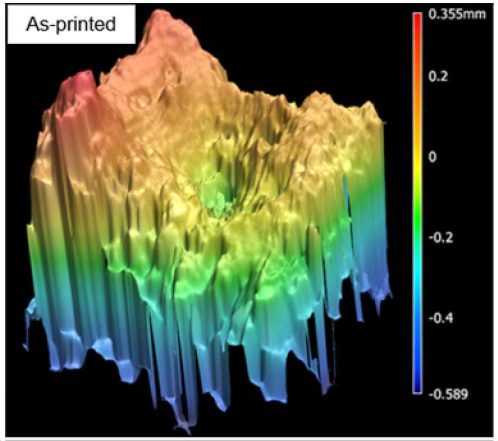


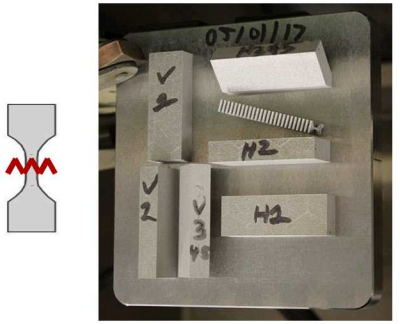


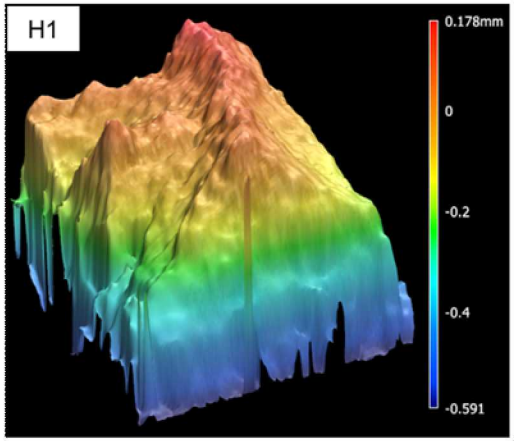


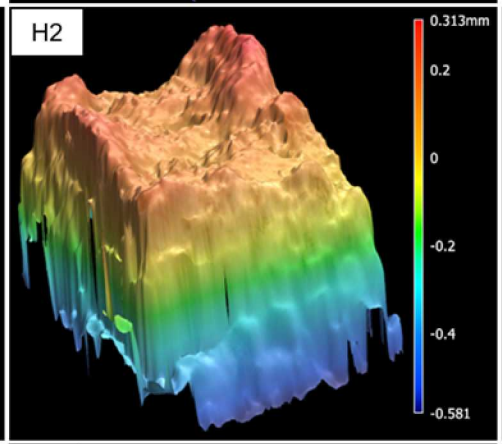
Fractography

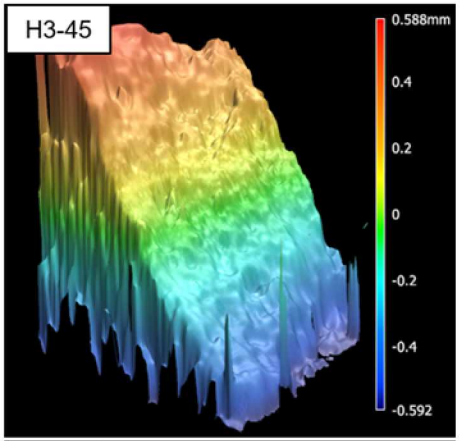
- Primarily ductile fracture
- More of a shear-like failure for parts built at 45˚
- H3-45 has sharper shear plane

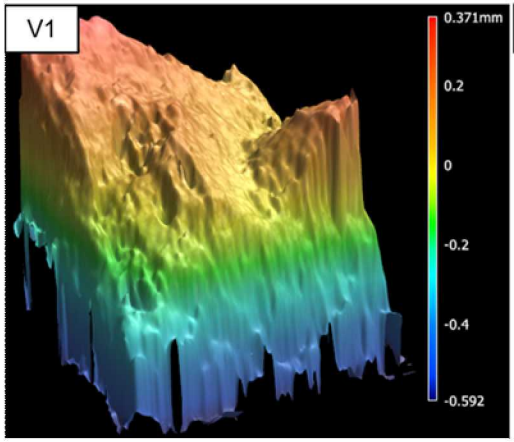


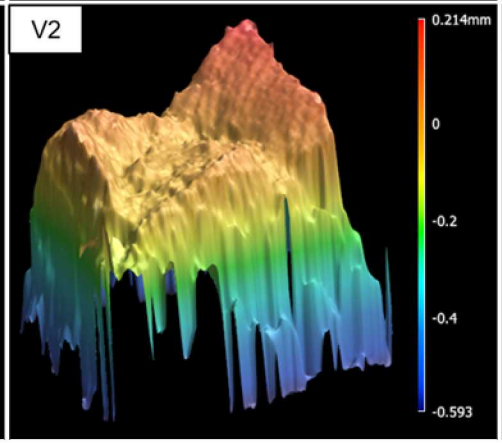


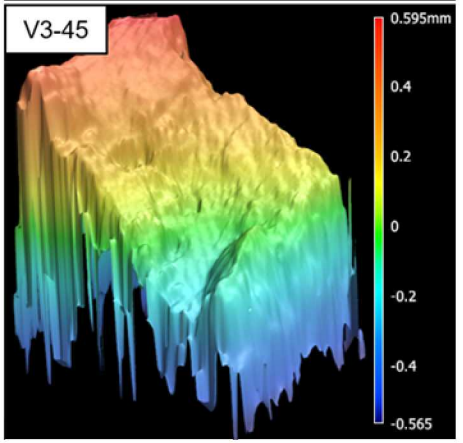


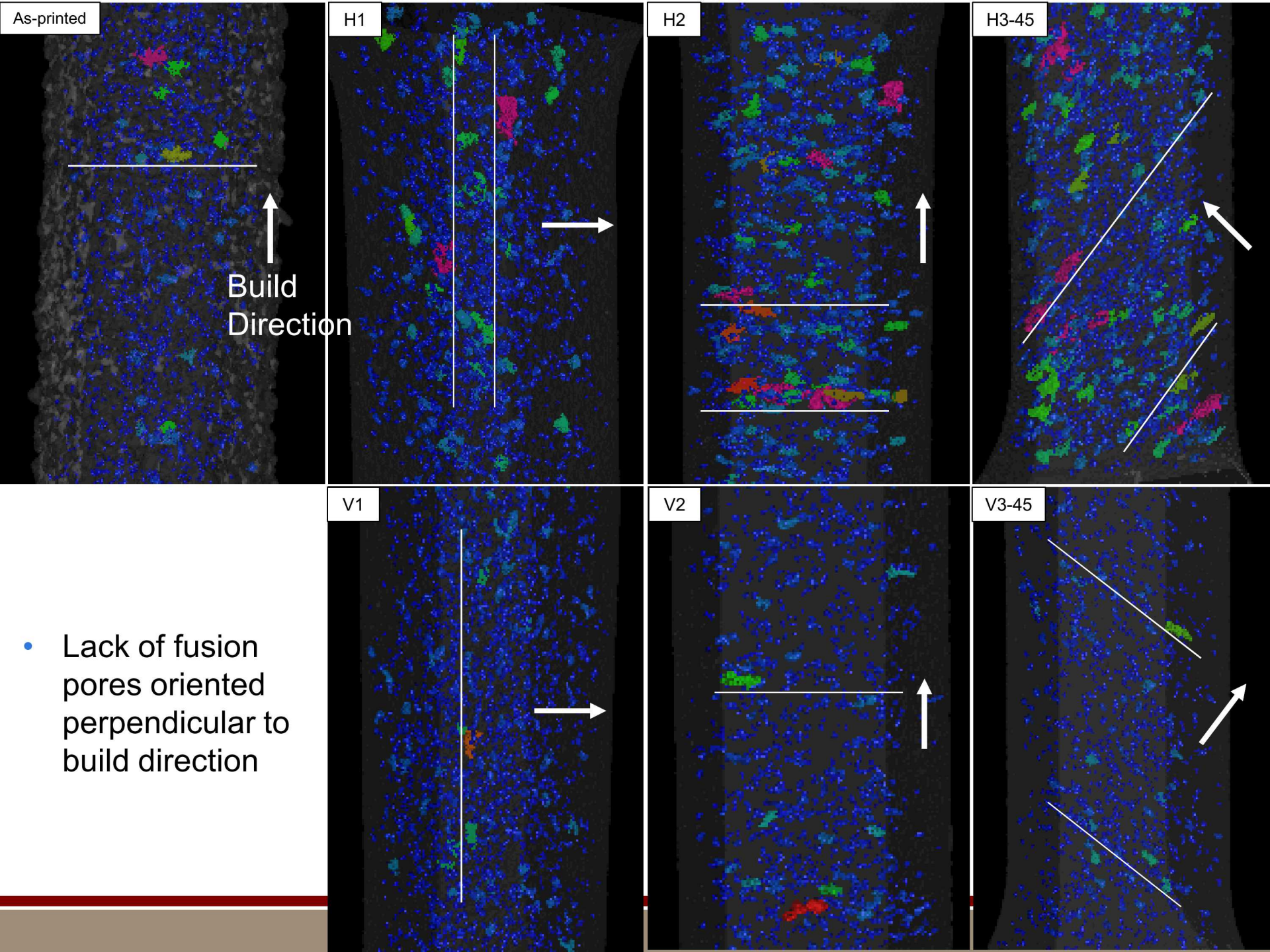




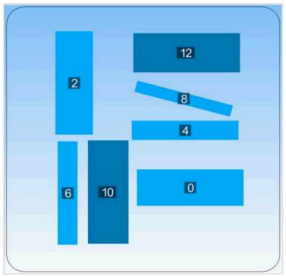


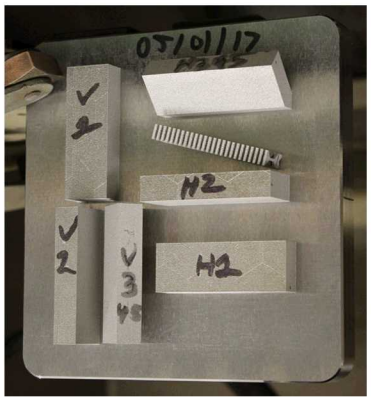


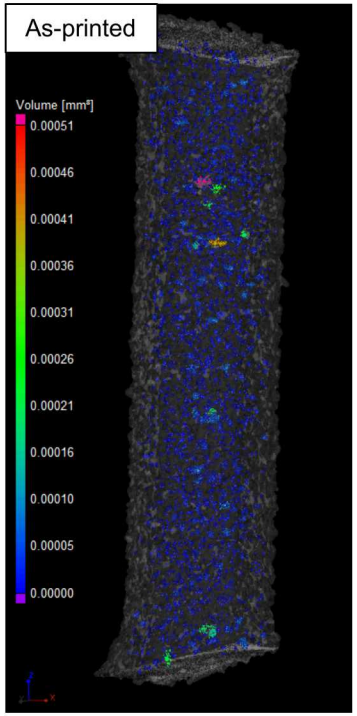


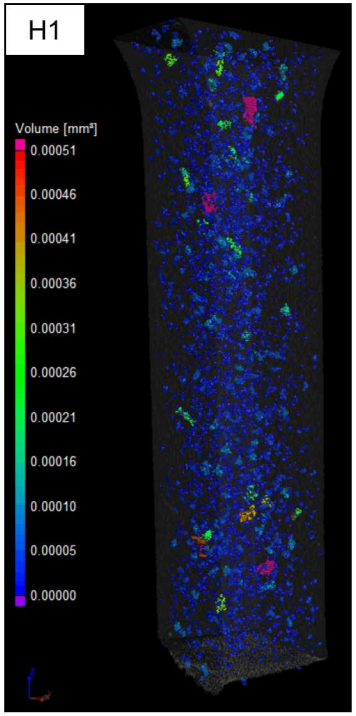


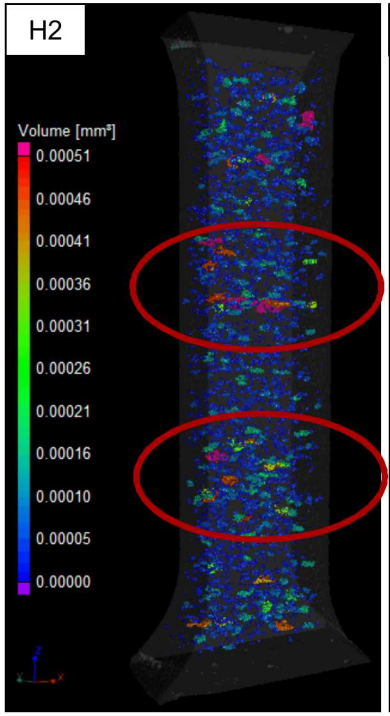
- Lack of fusion pores oriented perpendicular to build direction

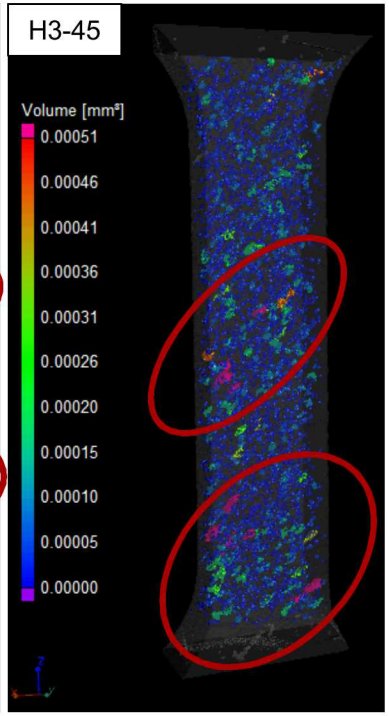




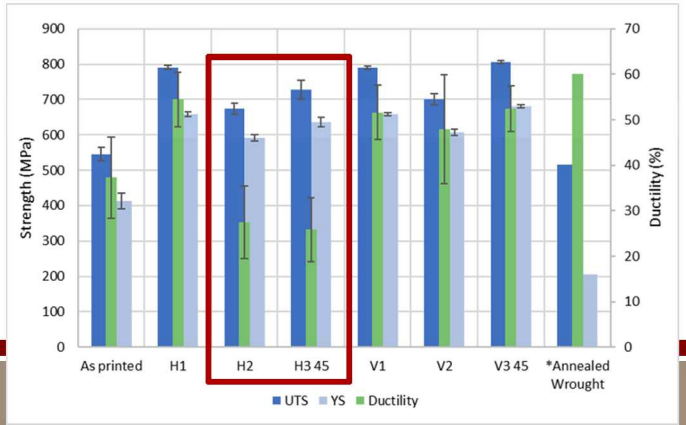


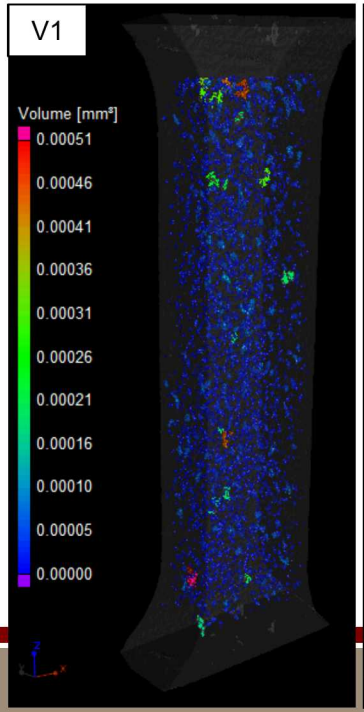


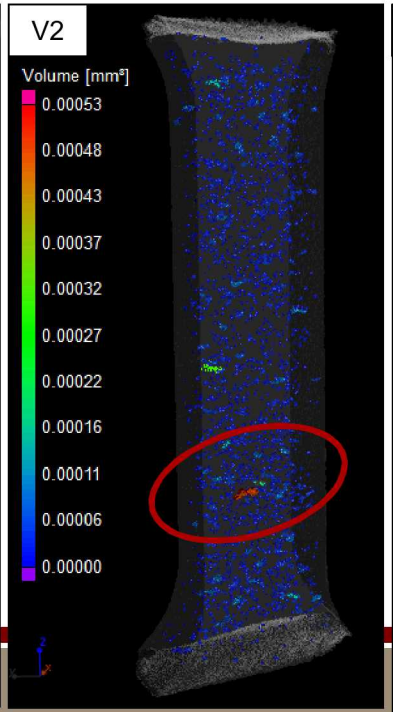


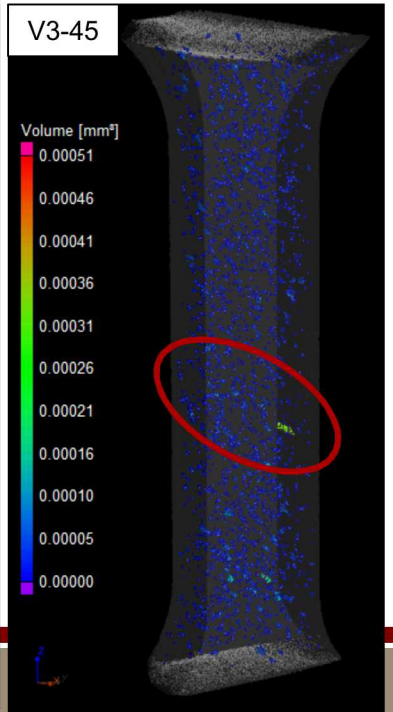


- Pores oriented perpendicular to build direction
- Higher concentration of large pores in H1, H2, V1, and H3-45
- H1 pores oriented parallel to tensile axis



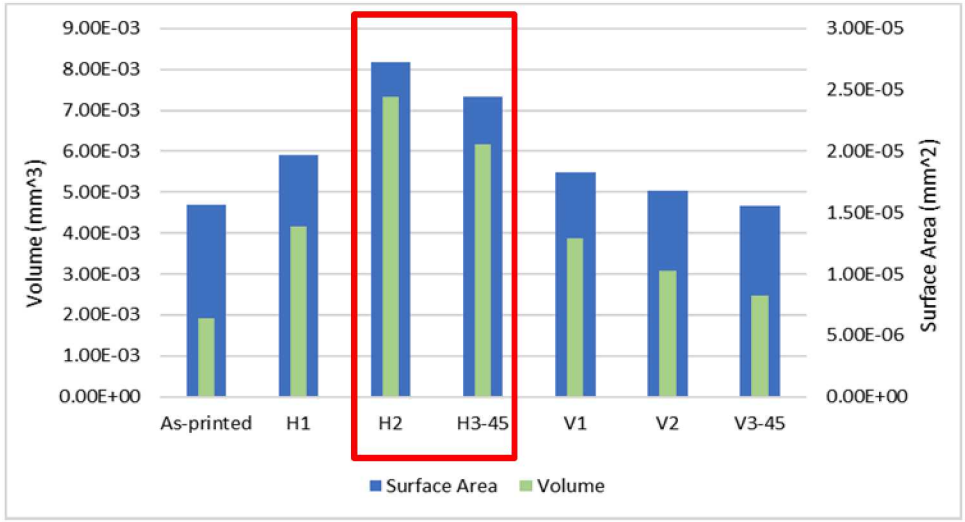




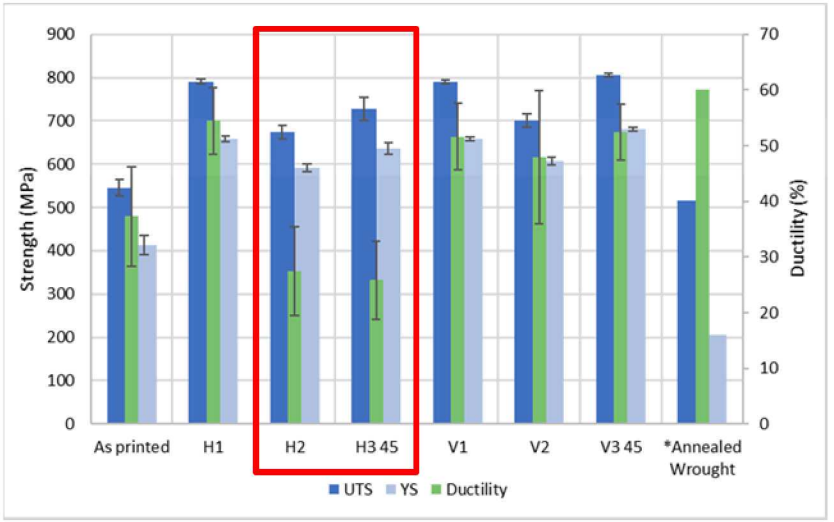


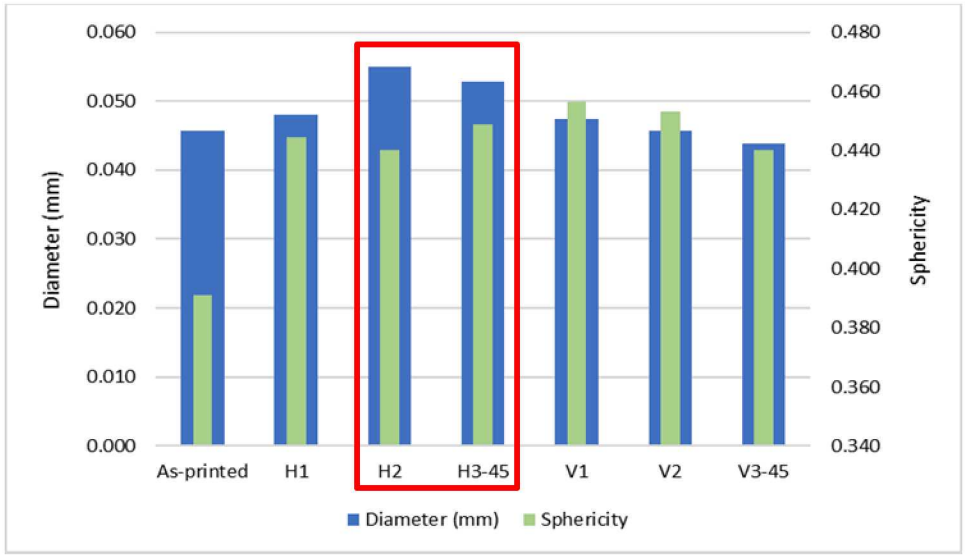
Porosity

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



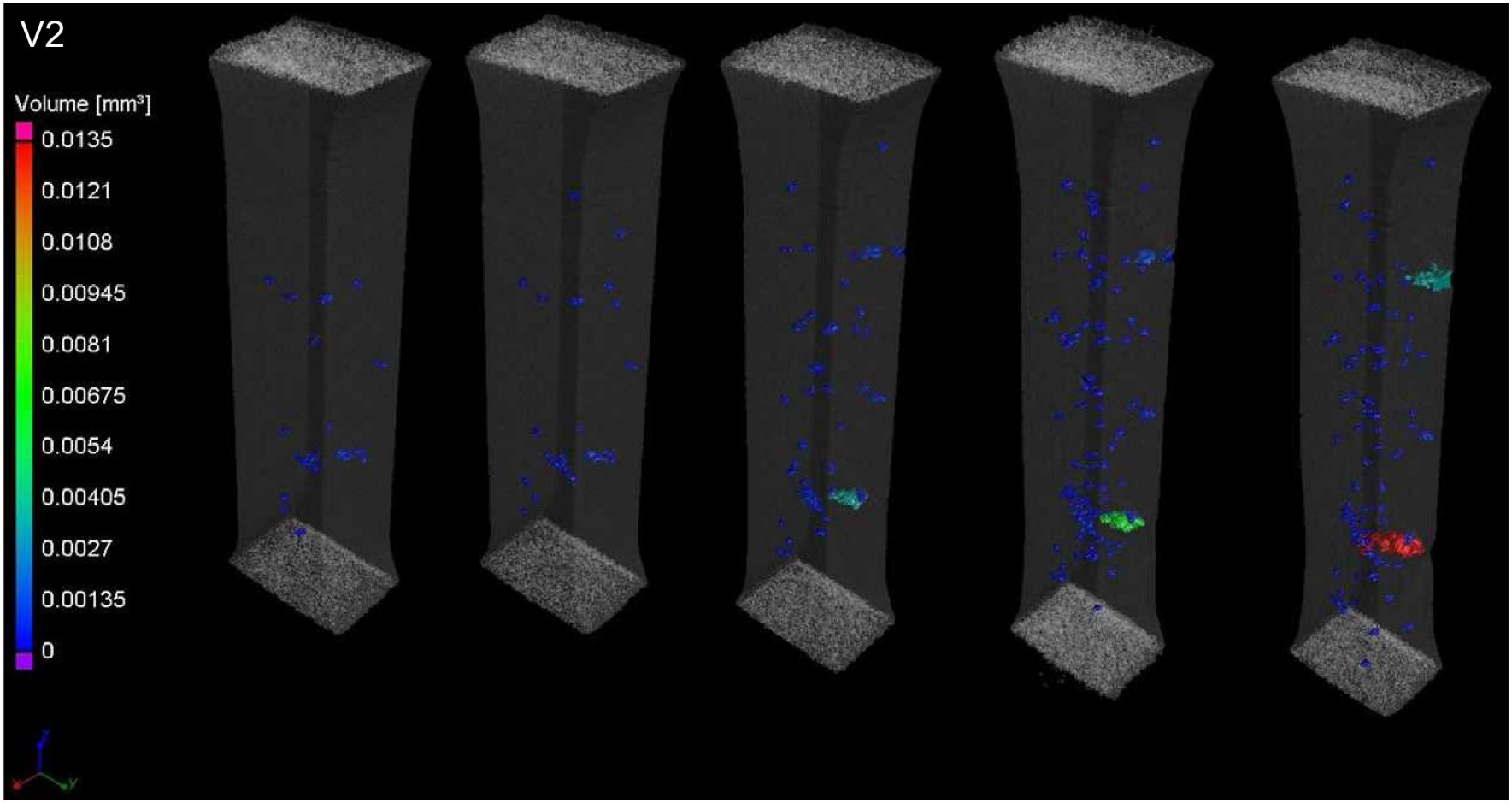
Mechanical Properties





- H1, H2, and V1 all have similar number of pores, yet H2 has lowest ductility
- Ductility influenced by larger average pore diameter, volume, and surface area

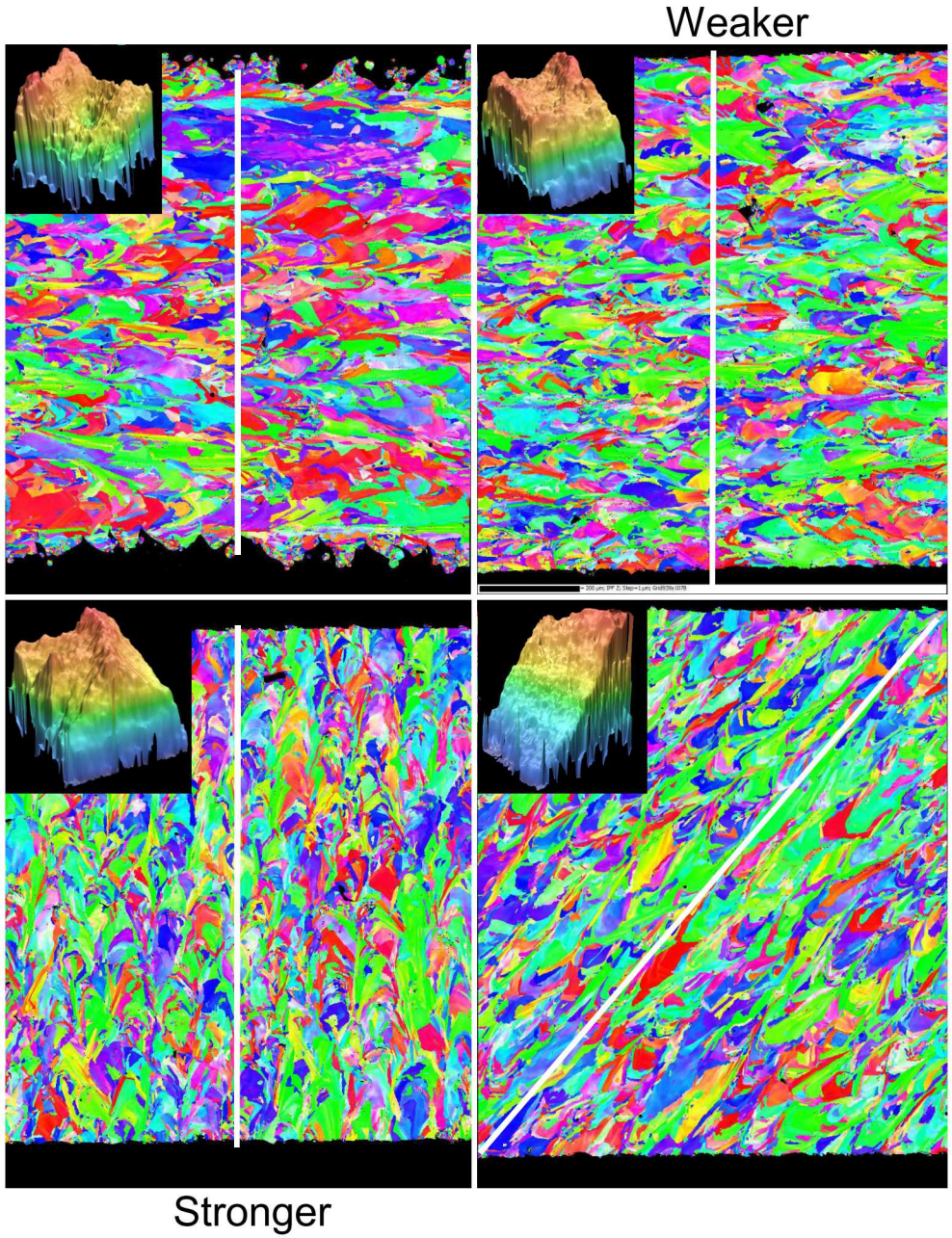
Porosity Coalescence and Growth



- Defects grow and coalesce with nearby pores
- Pores develop near surface and grow
- Necking and failure occurred near lower defect

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

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- Andrew Kustas

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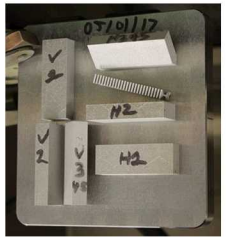
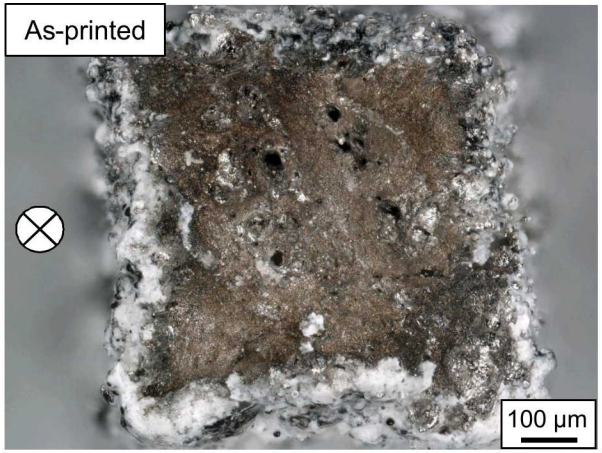
Z-Plane Pole Figure

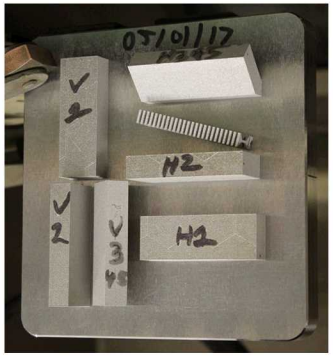


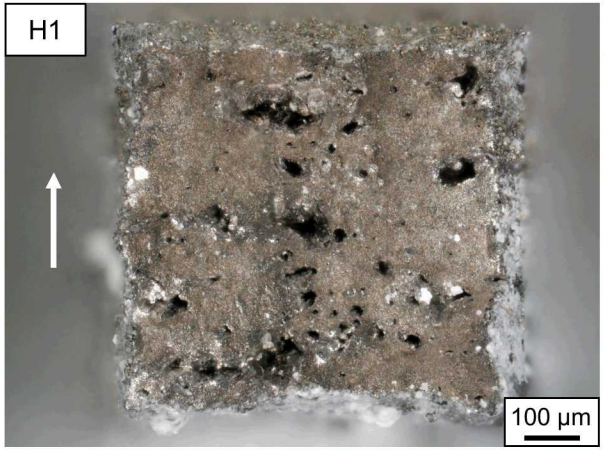
- H2, and V2 have similar textures
- H3-45 and V3-45 have similar textures
- V1 and As-printed are slightly rotated compared to H2 and V2
- H1 is very different
- Still doesn't explain why H2 and H3-45 have such reduced ductility

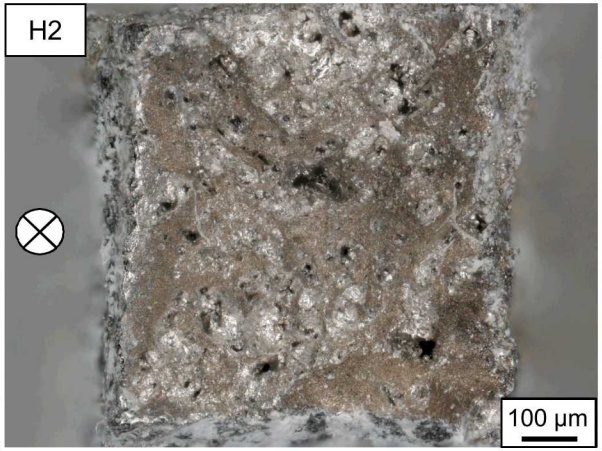
Fractography

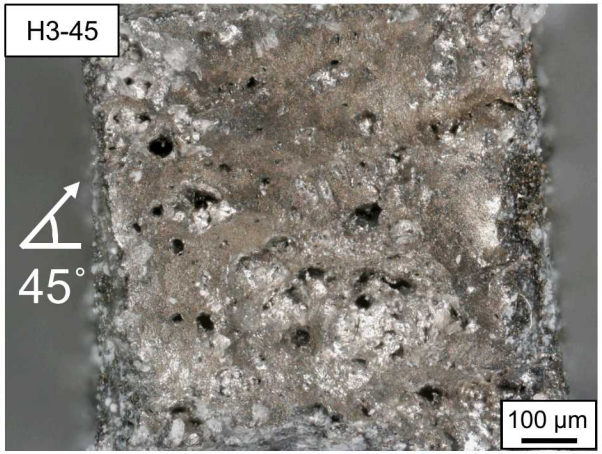
- 45˚ orientations fracture at that angle
- Out of page build direction ⊗

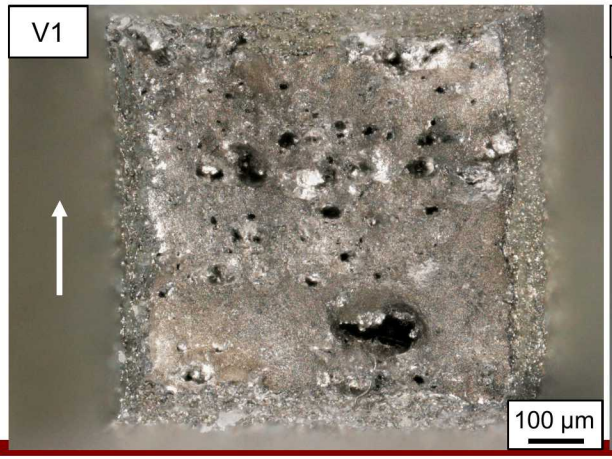


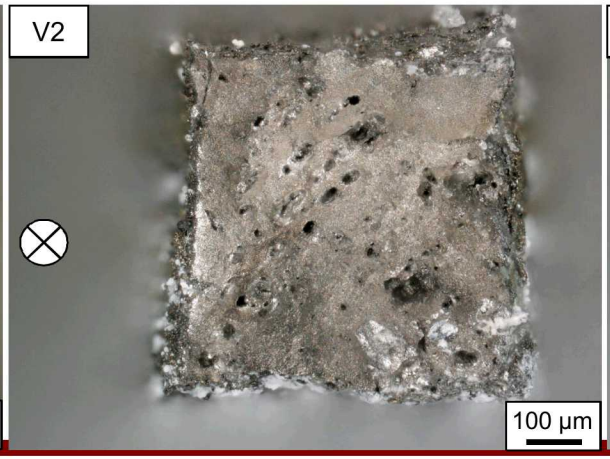


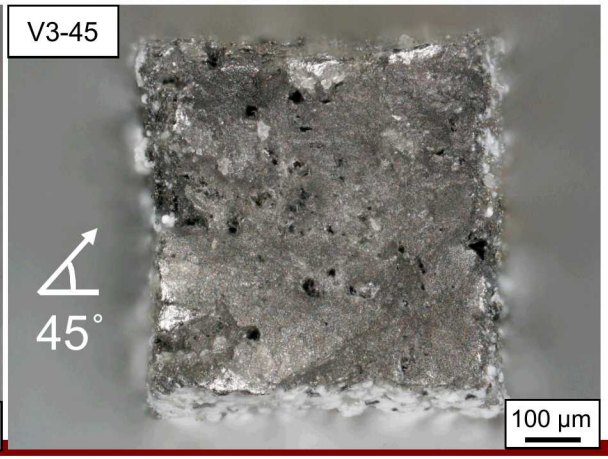


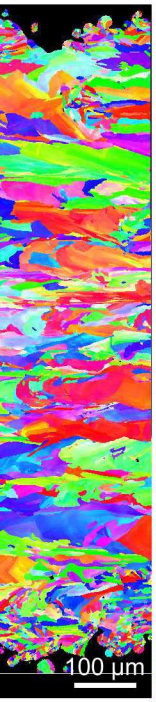








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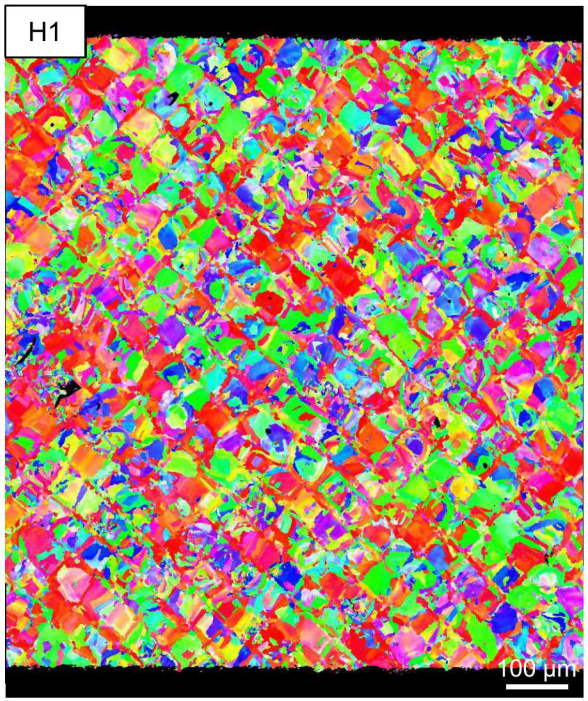
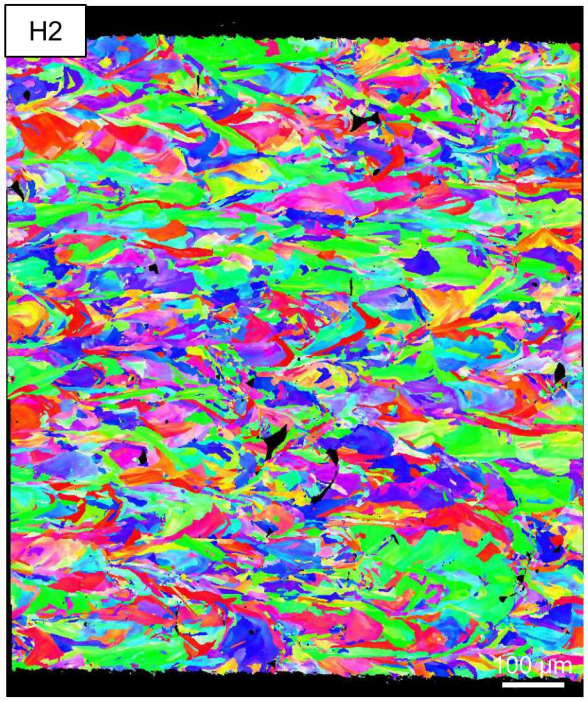
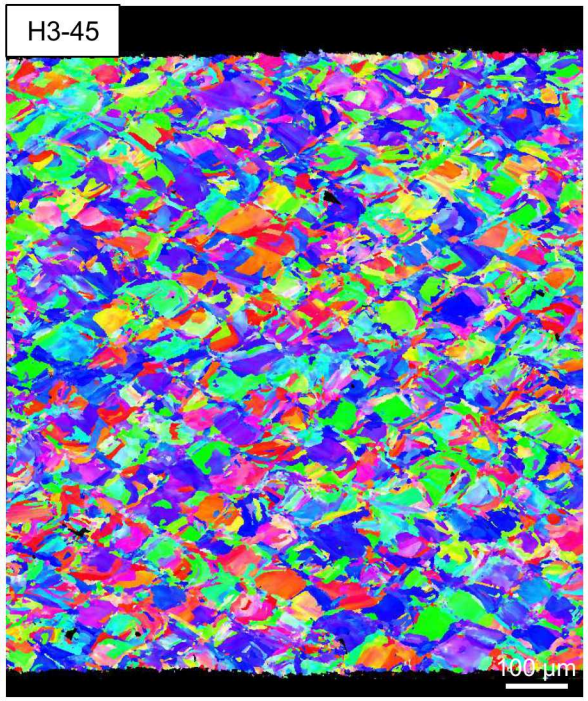

H1
100 µm


H2
100 µm


H3-45
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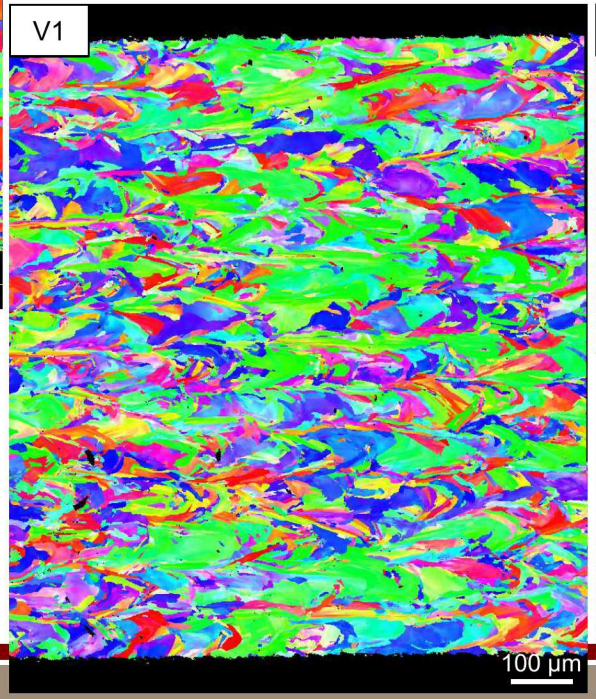
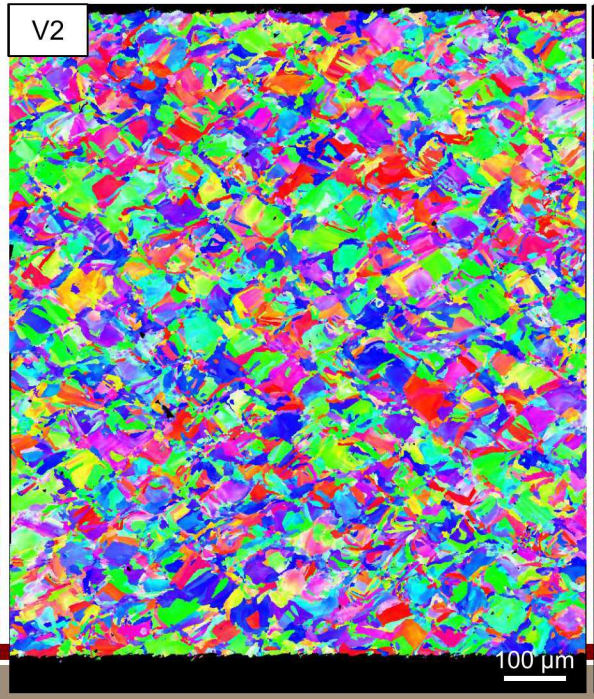
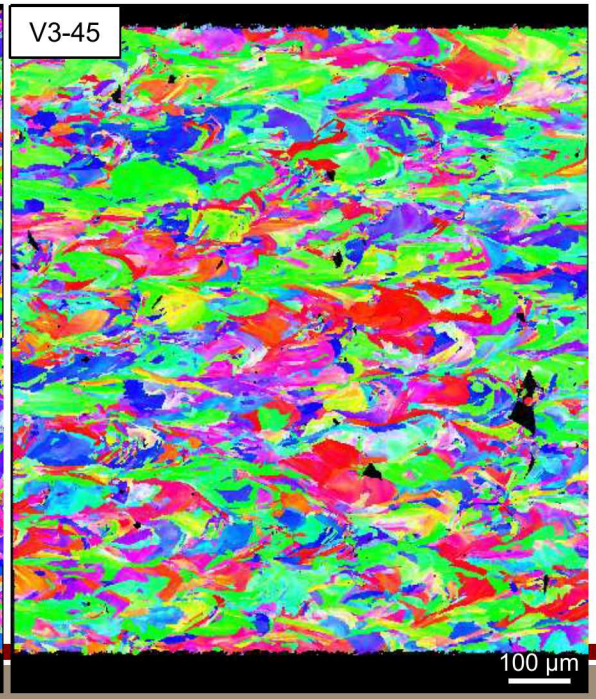
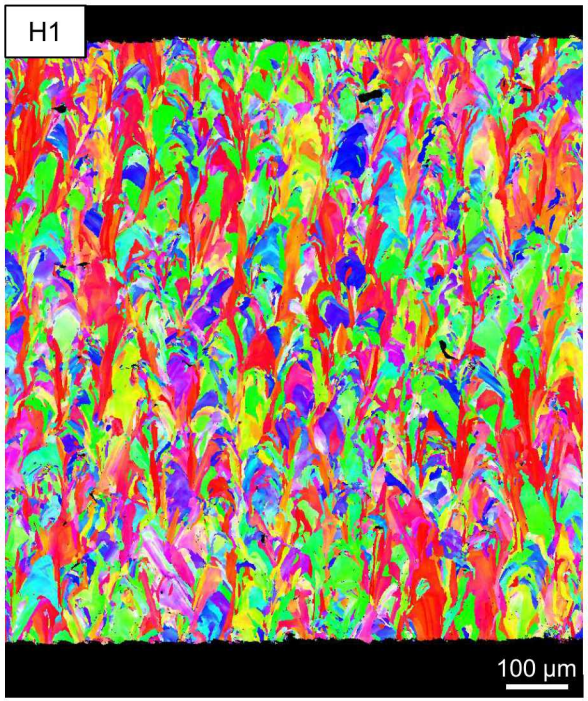

V1
100 µm


V2
100 µm


V3-45
100 µm


100 µm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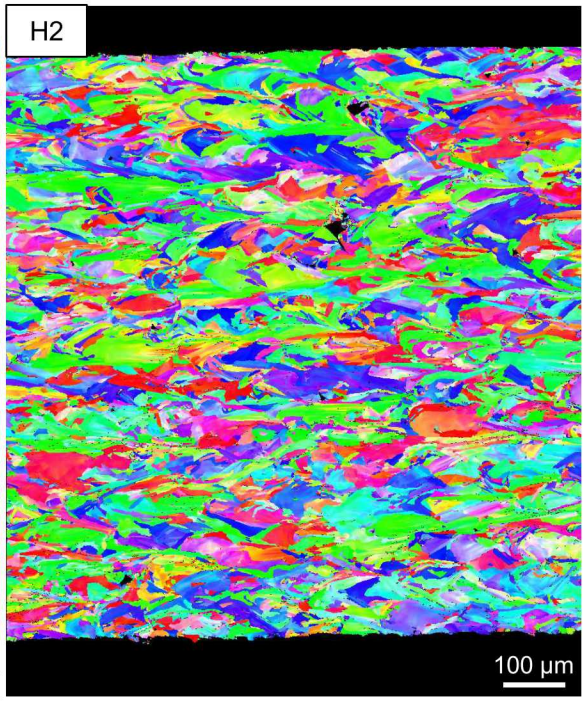
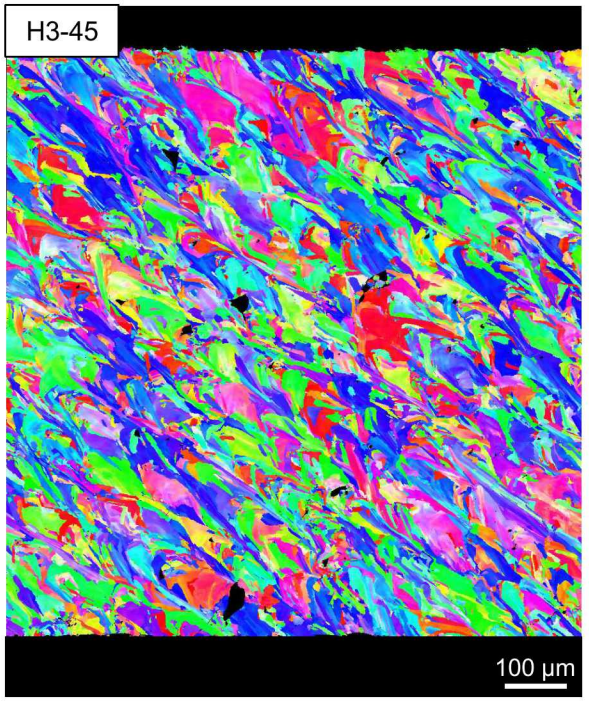

H2
100 µm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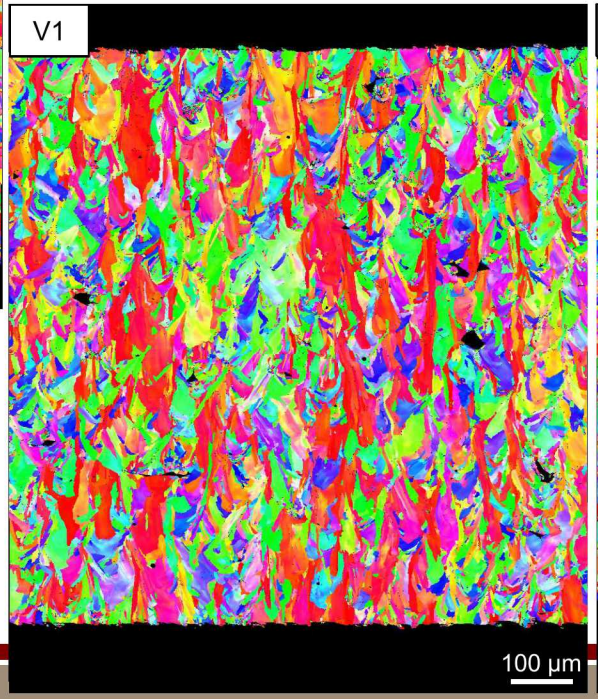
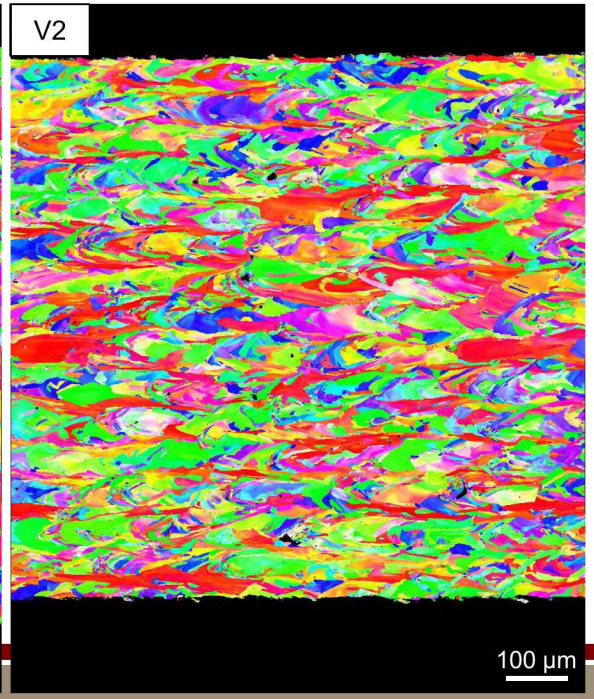
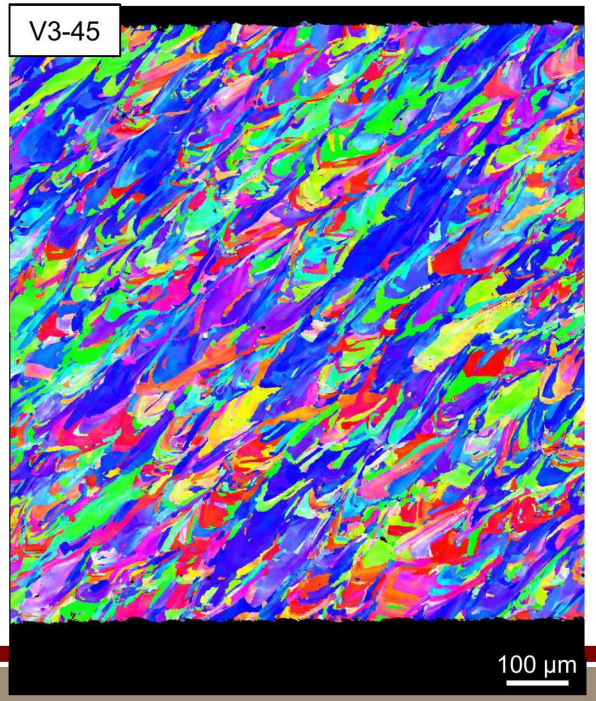

V1
100 µm


V2
100 µm


V3-45
100 µm