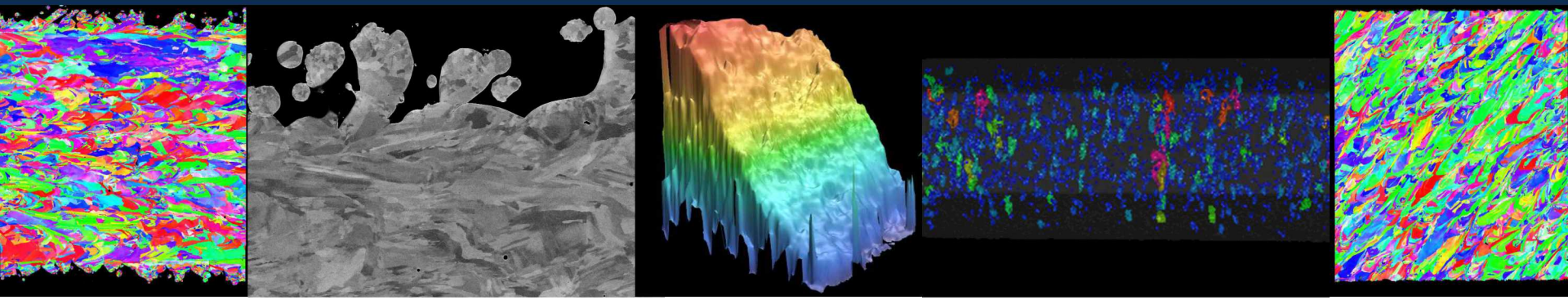
SAND2020-2017C



Effect of Build Orientation and Post Machining on AM 316L Part Failure

Michael Heiden, David Saiz, Dan Tung, John Miers, David Moore, Bradley Jared

Sandia National Laboratories, Albuquerque, NM

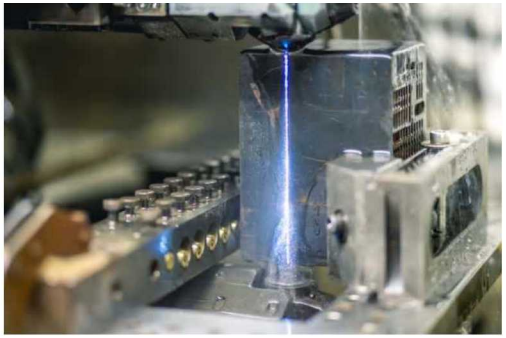
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Motivation

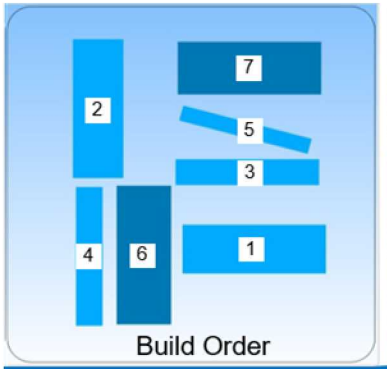
Sandia National Laboratories

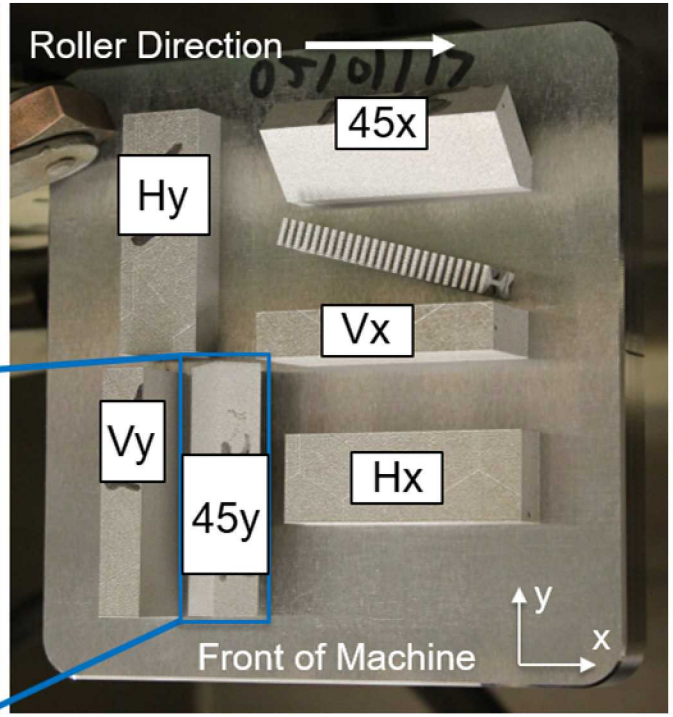
Electro-discharge machining (EDM) of as-printed material:

- Reduces surface microcracks
- Reduces surface roughness
- Increases strength



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

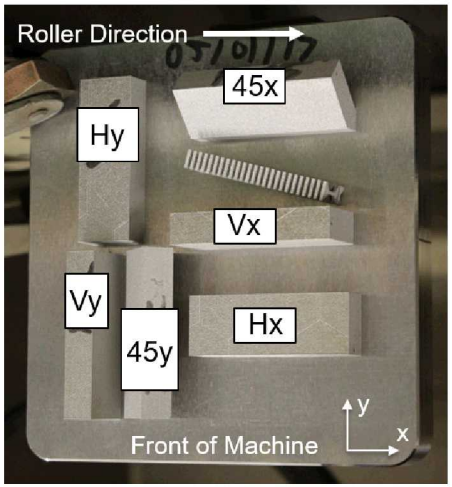


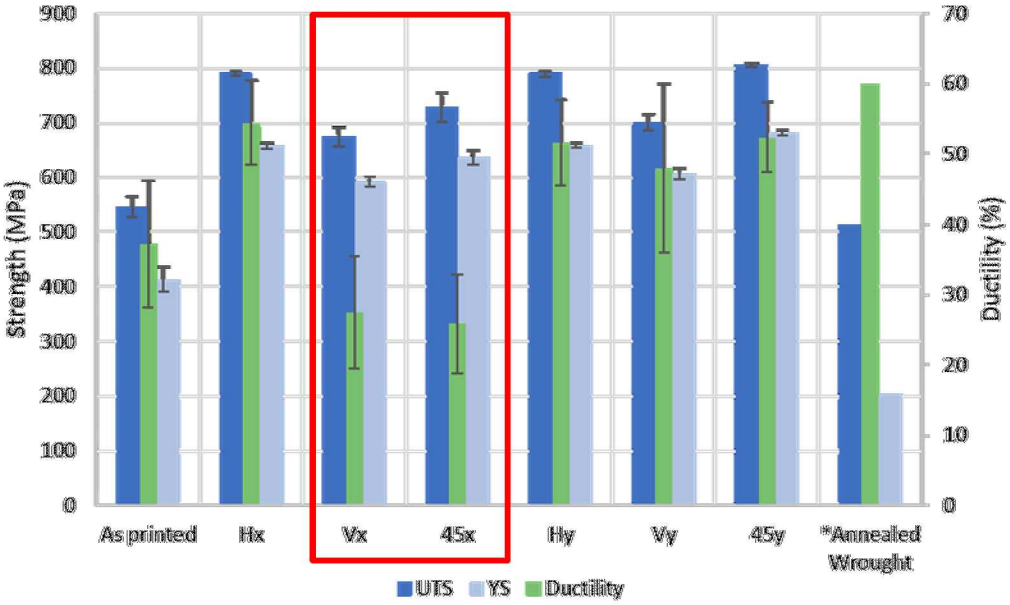


➢ What are the failure mechanisms of AM as-printed and EDM samples in various orientations?

Mechanical Properties

- Highest UTS, YS, and Ductility:
  Horizontal and V-45˚ Builds
- Lowest properties:
  As-printed, H2, and H3-45



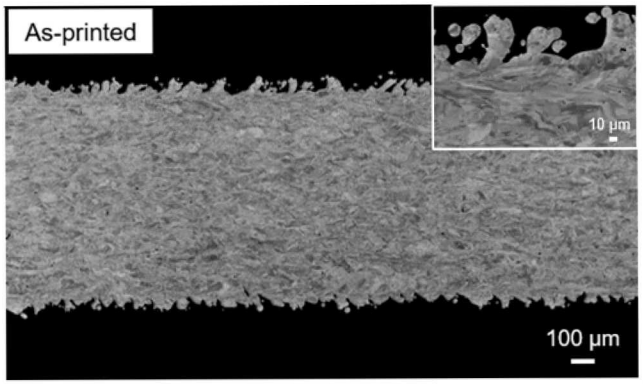


Sample (Stdev)	UTS (MPa)	Yield (MPa)	Ductility (%)	Density (g/mm³)	Sa (µm)	Grain Size (um)	Grain Aspect Ratio
As printed	546 (19)	414 (22)	37 (9)	7.87	15.0 (1.4)	10.7 (10.3)	3.4 (2.4)
Hx	791 (5)	658 (6)	54 (6)	7.94	6.5 (0.7)	9.8 (7.7)	3.4 (2.2)
Vx	674 (16)	592 (9)	28 (8)	7.92	5.5 (0.7)	10.2 (8.6)	3.5 (2.3)
45x	728 (27)	636 (13)	26 (7)	7.90	9.0 (0.0)	10.4 (8.9)	3.5 (2.2)
Hy	790 (5)	659 (4)	52 (6)	7.92	3.0 (0.0)	10.0 (8.3)	3.7 (2.5)
Vy	701 (15)	607 (9)	48 (12)	7.93	6.0 (1.4)	10.8 (9.1)	3.7 (2.5)
45y	806 (4)	682 (5)	52 (5)	7.94	4.0 (0.0)	10.4 (8.9)	3.5 (2.2)
Literature, ASM	515	205	60	7.96	-	-	-

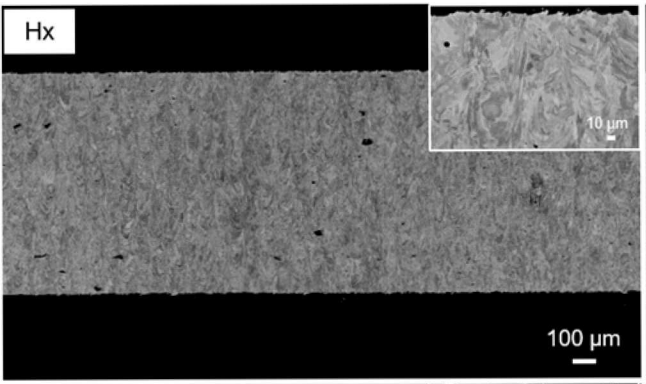
- Why lower performance for as-printed?
- Why ductility so low for Vx & 45x?
- Why horizontal better than vertical?

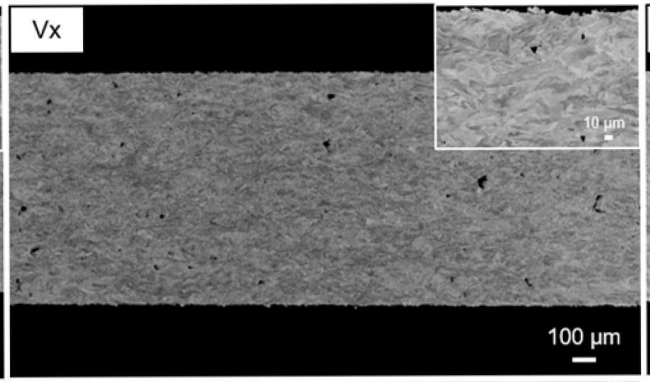
High Surface Roughness for As-printed

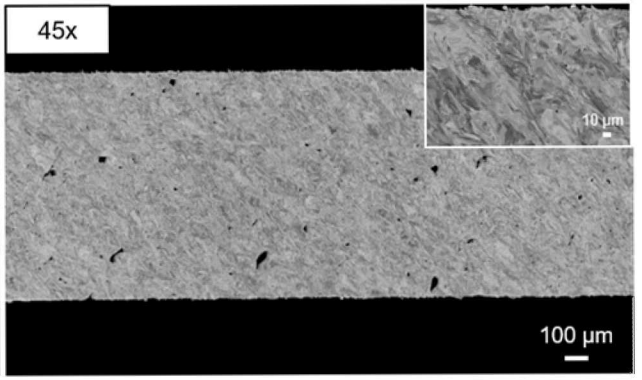
Sample	Sa (µm)	stdev (µm)
As printed	15.0	1.4
Hx	6.5	0.7
Vx	5.5	0.7
45x	9.0	0.0
Hy	3.0	0.0
Vy	6.0	1.4
45y	4.0	0.0

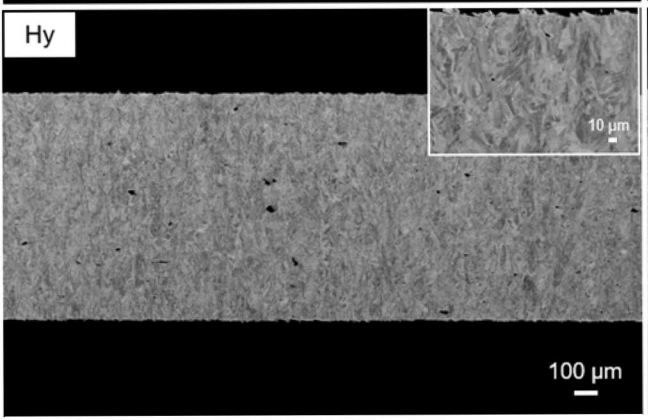


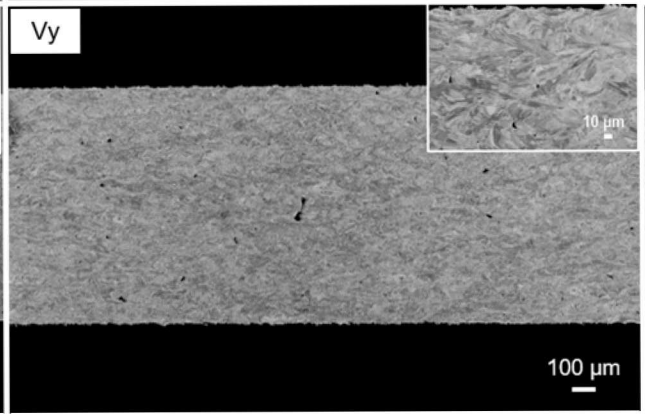
- As-printed surface layer ~ 60 µm thick
- EDMed surface is ~ 5-10 µm thick

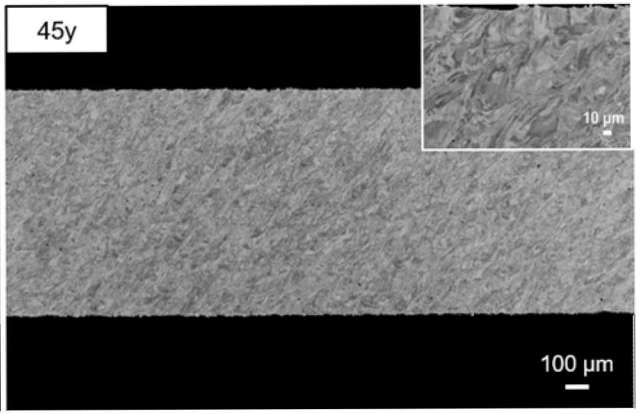




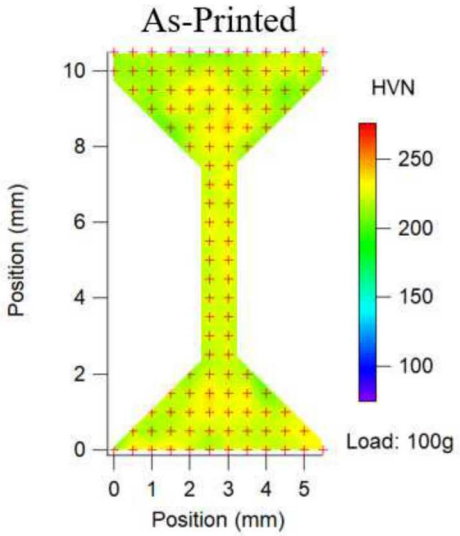


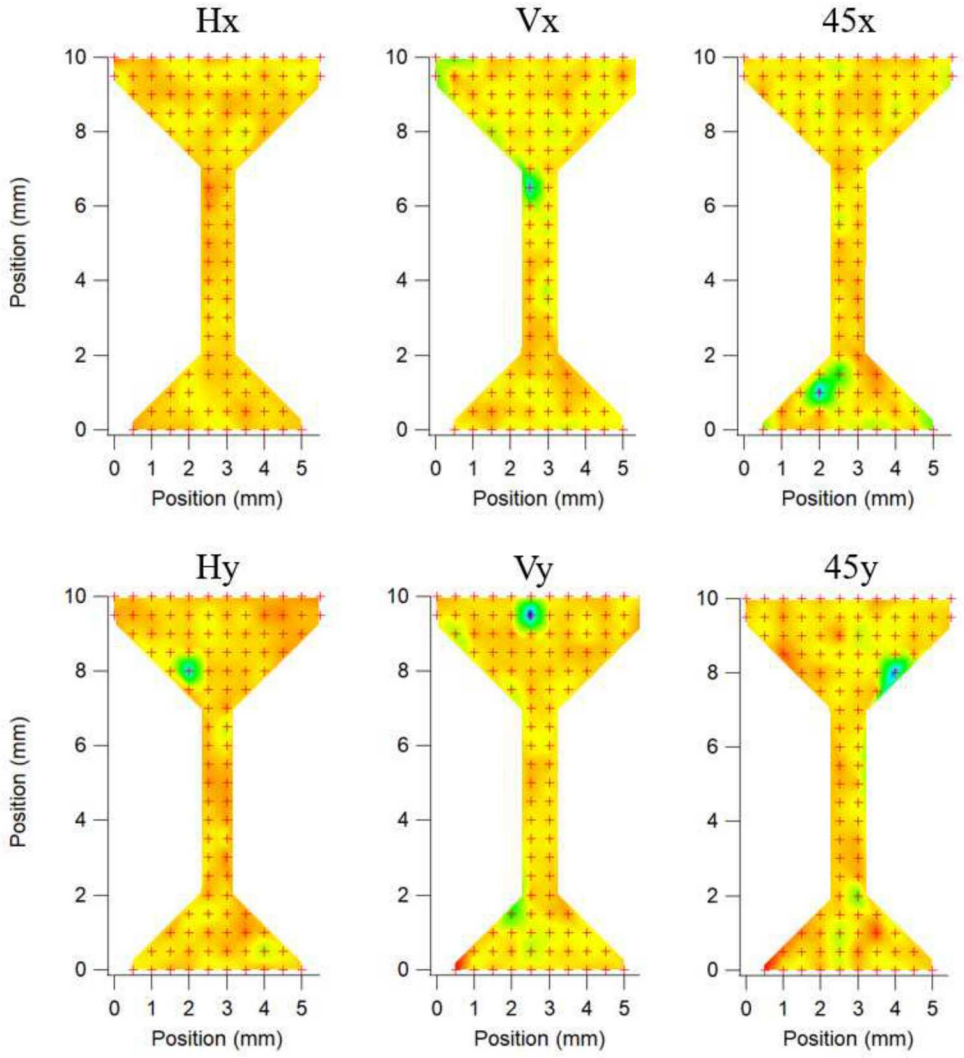






Lower hardness for as-printed tensile samples



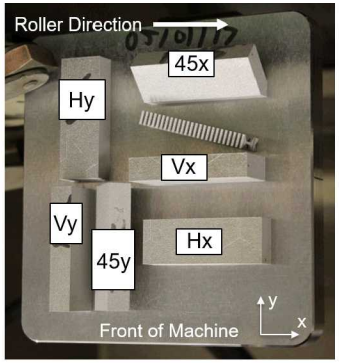


Keep this in mind for witness coupons and varying part thickness

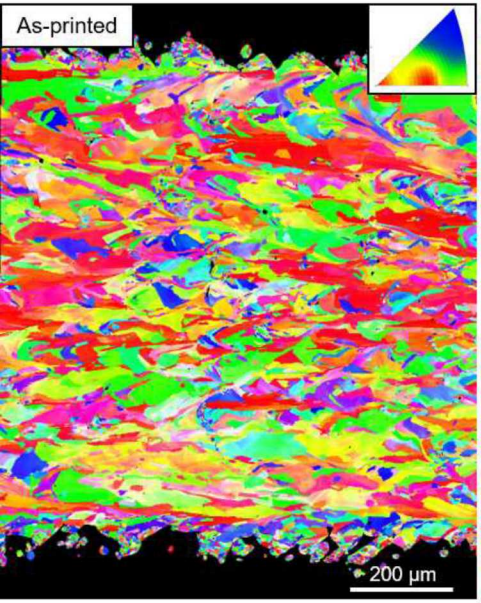
	As-Printed	Hx	Vx	45x	Hy	Vy	45y
Average	222.6	237.5	232.2	232.9	237.9	234.5	235.6
Max	239	263	252	253	255	273	272
Min	202	220	123	102	118	83.9	108
St.Dev.	7.9	7.0	14.4	16.8	14.2	17.5	16.1

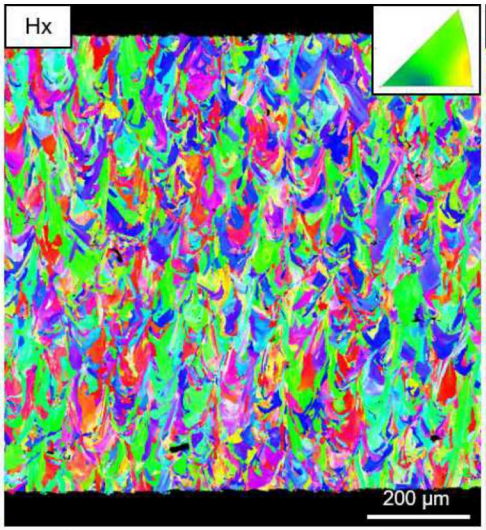
Grains oriented in build direction

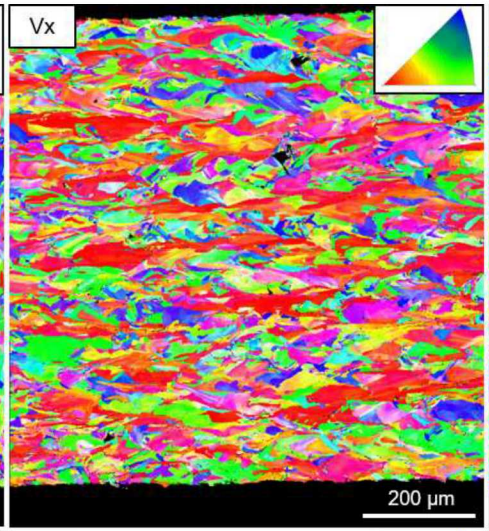
Sample	UTS (MPa)	YS (MPa)	Ductility (%)	Grain Size (um)	Aspect Ratio
As printed	546 (19)	414 (22)	37 (9)	10.9 (10.6)	3.4 (2.4)
Hx	791 (5)	658 (6)	54 (6)	9.8 (7.7)	3.4 (2.2)
Vx	674 (16)	592 (9)	28 (8)	10.2 (8.6)	3.5 (2.3)
45x	728 (27)	636 (13)	26 (7)	10.4 (8.9)	3.5 (2.2)
Hy	790 (5)	659 (4)	52 (6)	10.0 (8.3)	3.7 (2.5)
Vy	701 (15)	607 (9)	48 (12)	10.8 (9.1)	3.7 (2.5)
45y	806 (4)	682 (5)	52 (5)	10.4 (8.9)	3.5 (2.2)

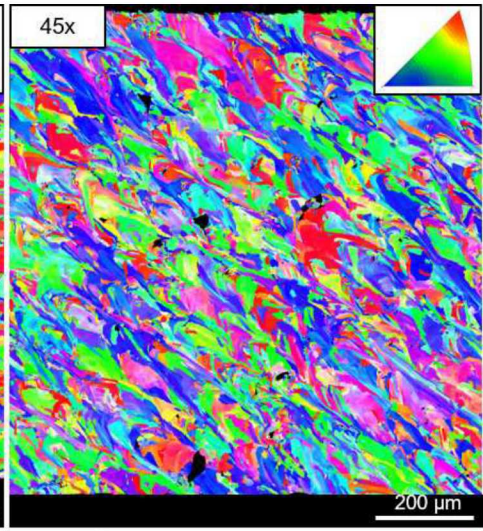


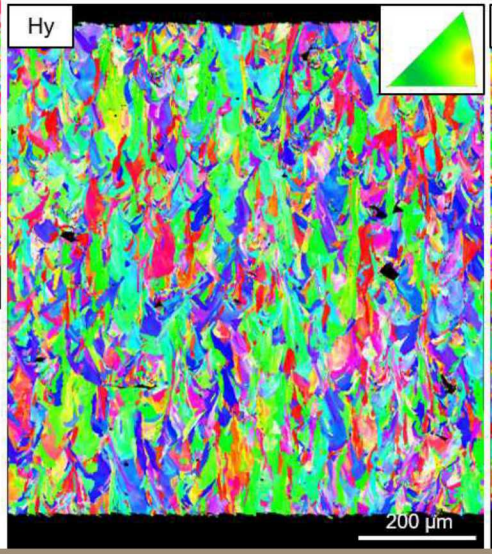
Keep this in mind for witness coupons and angles of build

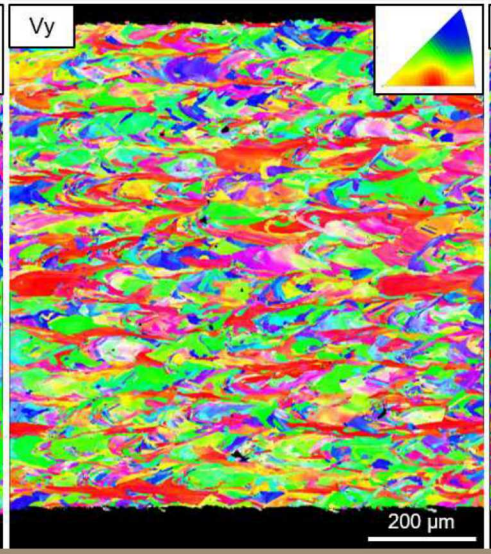


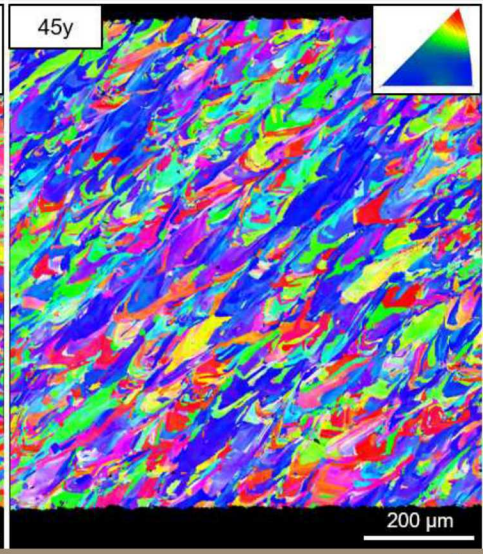


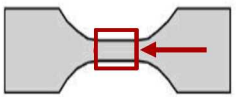


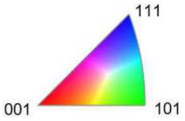






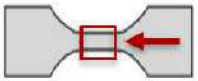


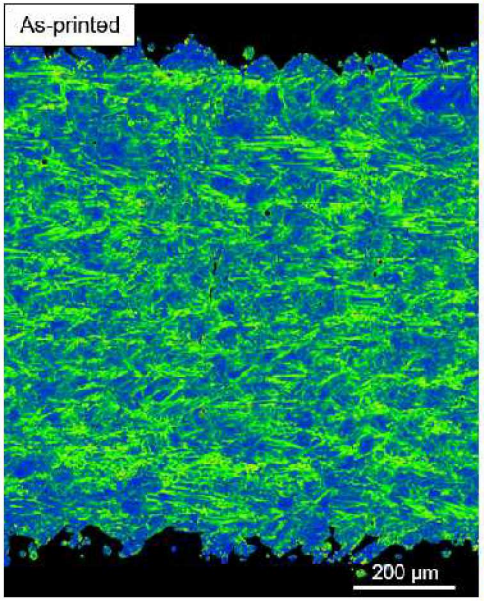


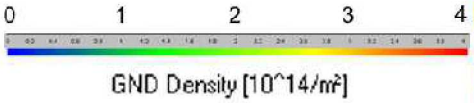


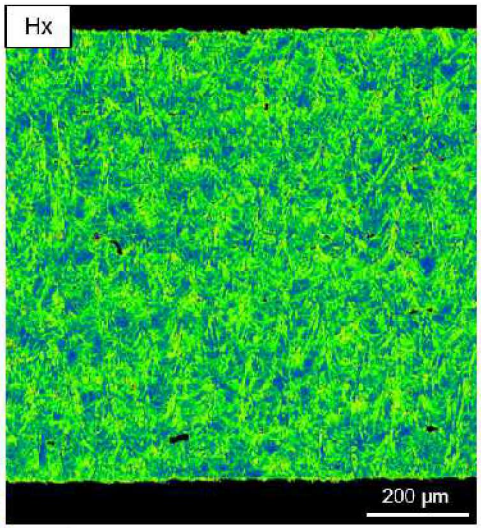
Dislocations build up near grain boundaries and pores

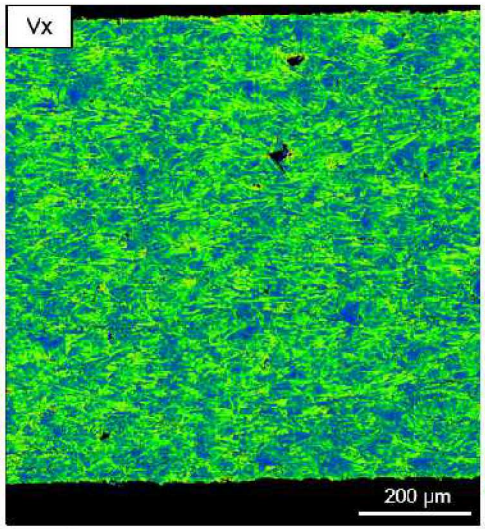
- Geometrically necessary dislocations (GNDs) – Kernel Average Misorientation
- Higher dislocations in EDMed parts due to thermal gradient-driven residual stresses

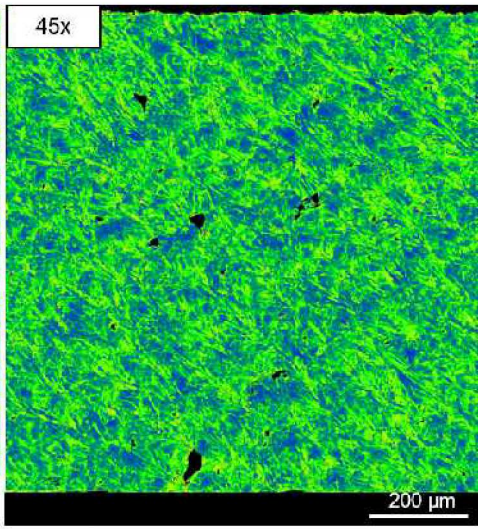


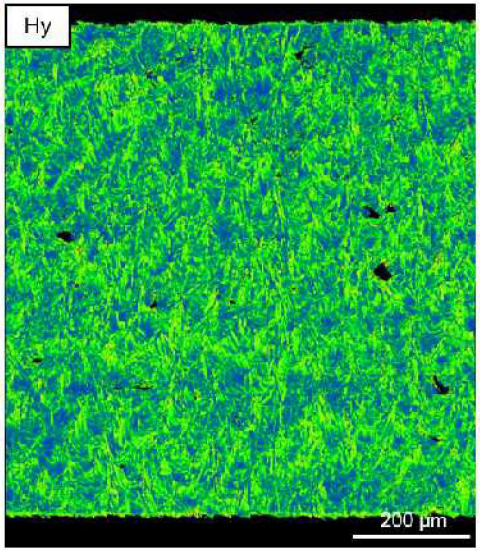


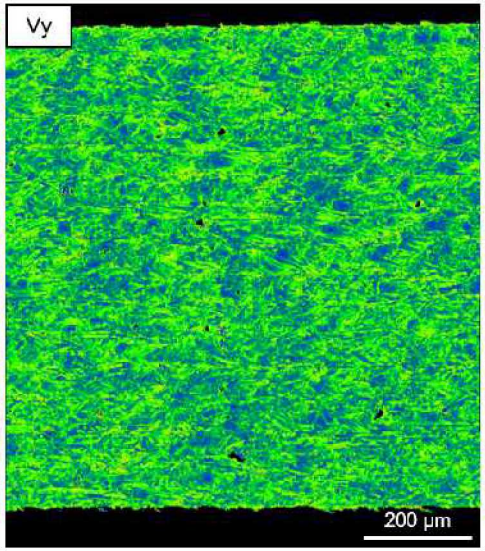


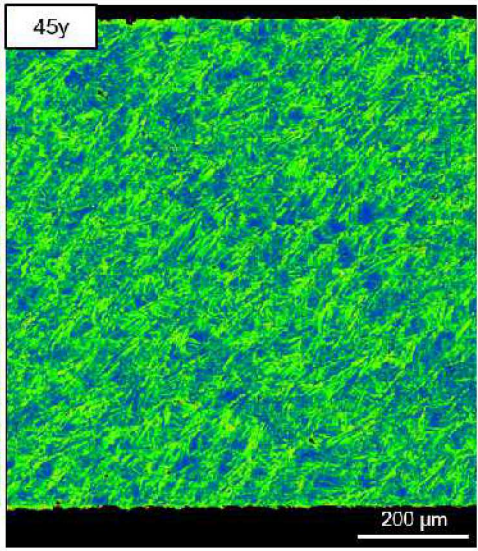






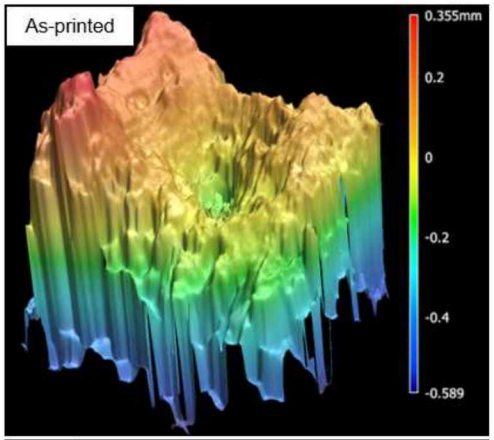


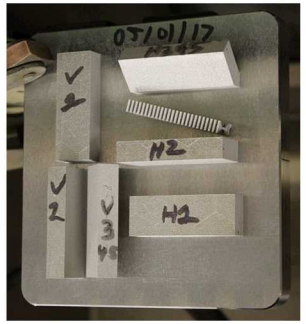


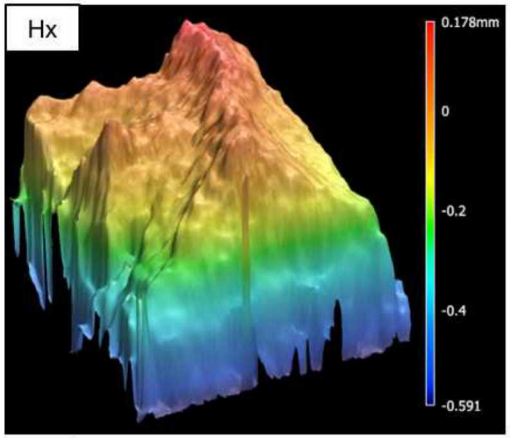


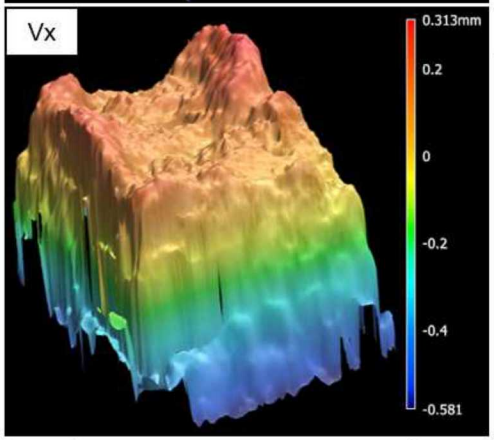
Primarily ductile fracture

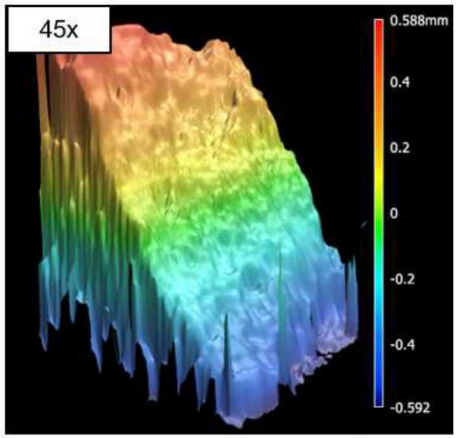
- More of a shear-like failure for parts built at a 45˚
- Sharper shear plane for 45x

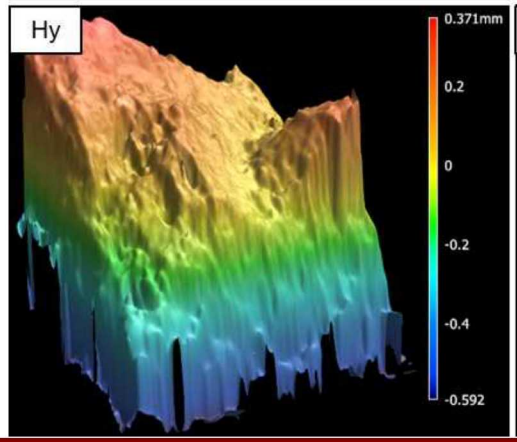


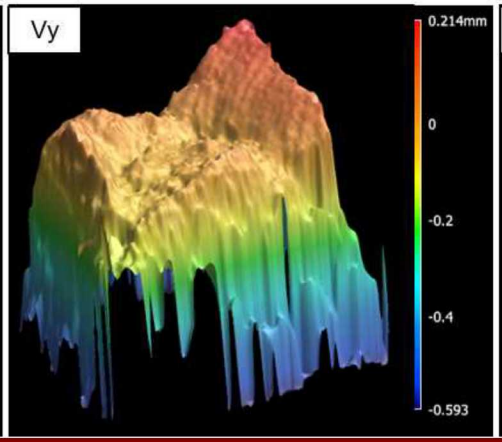


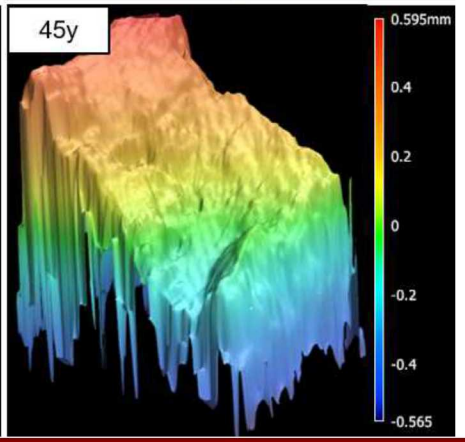


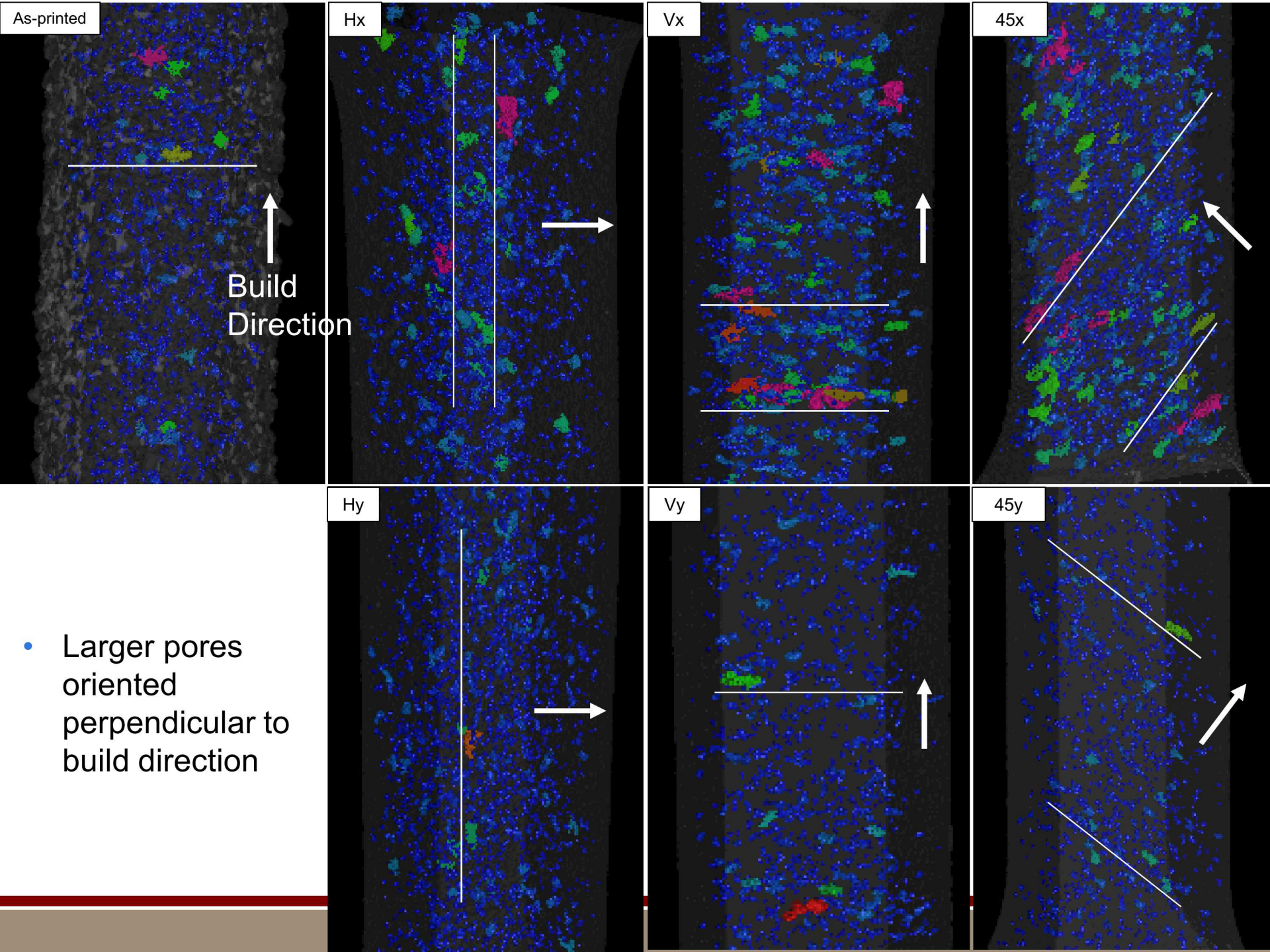




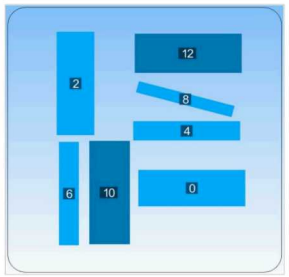


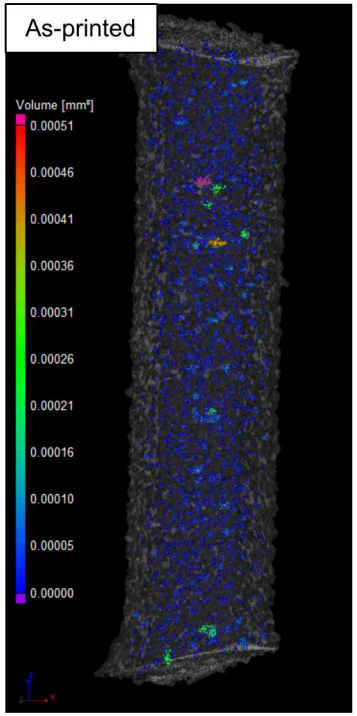


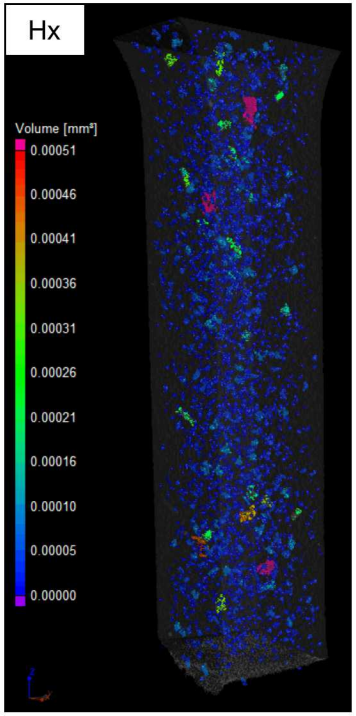


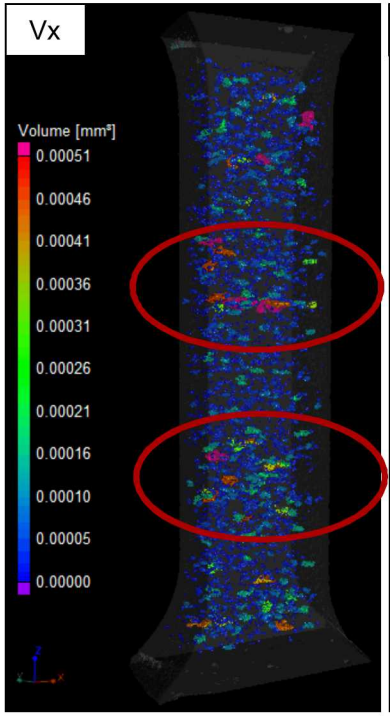


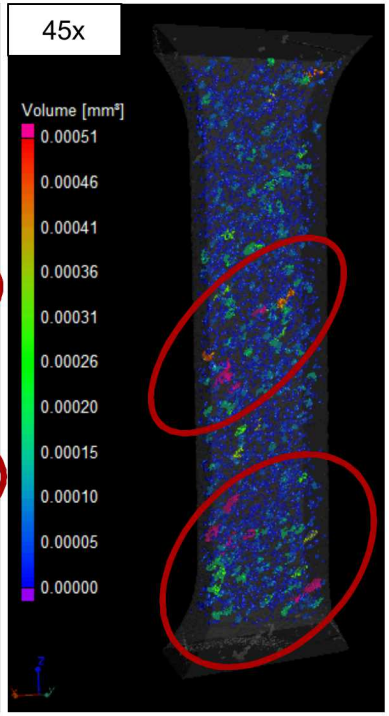
- Larger pores oriented perpendicular to build direction



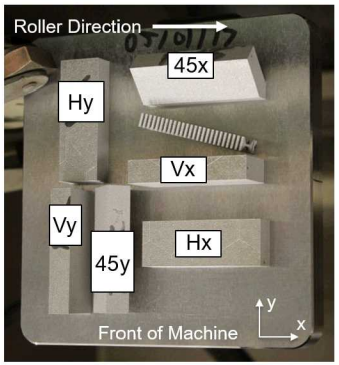


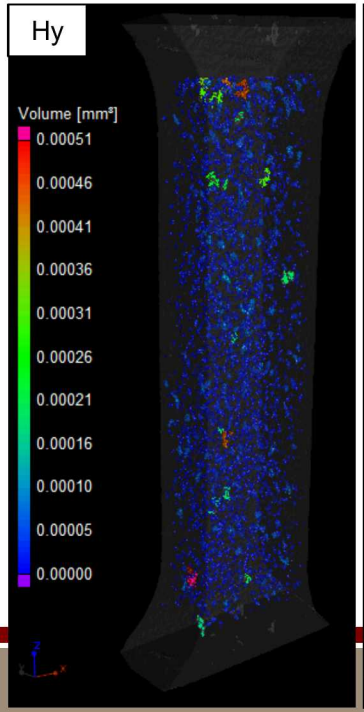


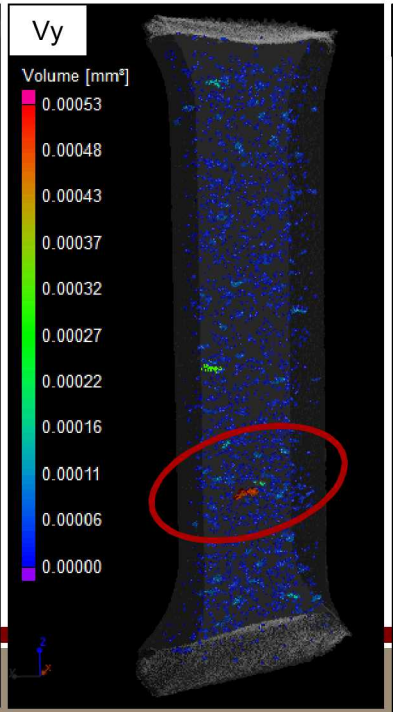


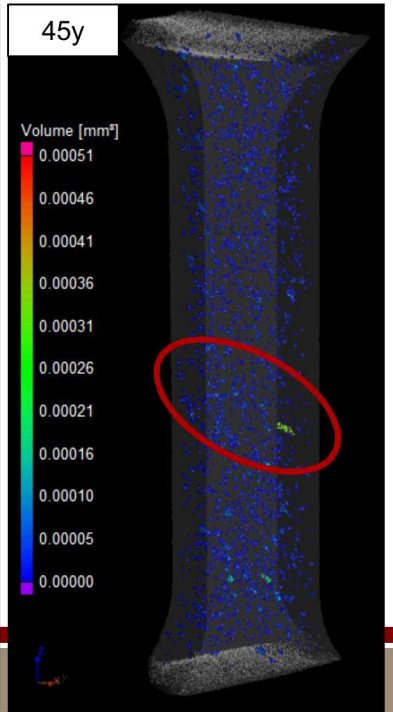


- Pores oriented perpendicular to build direction
- Higher concentration of large pores in Hx, Vx, Hy, and 45x

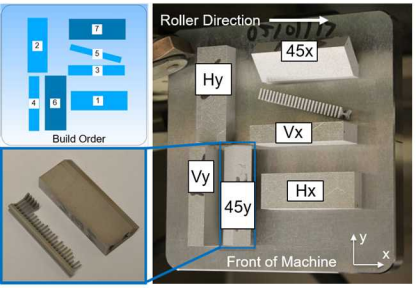


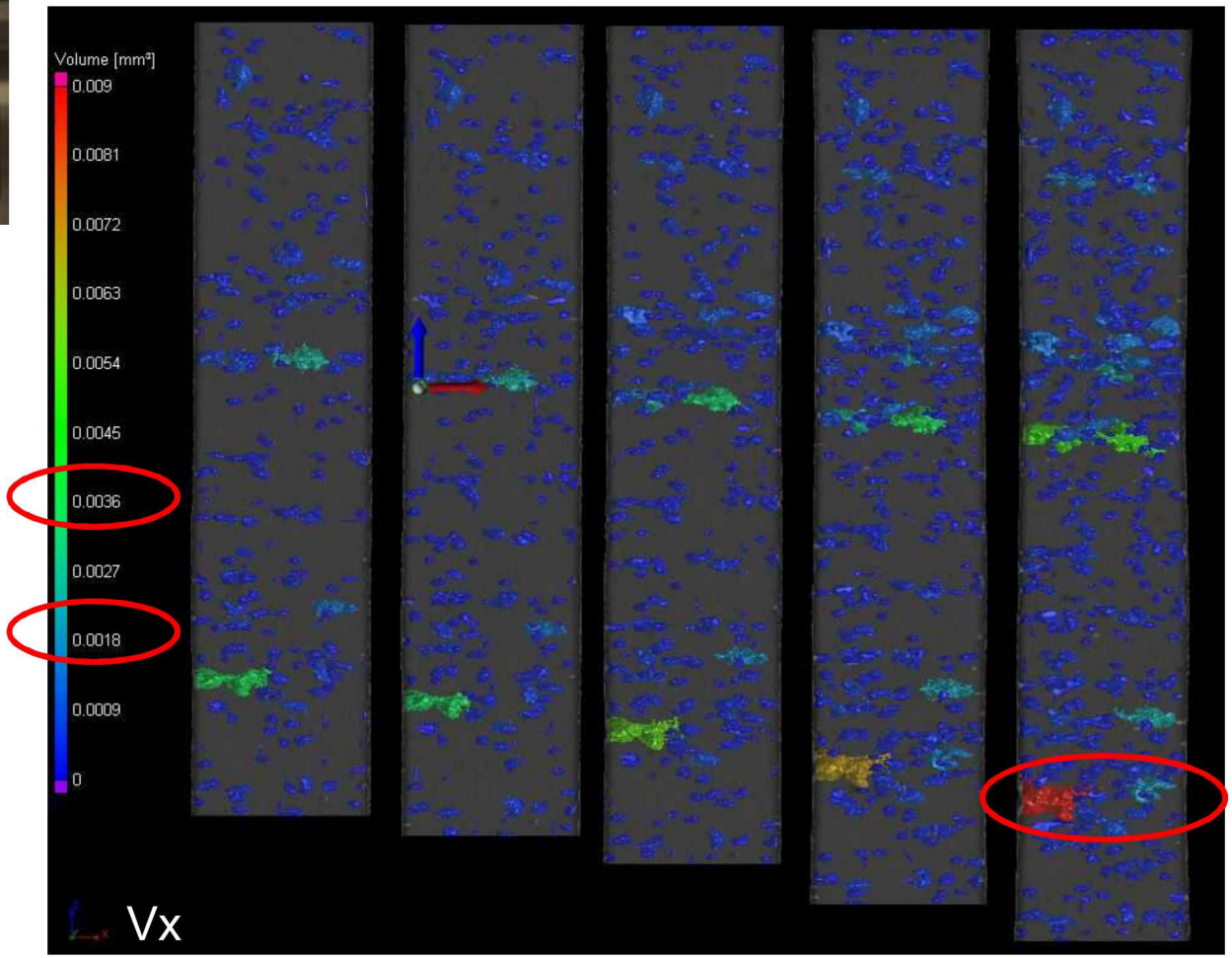






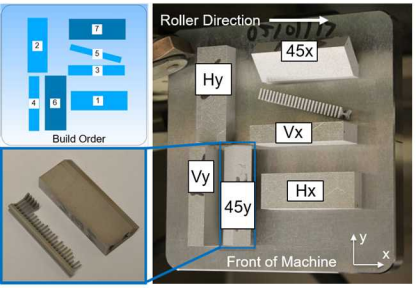
Defects Grow and Coalesce with Nearby Pores

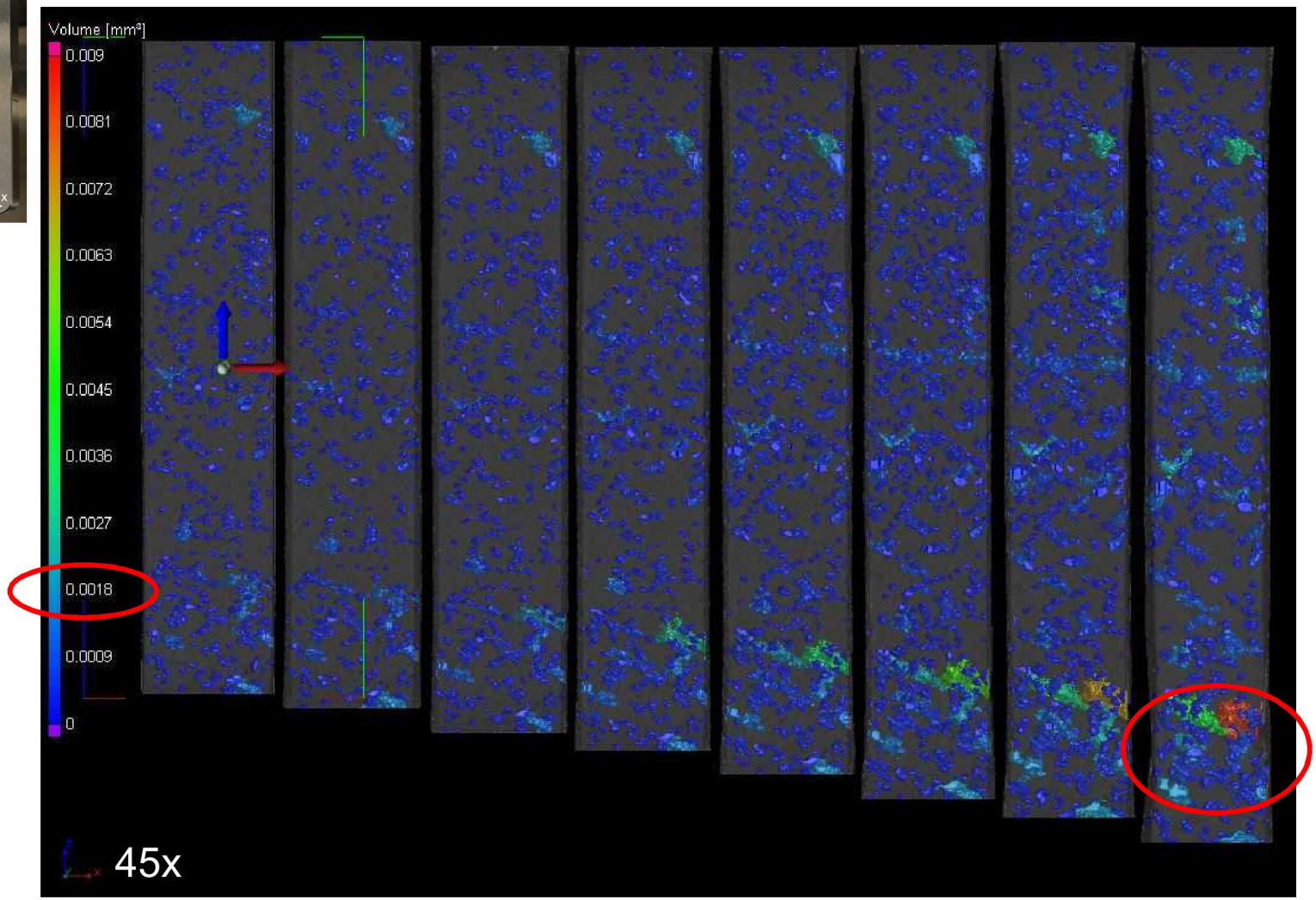




- Pores nearest to the surface dominate growth
- Necking and failure occurred near lower defect

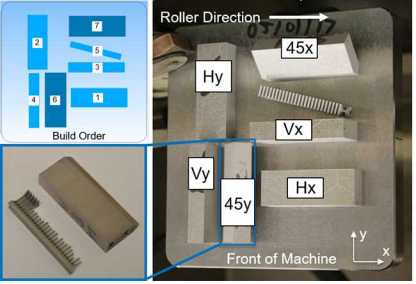
Defects Grow and Coalesce with Nearby Pores



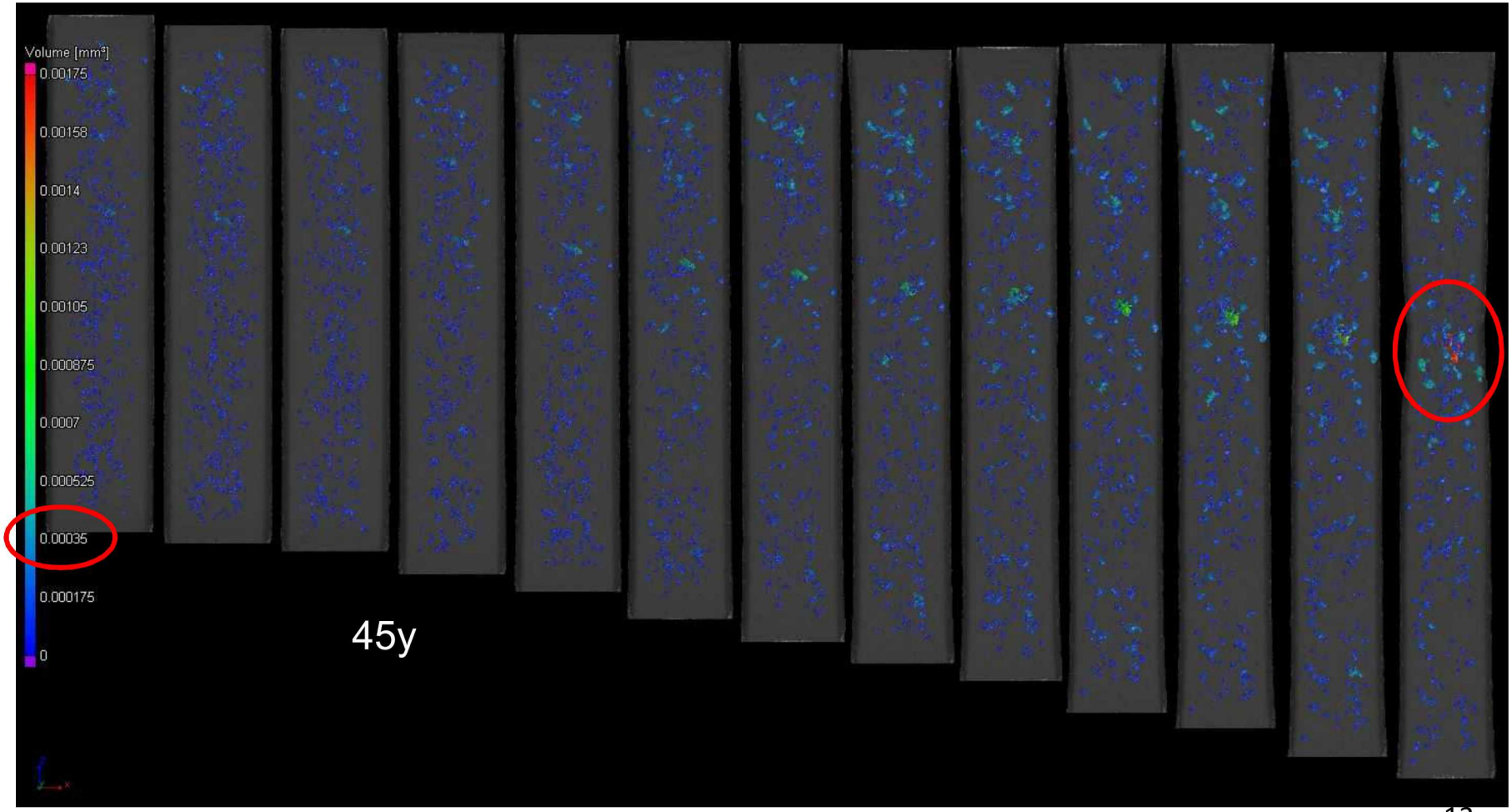


Pore volumes greater than 0.001 mm^3 may lead to failure

~125 μm diameter pores grow to failure

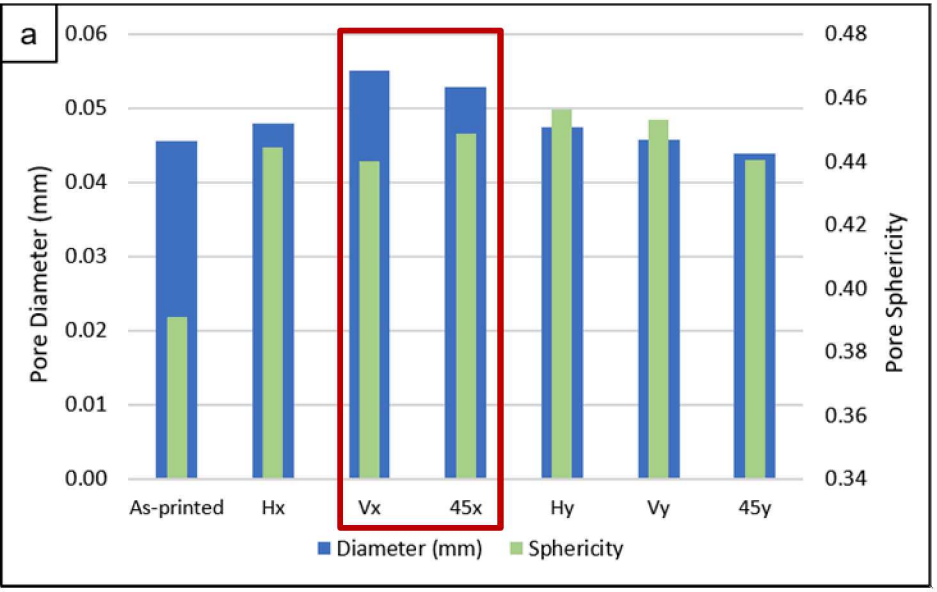


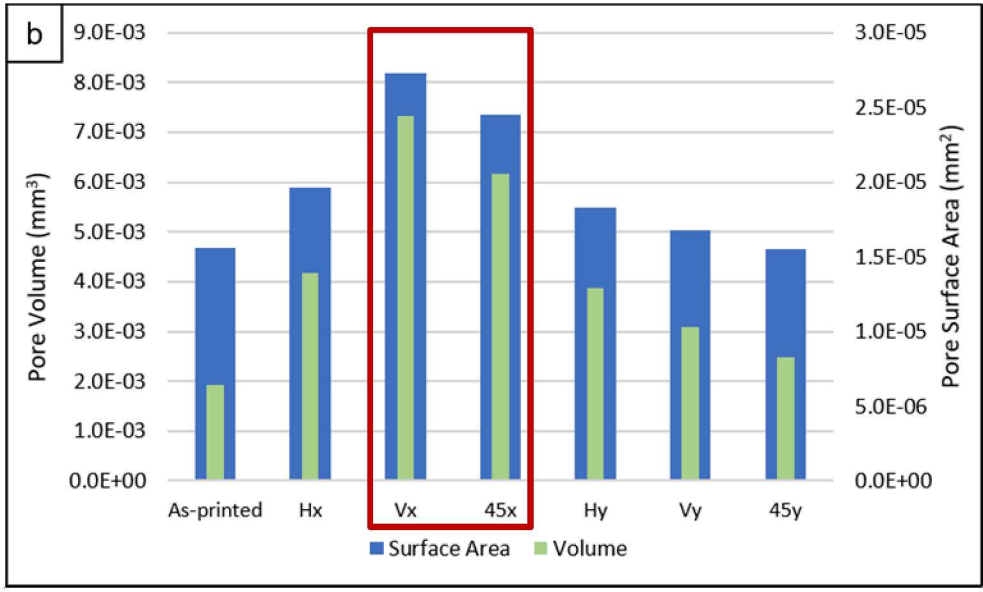
Sandia National Laboratories



High porosity in many “good” samples

	As-printed	Hx	Vx	45x	Hy	Vy	45y
# of pores	2459	3191	3129	4381	3178	2488	2515

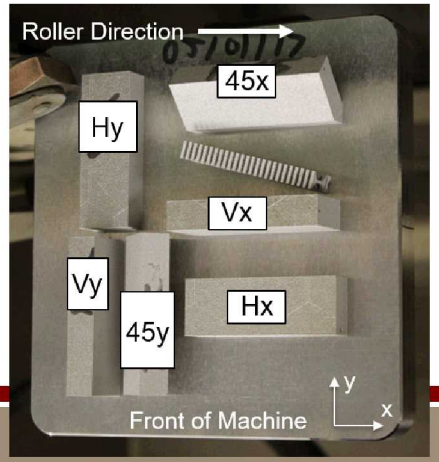


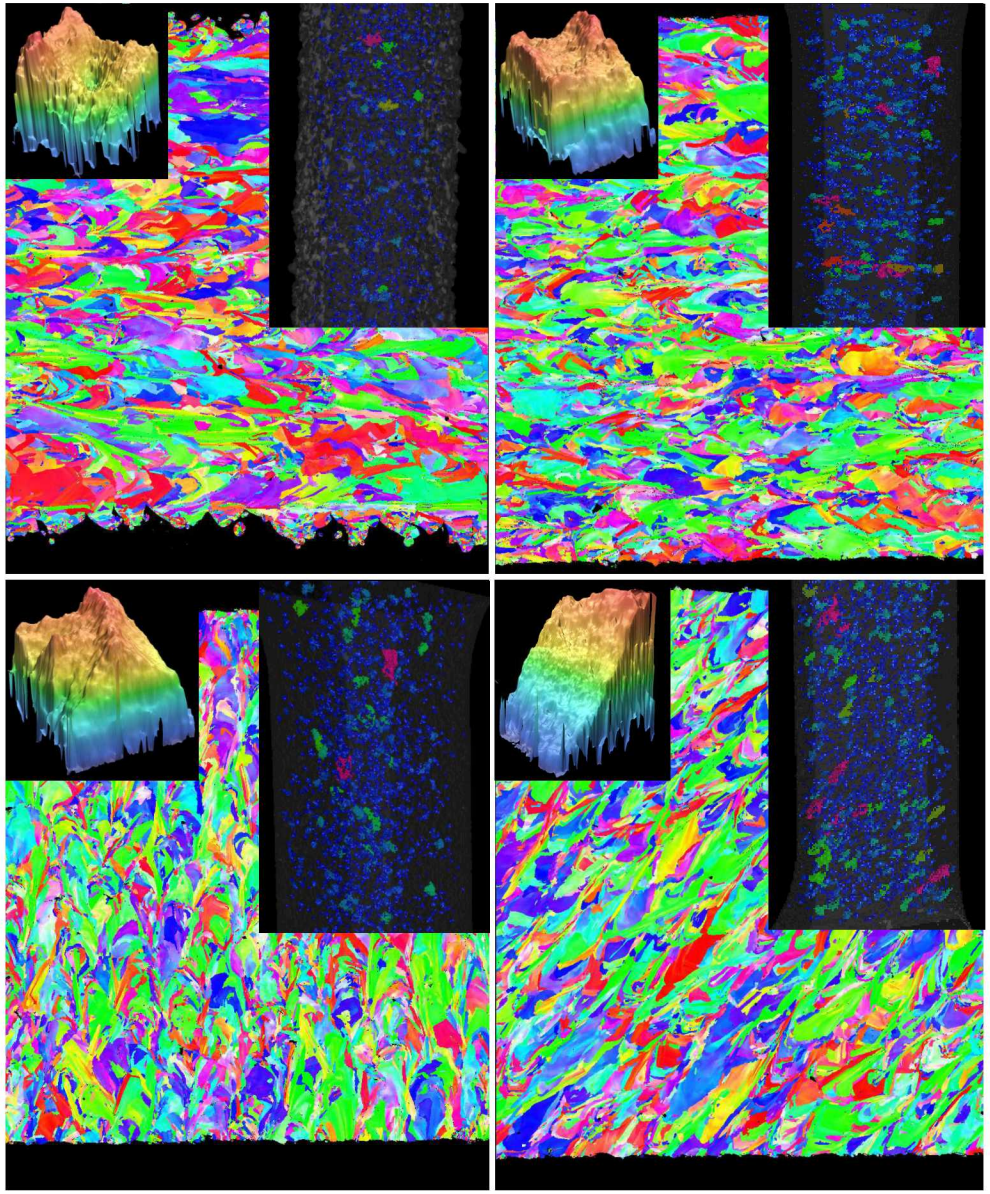


- Hx, Vx, and Hy all have similar number of pores, yet Vx has lowest ductility
- 45x has more more pores than Vx, but has slightly greater properties
- Ductility appears influenced by larger pore diameter, volume, and surface area

Conclusions

- As-printed surface roughness and slower cooling rates limit mechanical properties
- Generally, “thicker” parts built to be post-machined have higher mech. properties
- Build direction influences grain orientation, GND density, pore orientation and fracture
- Orientation wrt build chamber not affected
- 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



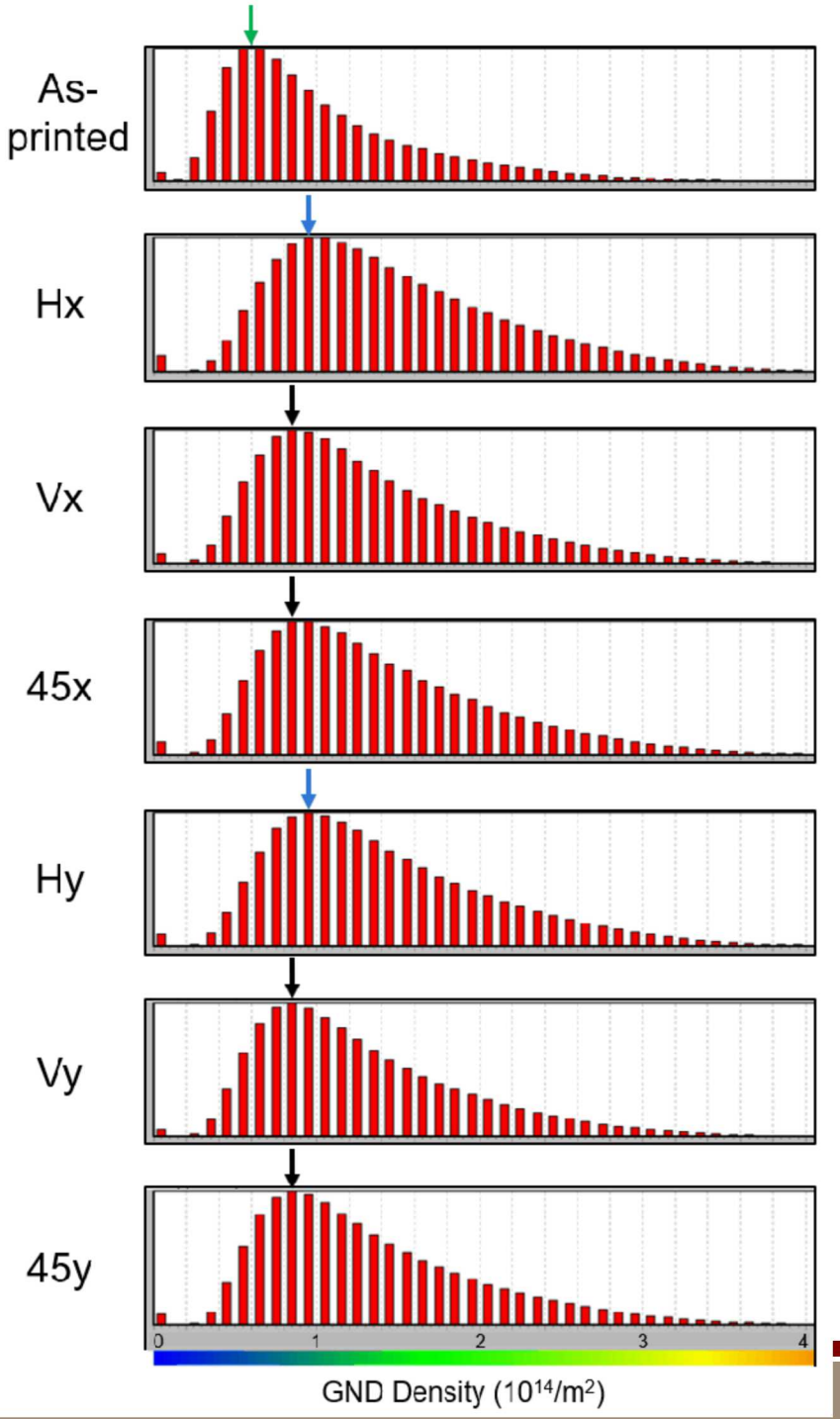


Acknowledgements

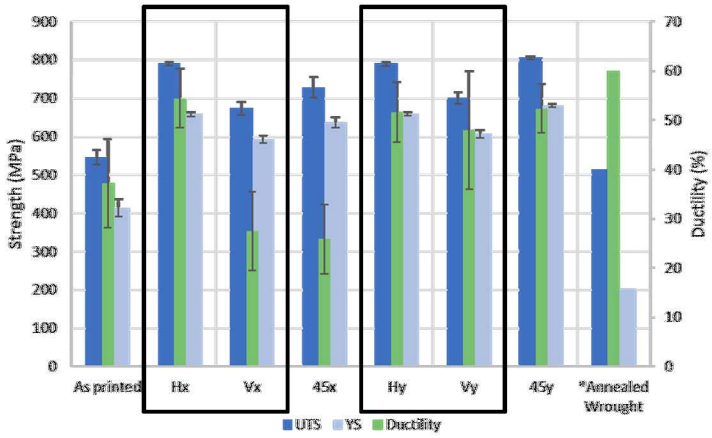
- Josh Koepke
- Joe Michael
- Andrew Lentfer
- Sara Dickens
- Christina Profazi
- Celedonio Jaramillo
- Andrew Kustas

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525. Internal Presentation 2019

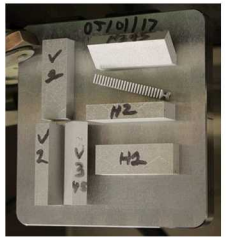
GND density shift for horizontally-built samples



- As-printed part has much lower distribution of dislocations
- Slightly higher distribution of dislocations in horizontally-built parts compared to vertical and 45˚



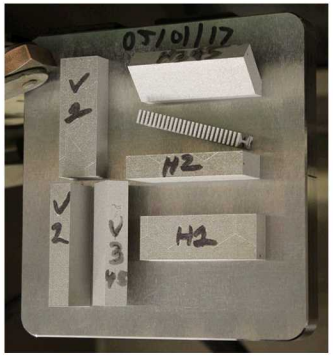
Z-Plane Pole Figure

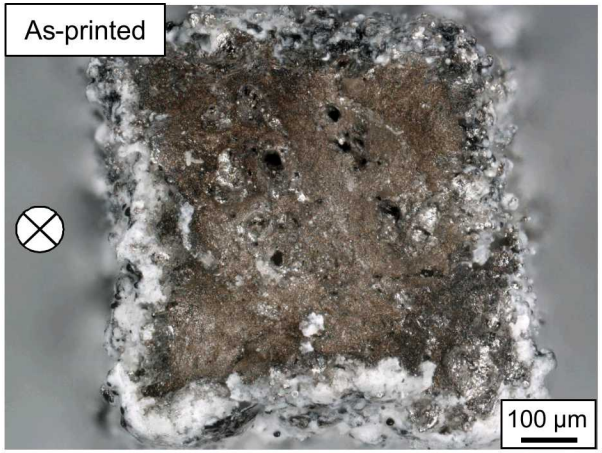


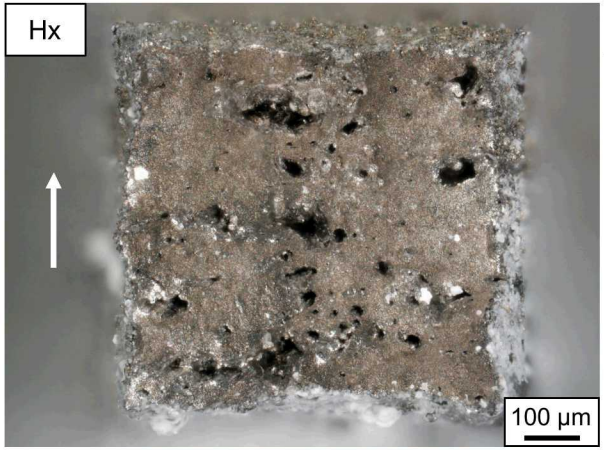
- H2, and V2 have similar textures
- H3-45 and V3-45 have similar textures
- V1 and As-printed are slightly rotated compared to H2 and V2
- H1 is very different
- Still doesn't explain why H2 and H3-45 have such reduced ductility

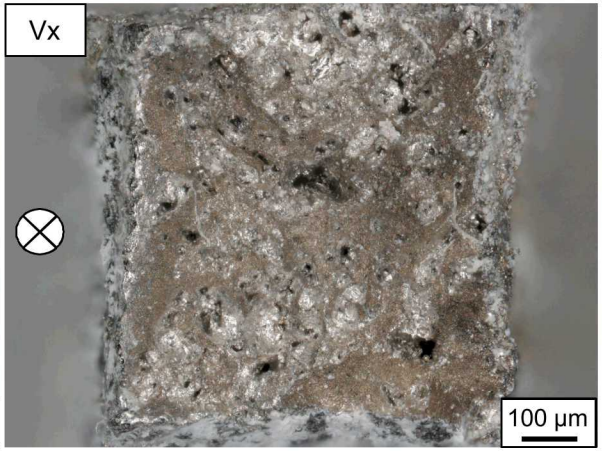
Fractography

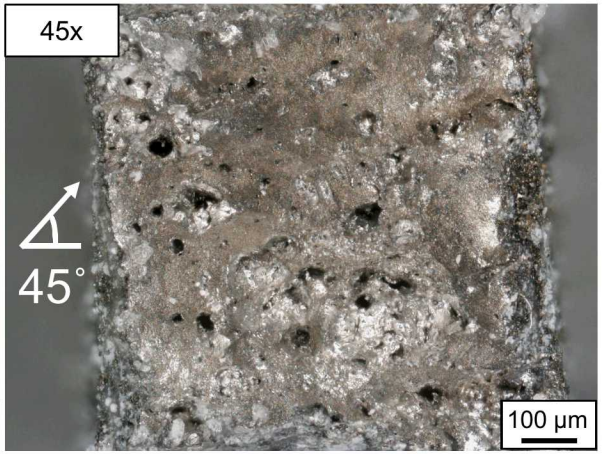
- 45˚ orientations fracture at that angle
- Out of page build direction ⊗

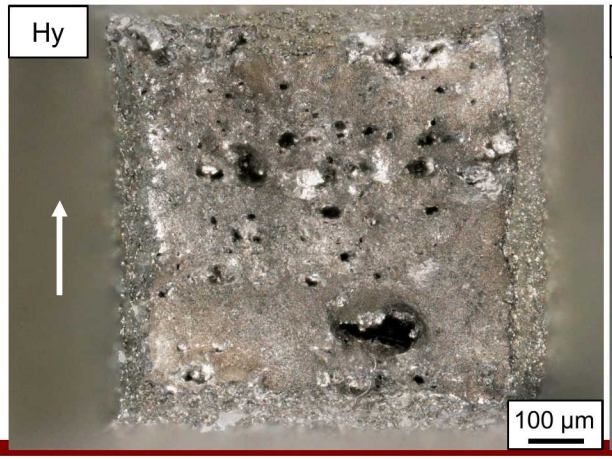


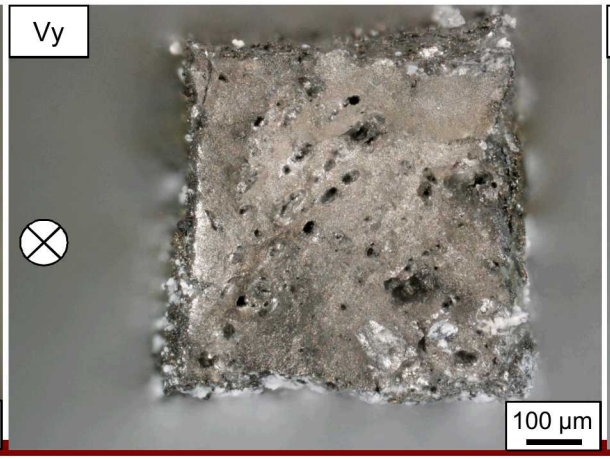


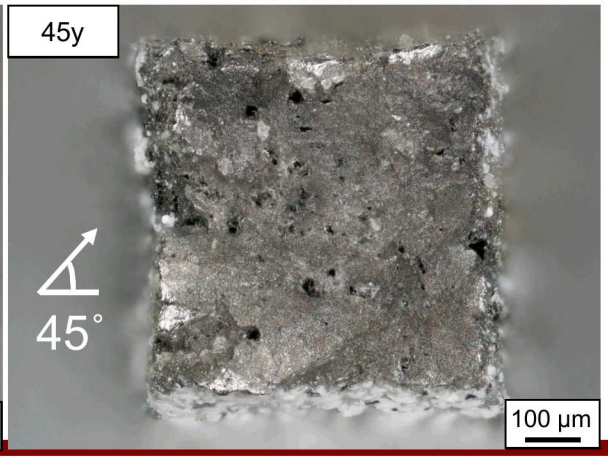


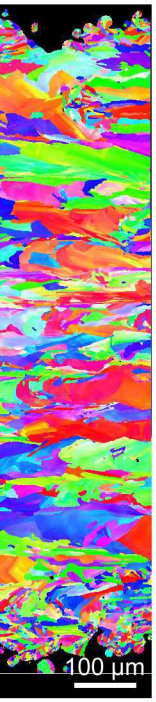


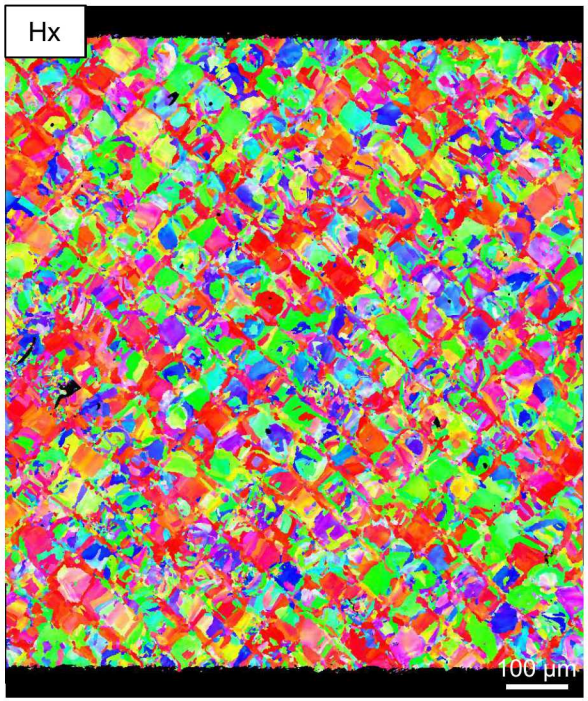


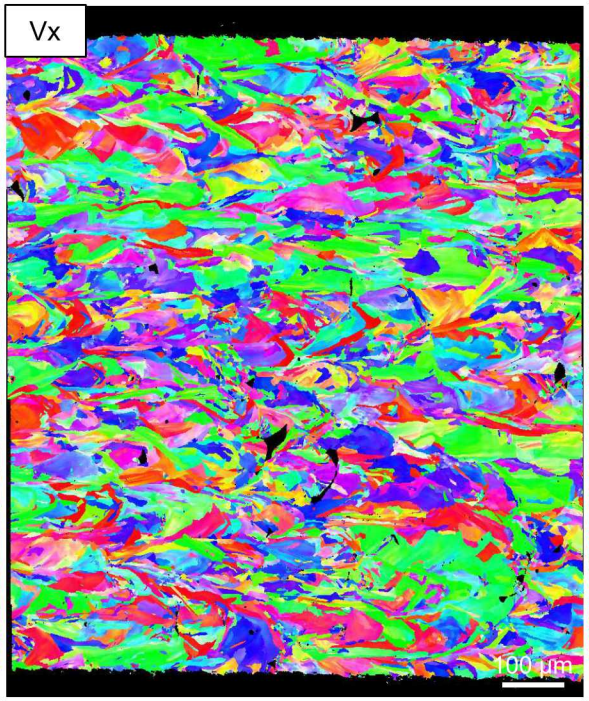


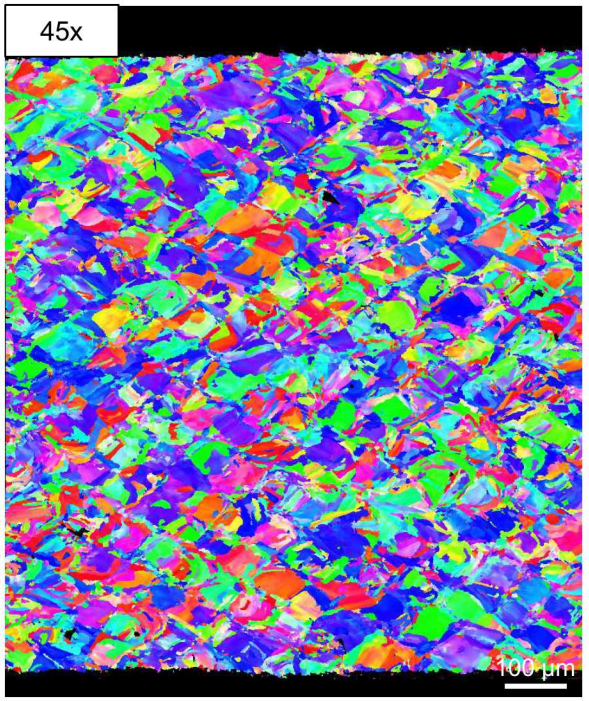


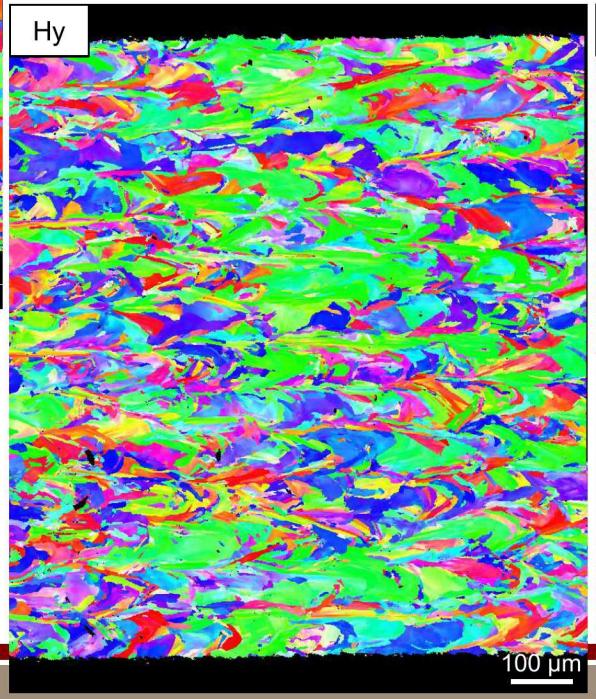


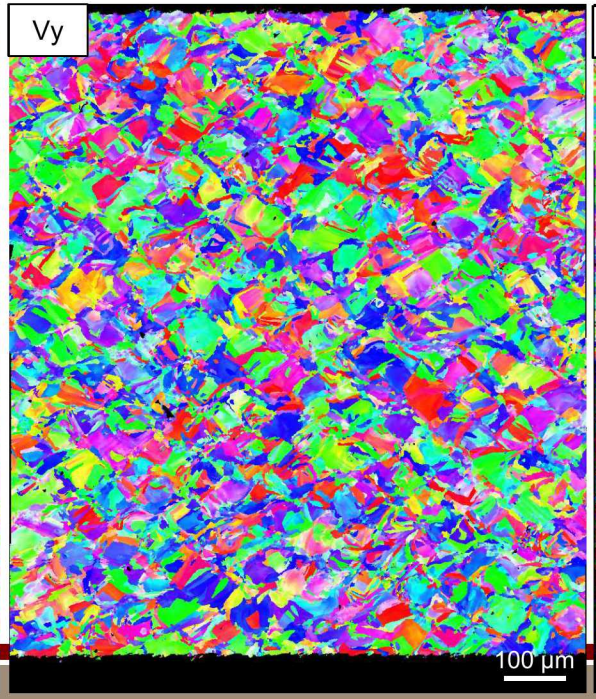

100 µm

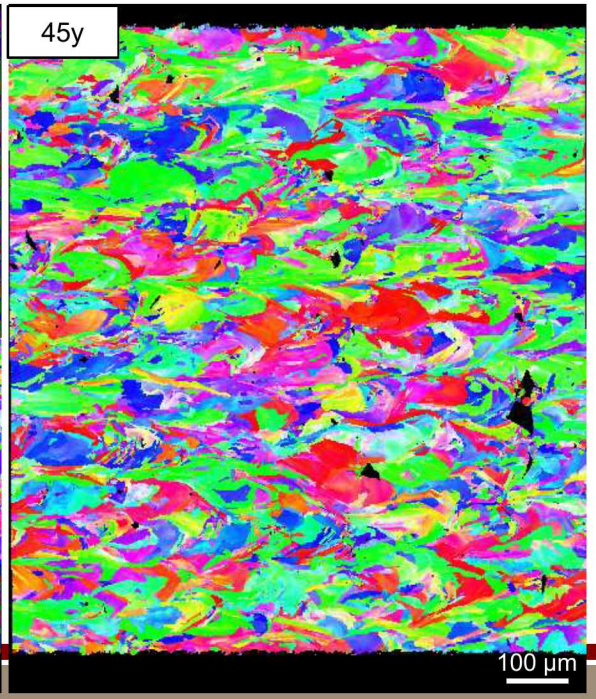

Hx
100 µm


Vx
100 µm

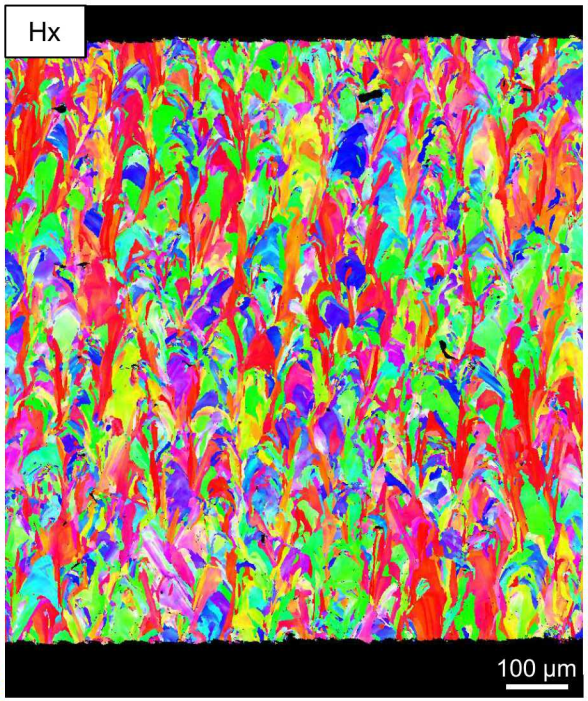

45x
100 µm

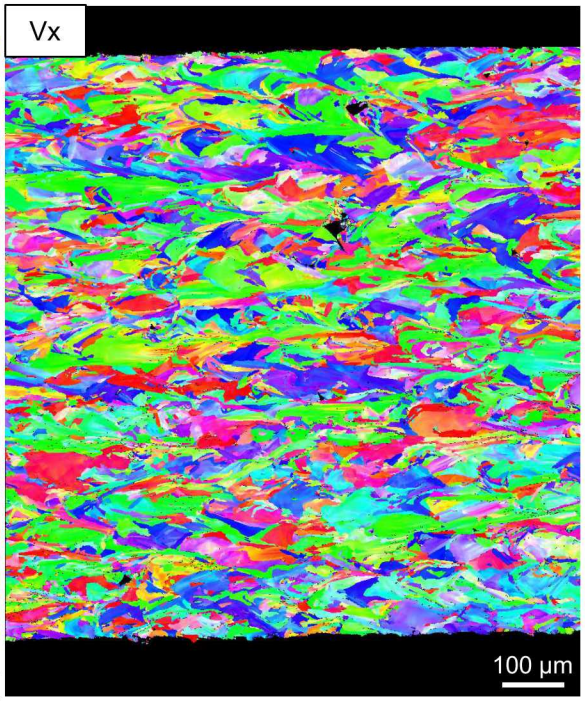

Hy
100 µm

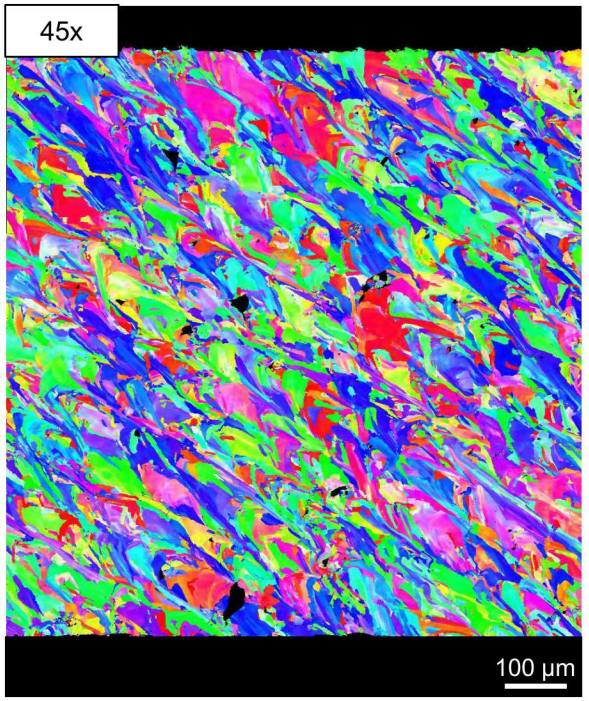

Vy
100 µm

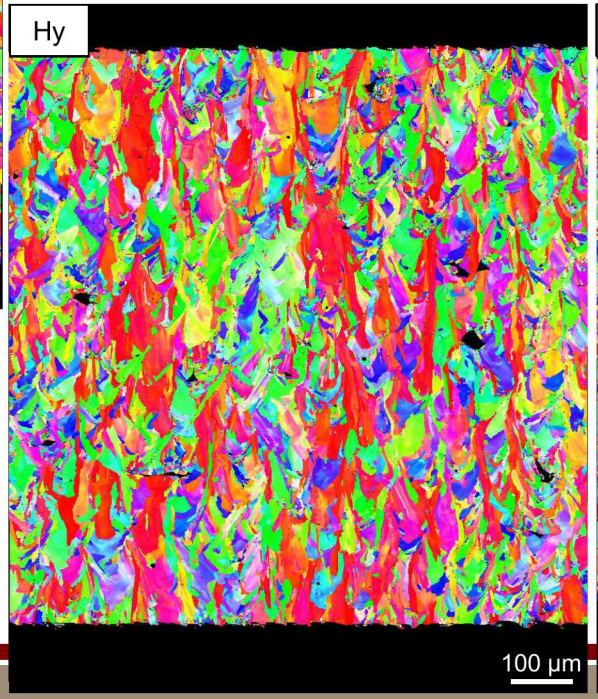

45y
100 µm

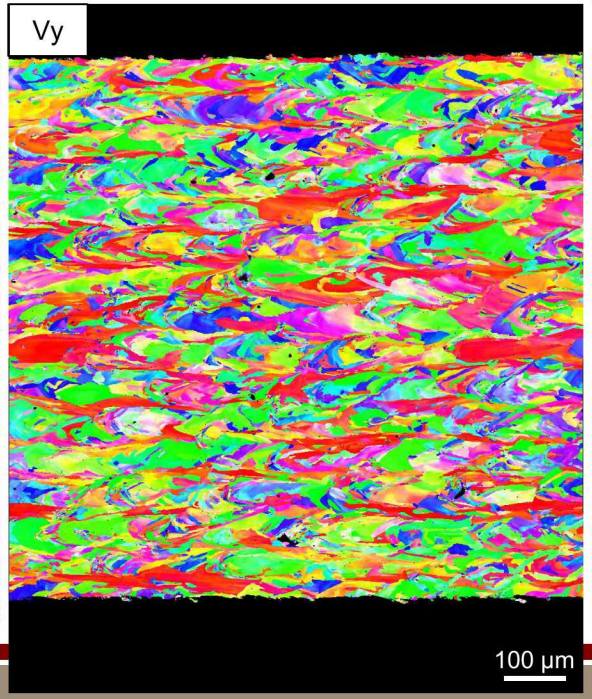

100 µm

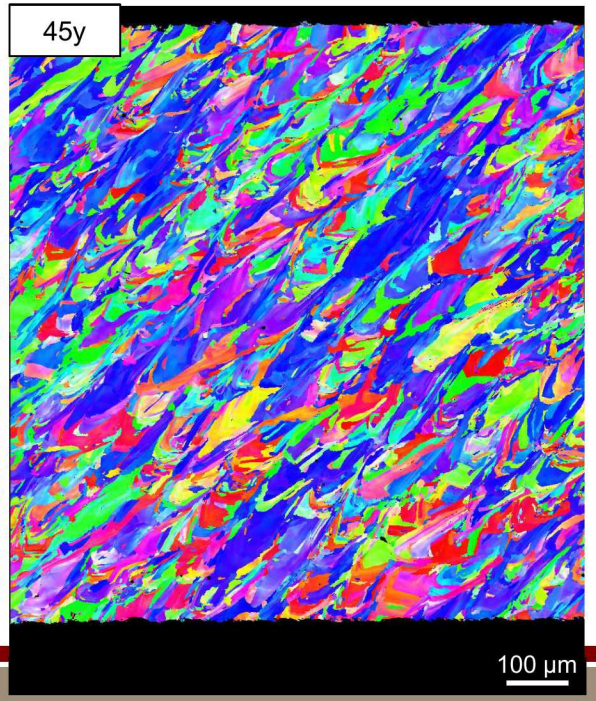

Hx
100 µm


Vx
100 µm


45x
100 µm


Hy
100 µm


Vy
100 µm


45y
100 µm