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3-D AM prototyping and the geometric factor on mechanical behavior and property of 316L stainless steel

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Outline

- Programmatic object and technical path forward
- LENS / PBF fundamentals and their resultant metallurgy
- 3-D LENS- and PBF- prototyping
- Effect of of geometry on mechanical behavior and property
- Summary

Programmatic objective

AM Science and Technology Maturation (LENS & PBF)

Technical integration

AM processing
(Development/control/optimization)

Materials
(Structure & properties)

Numerical simulation
(prediction and validation)

Establish

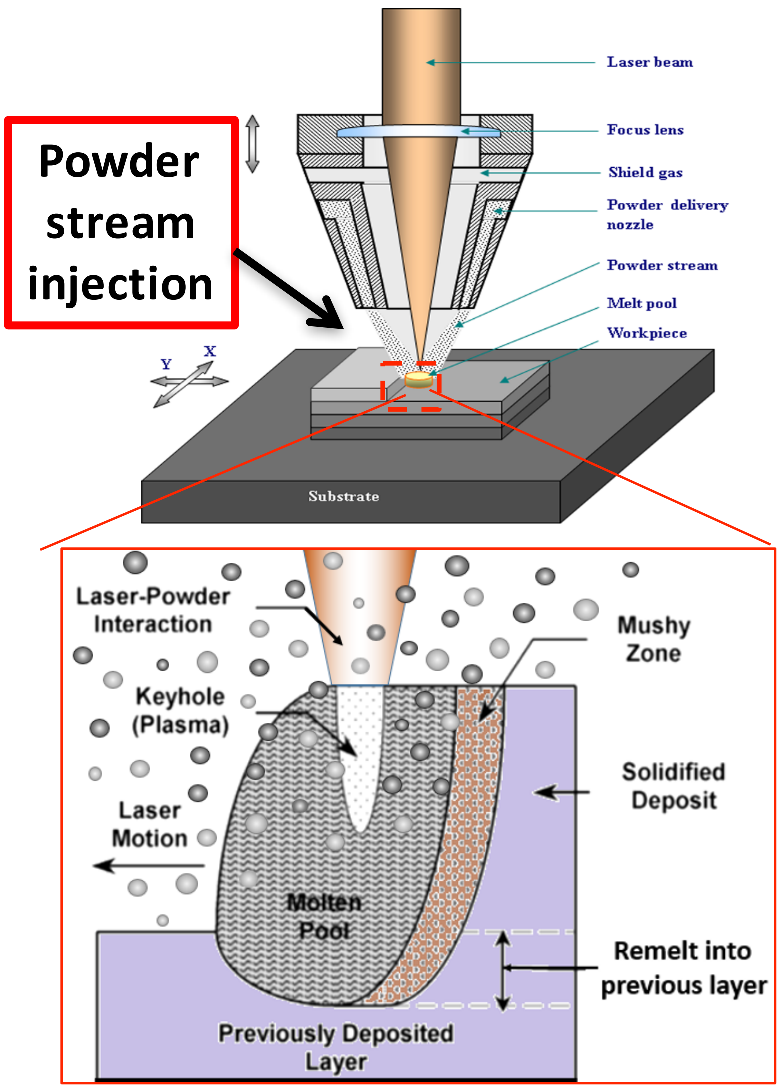
- Process-structure-property relationships
- Geometry/ precision & limitation/ manufacturing constraint
- Material property control and defect mitigation

To support

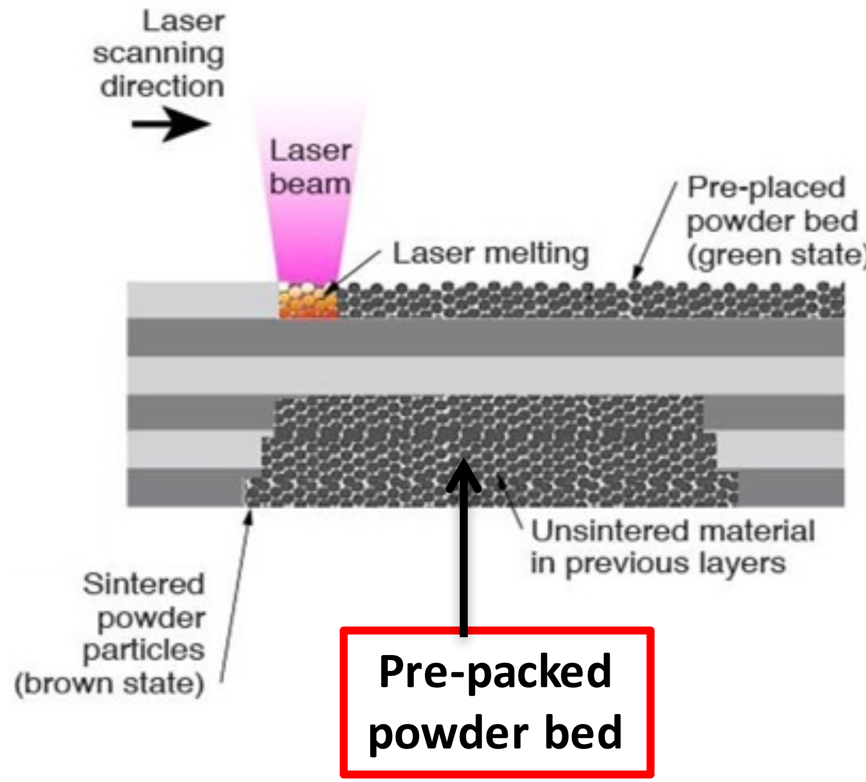
Sound science base AM system engineering

Fundamentals for powder-based 3-D LENS & PBF AM printing

Laser Engineered Net Shaping (LENS)



Powder Bed Fusion (PBF)

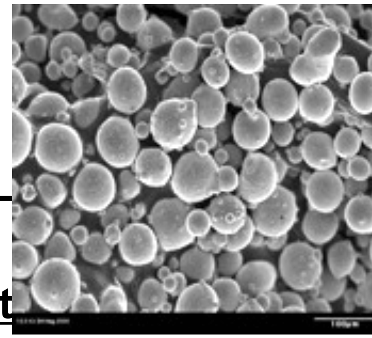


Printing steps common to LENS & PBF

- Powder melting
- Molten metal fusion
- Molten metal solidification

3-D LENS and PBF metal printing demonstration

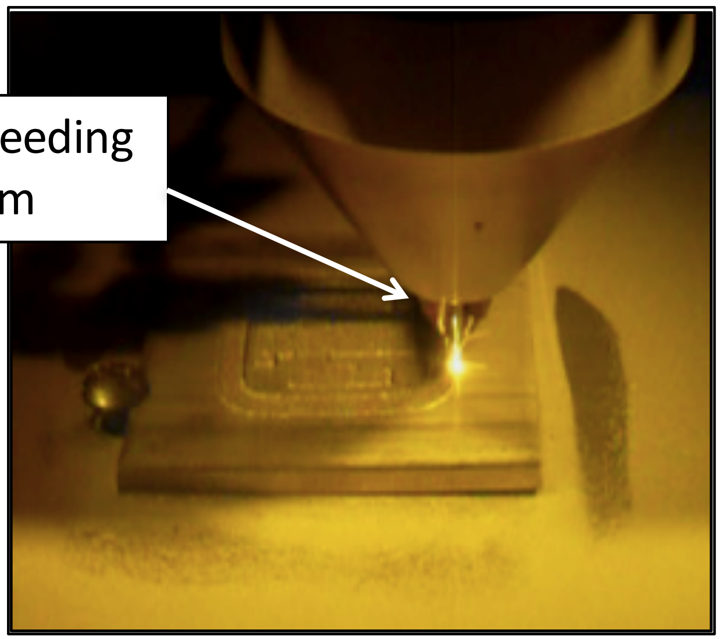
Starting 316L atomized feedstock powders



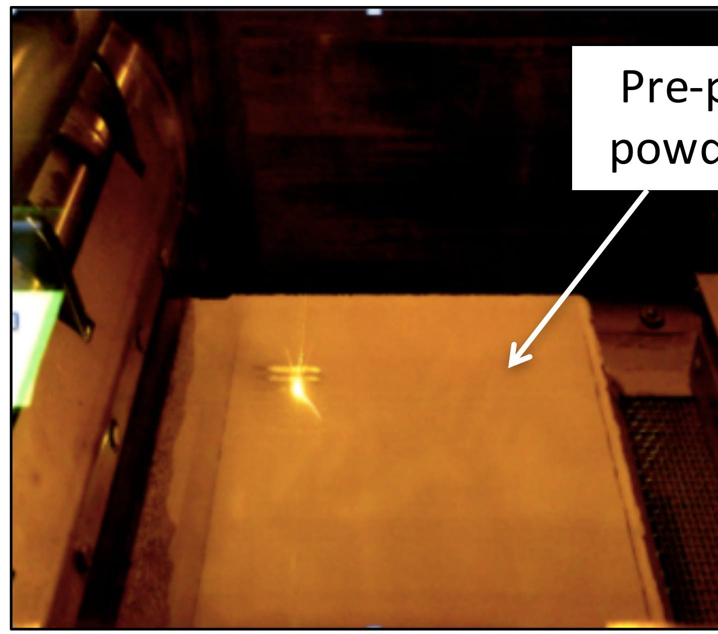
3-D LENS deposit

3-D PBF printing

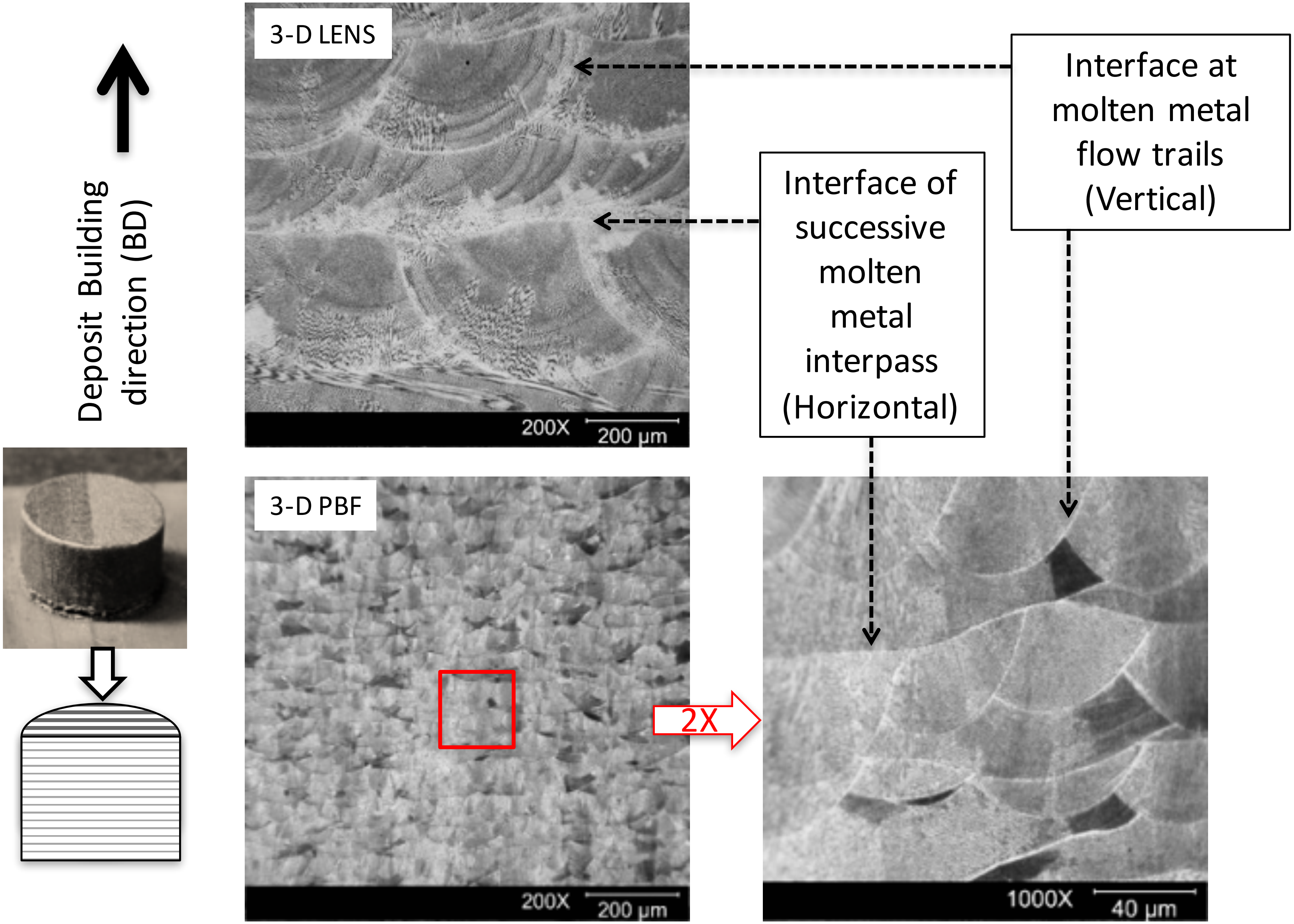
Powder feeding system



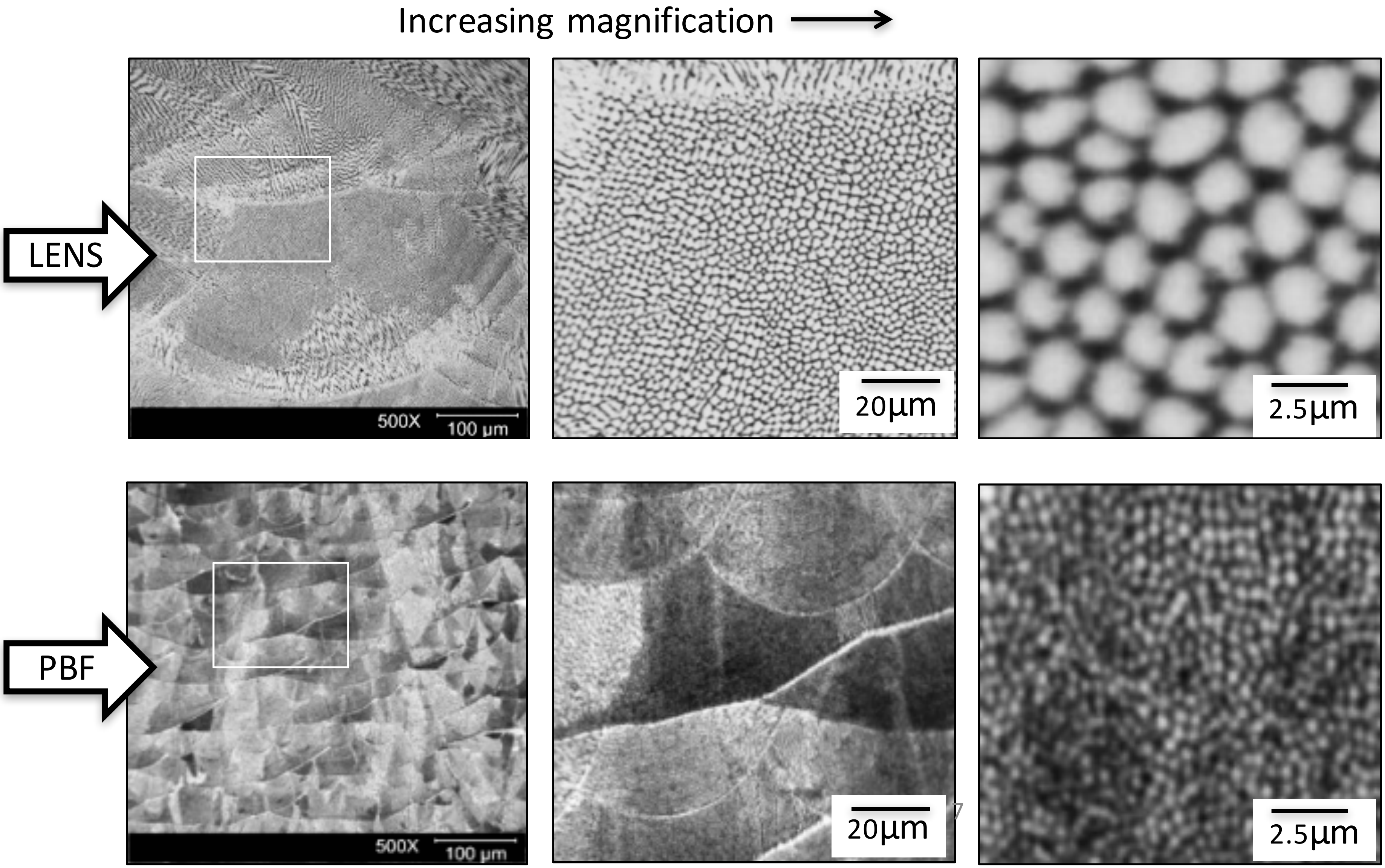
Pre-packed powder bed



Chemical etching reveals a composite structure of systematic solidified modules in the 3-D-LENS- & PBF- printed 316LSS

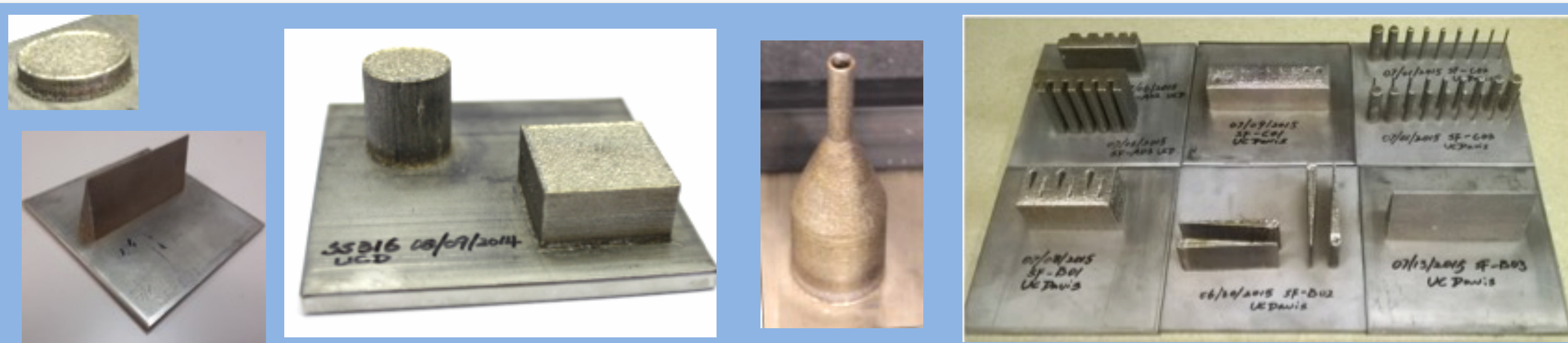


3-D LENS and PBF prints exhibit cellular solidified cells with extremely fine arm spacing, << 3µm



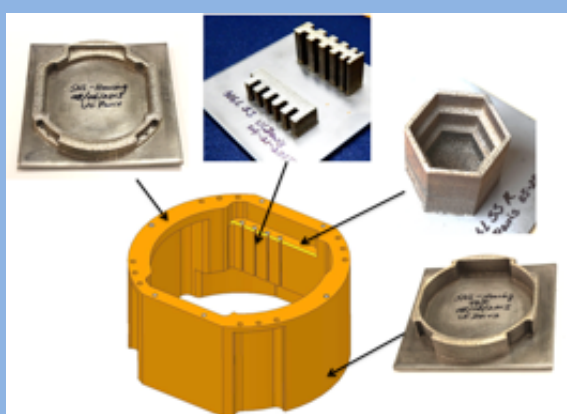
3-D LENS- PBF- prototyping for 316L stainless steel (316LSS)

SS316L for material science R&D

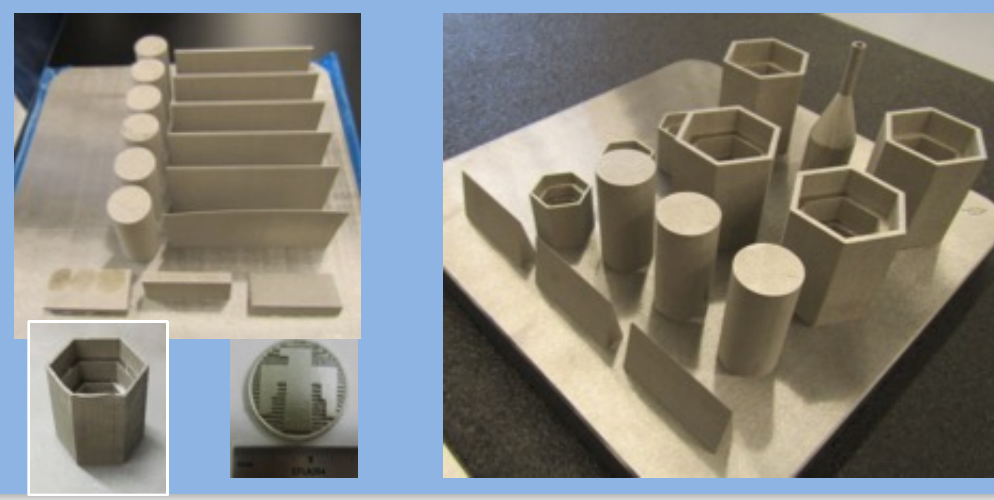


SS316L prototyping feasibility

3-D LENS prints using Optomec



3-D PBF print by ProX300 system



Printing parameters and conditions for 316LSS prototyping

3-D LENS printing (Optomec 750)

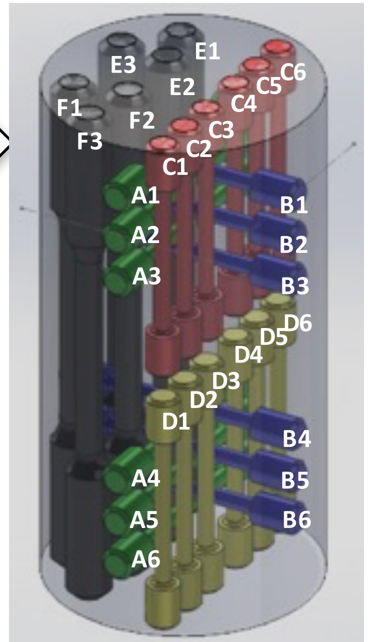
Part No.	Name	Dimension (mm)	Laser power (W)	Current (A)	Speed (mm/s)	Powder Feeder rate (g/min)
1	Short Cylinder	24.5 x 12.3	360	38	16.3	10
2	Thin wall funnel	50.0 x 1.0				
3	2" x 2" 3-tier hexagon	56 x 49 x 54				

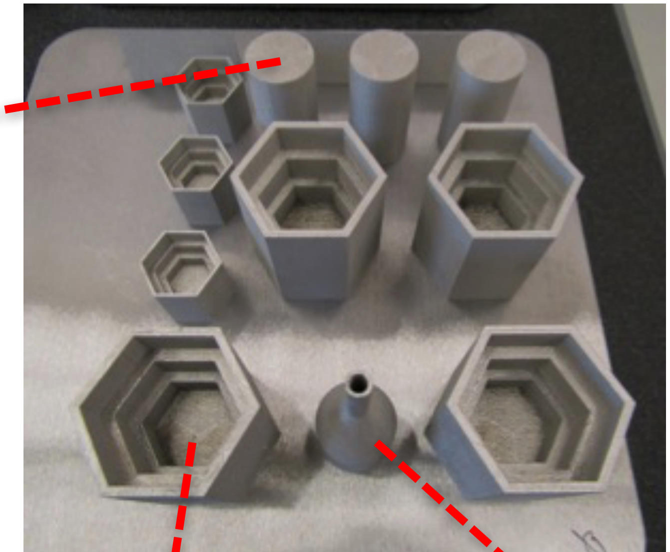
3-D PBF printing (3-D ProX300)

Part No.	Name	Dimension (mm)	Max. Laser power (W)	Avg. % Power Used (%)	Speed (mm/s)	Powder Layer Thickness (µm)
1	Short Cylinder	24.5 x 12.3	500	41	200	40
2	Thin wall funnel	50.0 x 1.0				
3	2" x 2" 3-tier hexagon	56 x 49 x 54				

LENS- and PBF- prototyping and properties of interest

Bulk cylinder



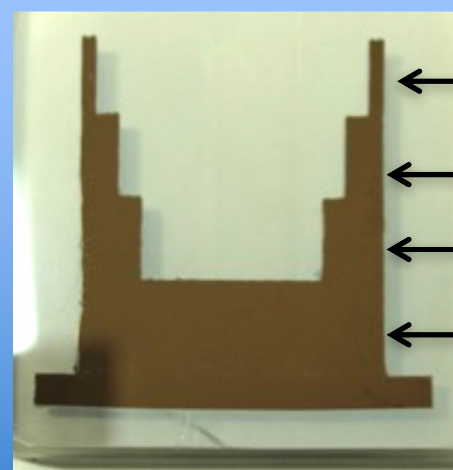


Deposit building direction (BD)

Stress-Strain curve

- Ultimate tensile strength (UTS)
- Engineering strength
- Ductility

3-tier Hexagon



Tier 1
Tier 2
Tier 3
Base

Thin wall funnel

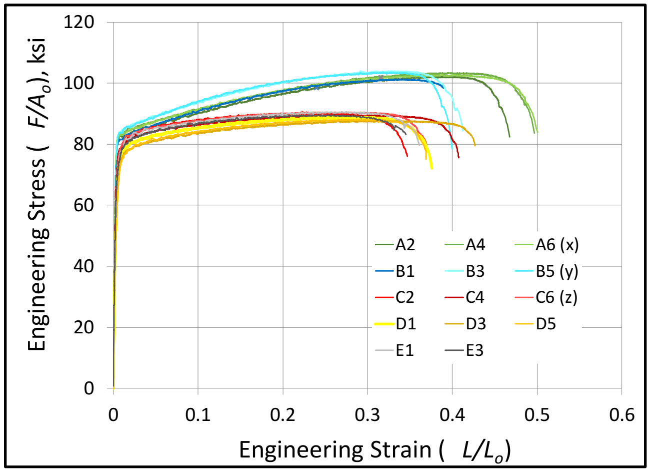
Geometry effect

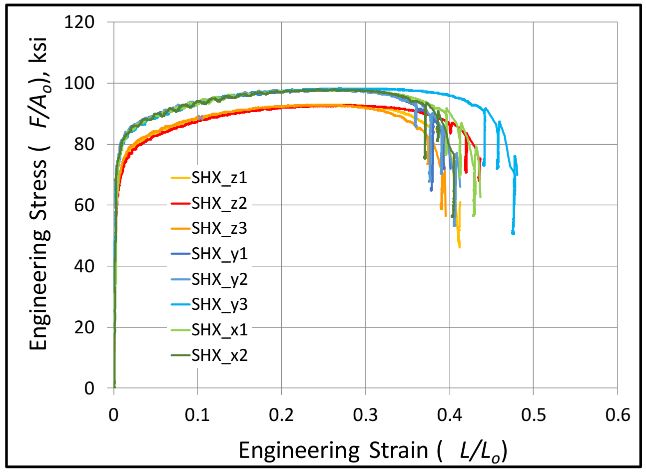
- Engineering properties
- Mechanical behavior (e.g., strength & ductility)
- Solidification structure

Tensile testing

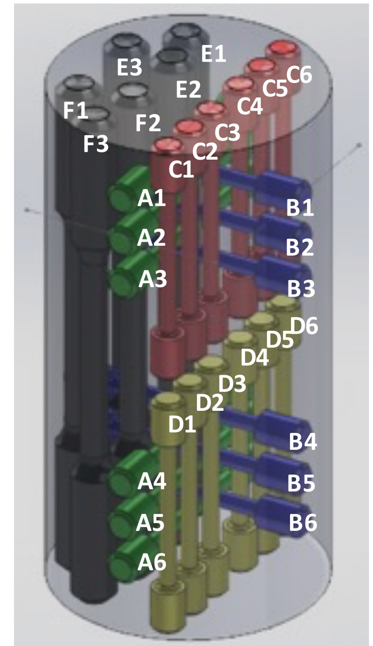
- Quasi-static with a strain rate about 0.001 s^{-1}.
- A laser extensometer was used to measure the elongation of the gage section.
- The tensile test was conformed to ASTM E8/E8M standard.

Tensile properties are consistent but anisotropic for both LENS- and PBF- printed 316LSS bulk deposit



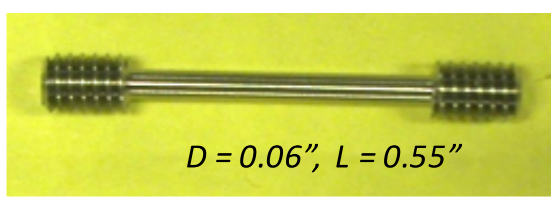


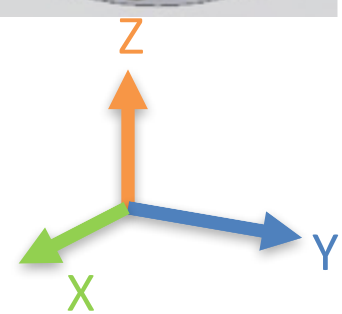
Stress-Strain curve



Specimen	Yield (ksi)	Strength (ksi)	Elongation (%)
2C	58	90	35
4C	74	90	41
6C	69	89	37
Average	67	90	37
1D	63	89	38
3D	62	88	43
5D	55	88	37
Average	60	88	39
1E	67	91	36
3E	68	90	35
Average	68	90	35
2A	79	102	47
4A	80	103	50
6A	82	103	50
Average	81	103	49
1B	80	101	39
3B	82	104	41
5B	81	104	40
Average	81	103	40
Typical*	25	70	40

Specimen	Yield (ksi)	Strength (ksi)	Elongation (%)
SHX_z1	61	93	41
SHX_z2	60	93	45
SHX_z3	61	93	40
Average	61	93	42
SHX_x1	70	98	44
SHX_x2	71	98	41
Average	70	98	42
SHX_y1	72	98	40
SHX_y2	73	98	41
SHX_y3	71	98	48
Average	72	98	43

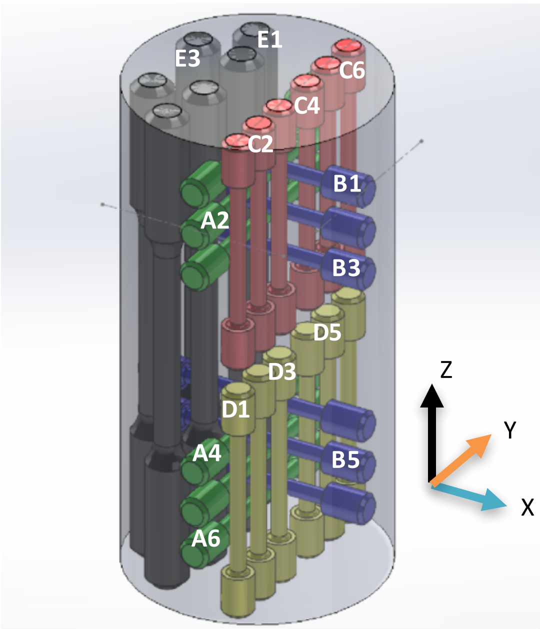


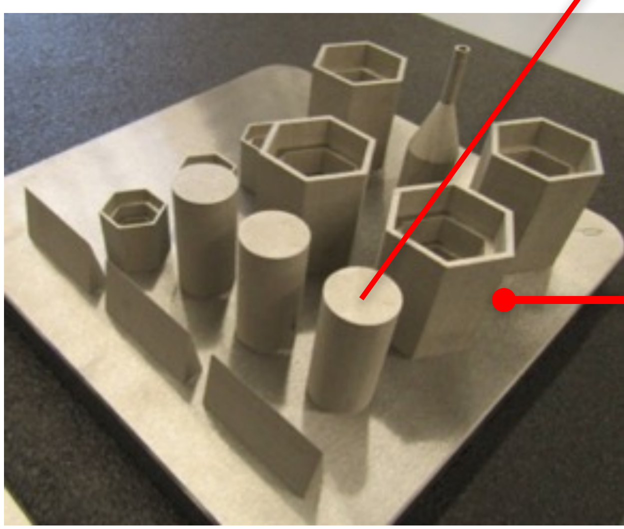


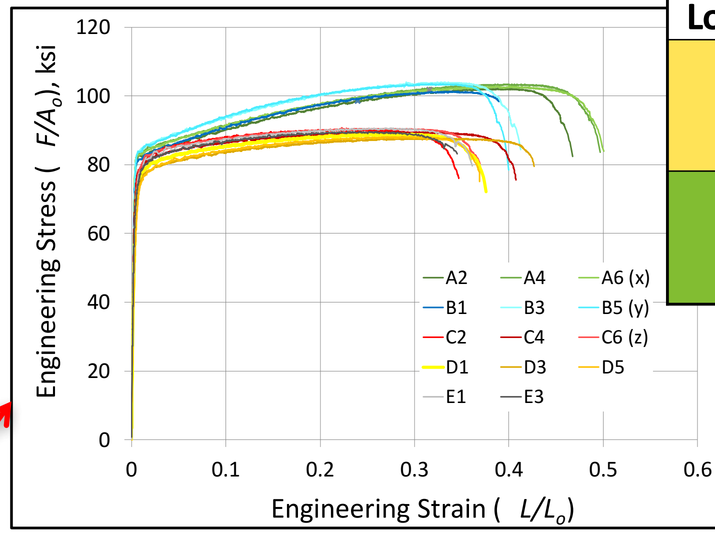
Z: Deposit building direction

X &Y Laser moving direction

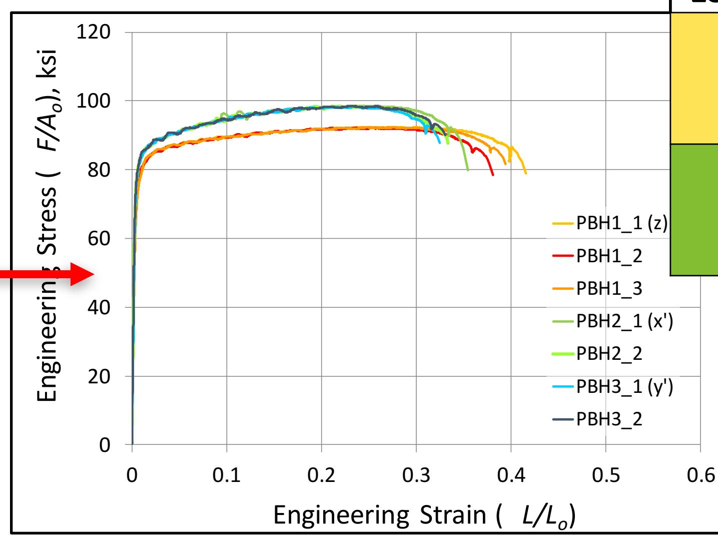
Lower UTS and elongation of PBF hexagon attributes to geometry, defect, material/testing uncertainty ?







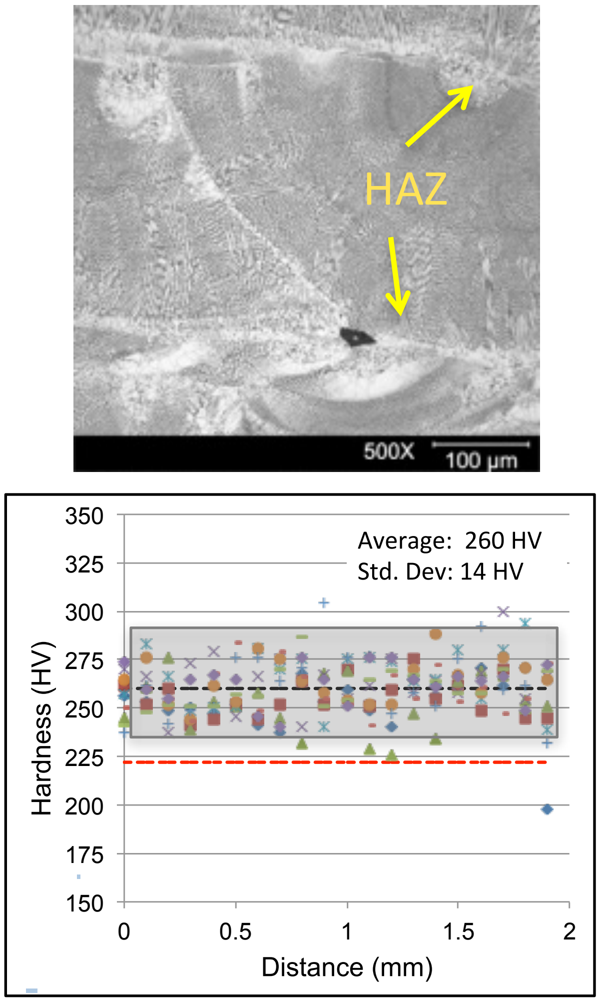
Loading	Tensile data	
Z	YS (ksi)	68
	UTS(ksi)	90
	Elongation(%)	36
X, y	YS	81
	UTS	103
	Elongation	45



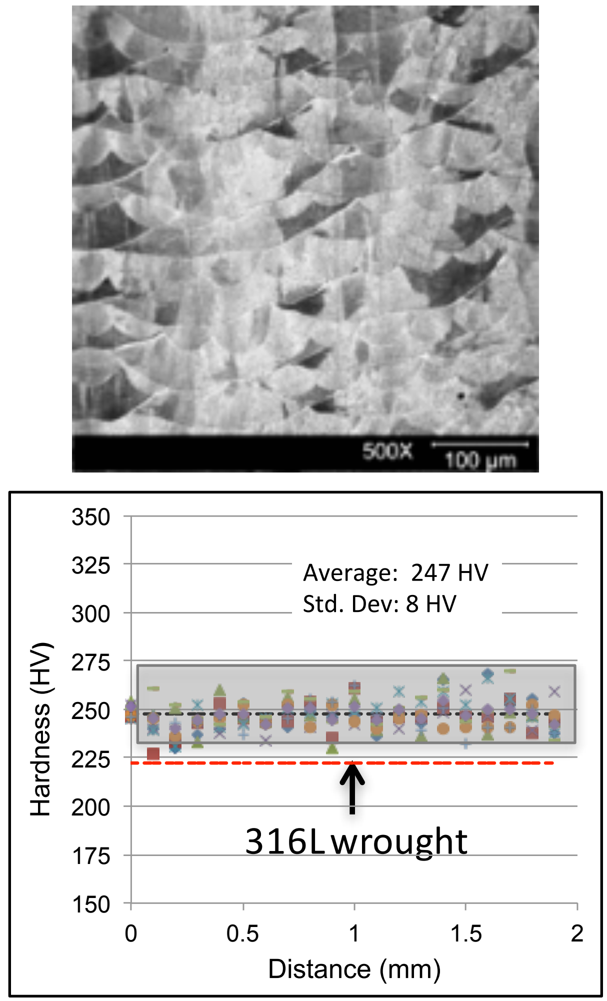
Loading	Tensile data	
Z	YS	67
	UTS	92
	Elongation	40
x, y	YS	76
	UTS	98
	Elongation	33

Local thermal transport and heat distribution dictate bulk physical metallurgy that the mechanical behavior

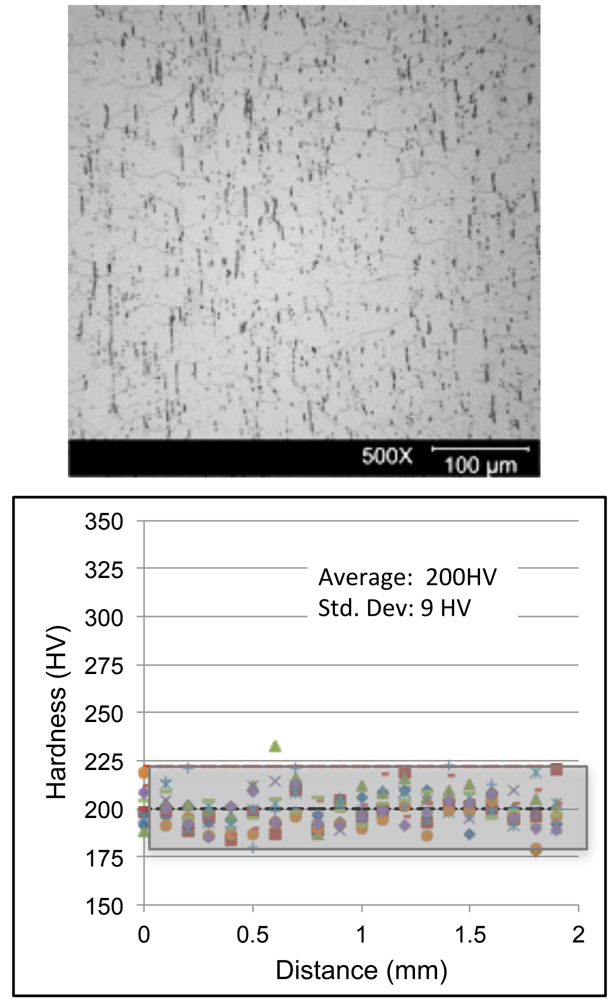
3-D LENS



3-D PBF

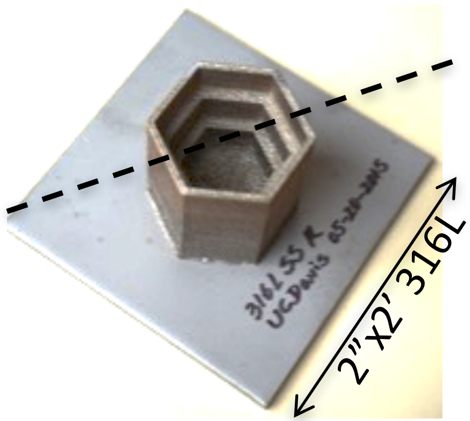


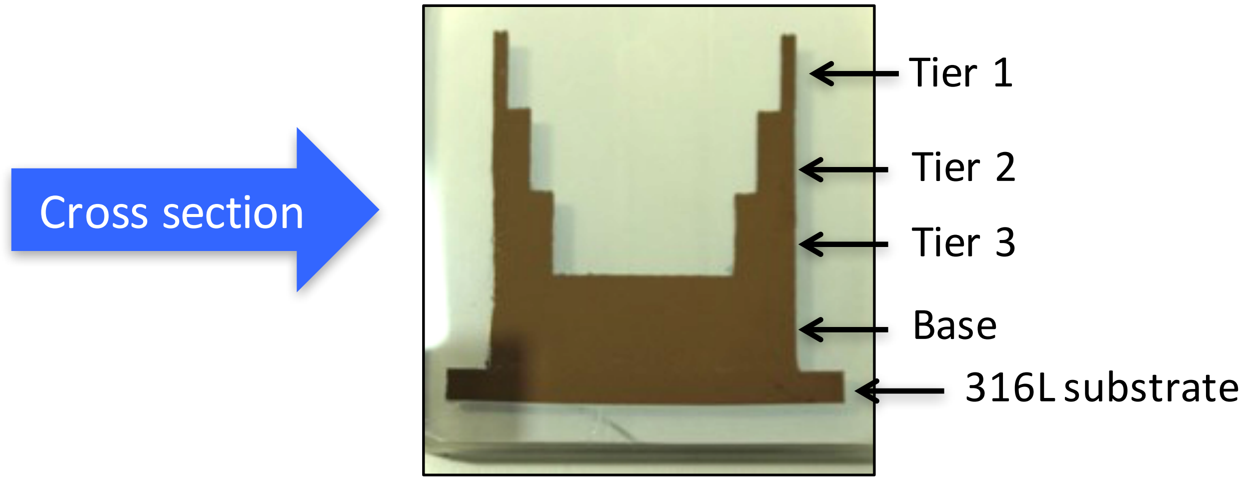
Annealed wrought 304LSS

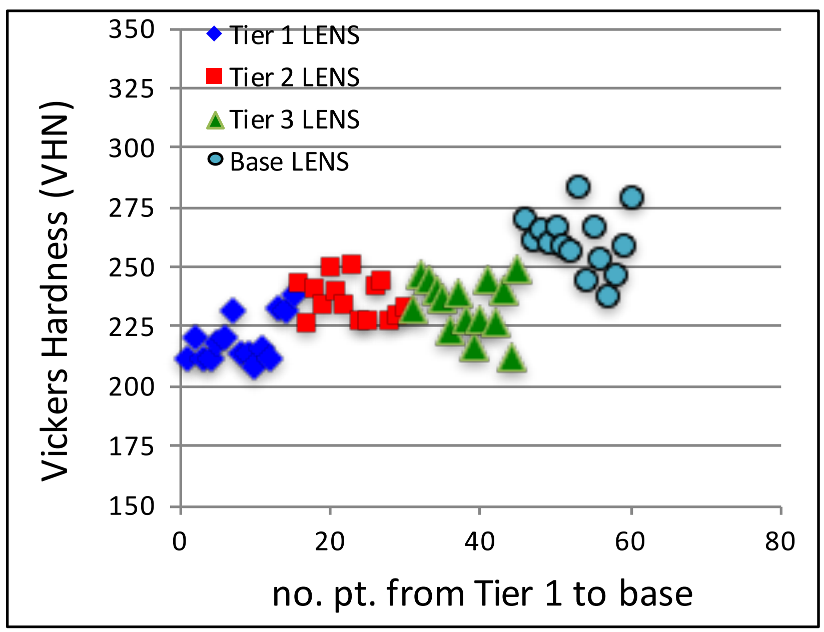


Localized interpass heat-affect-zone (HAZ) is responsible for the larger micro hardness variation seen at the base of the LENS hexagon

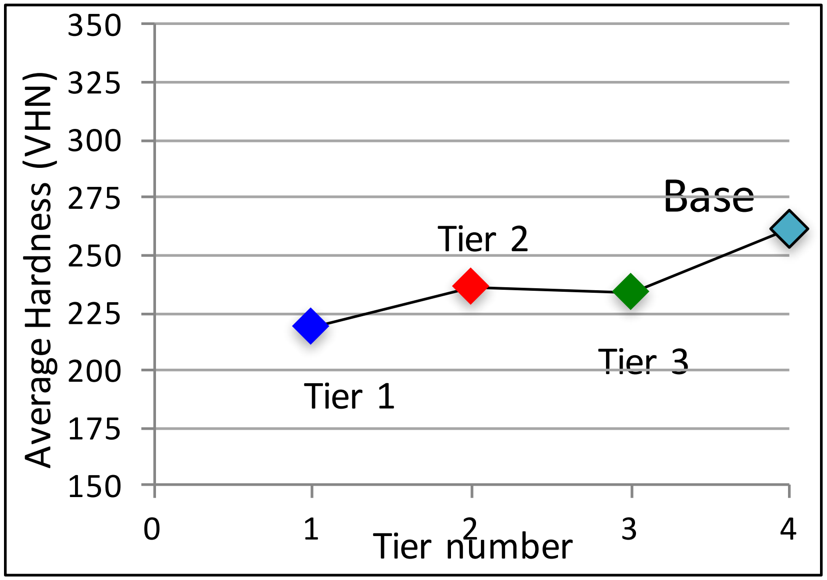
Vickers microhardness in the 3-D LENS-hexagon printed is geometry dependent



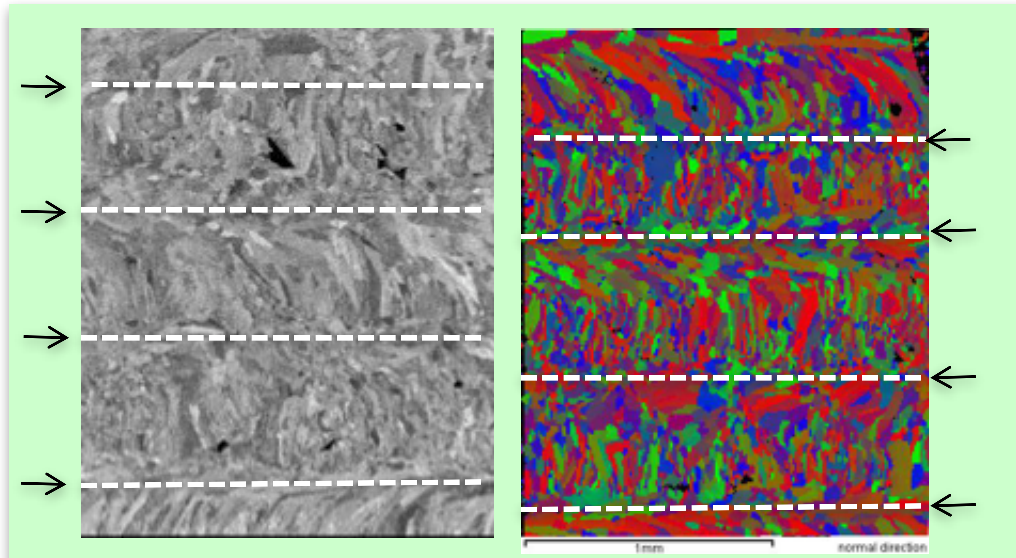


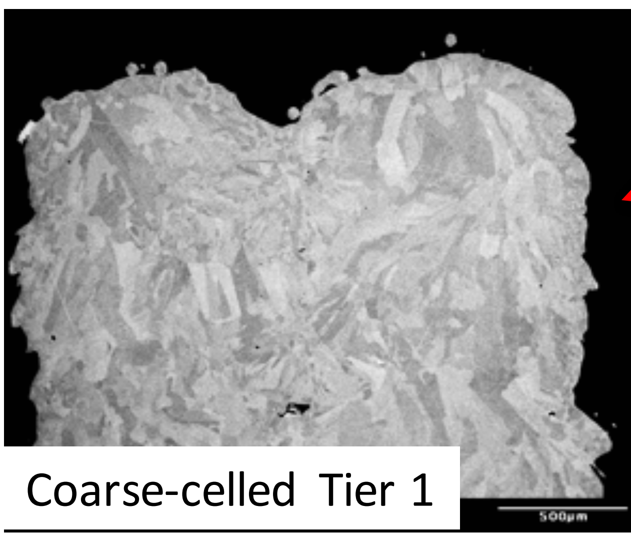


The LENS hexagon softens gradually toward the Tier 1, attributed to cell coarsening in absence of interpass?

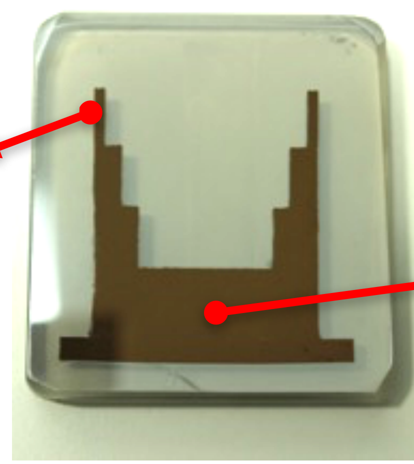


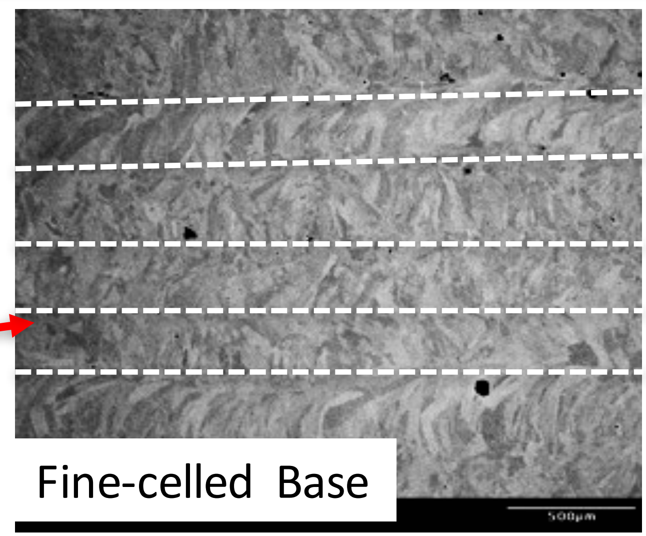
Solidified cell growth is restricted at interpass





Coarse-celled Tier 1

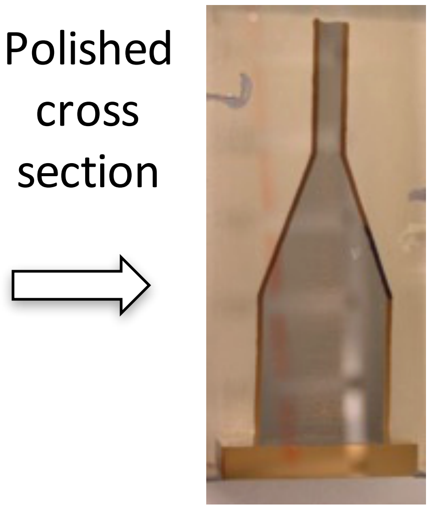


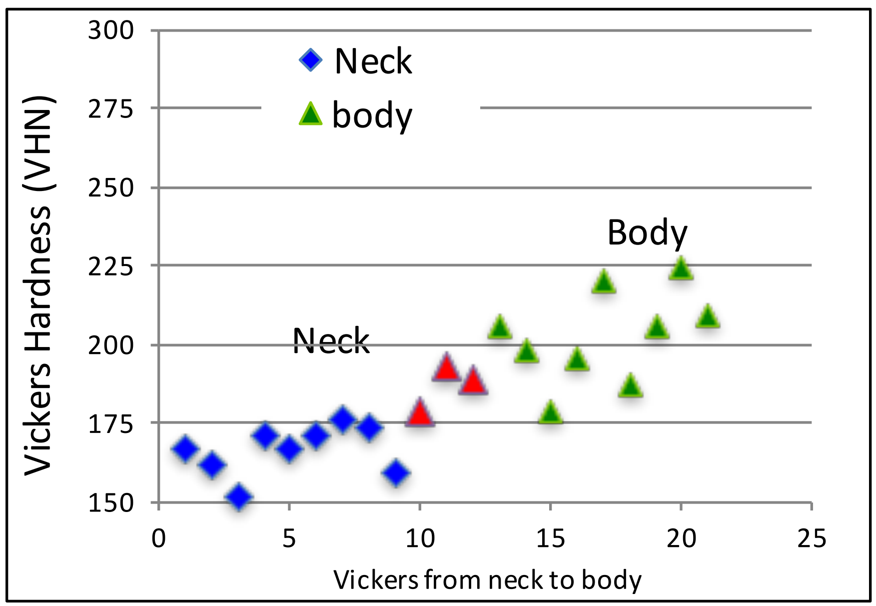


Fine-celled Base

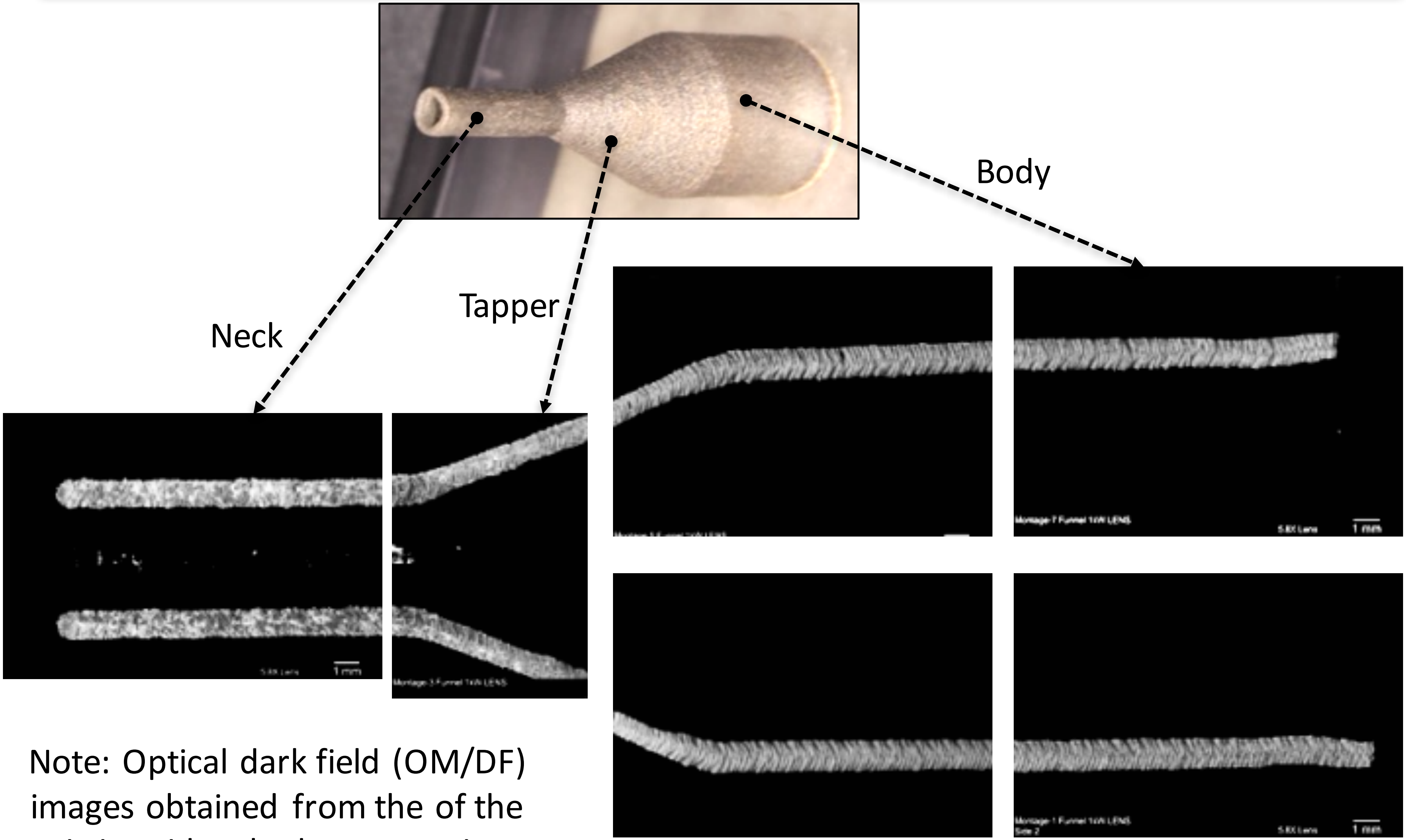
Similar to the LENS hexagon, the 3-D LENS thin-wall funnel also softens toward the upper neck of smaller diameter

Polished cross section



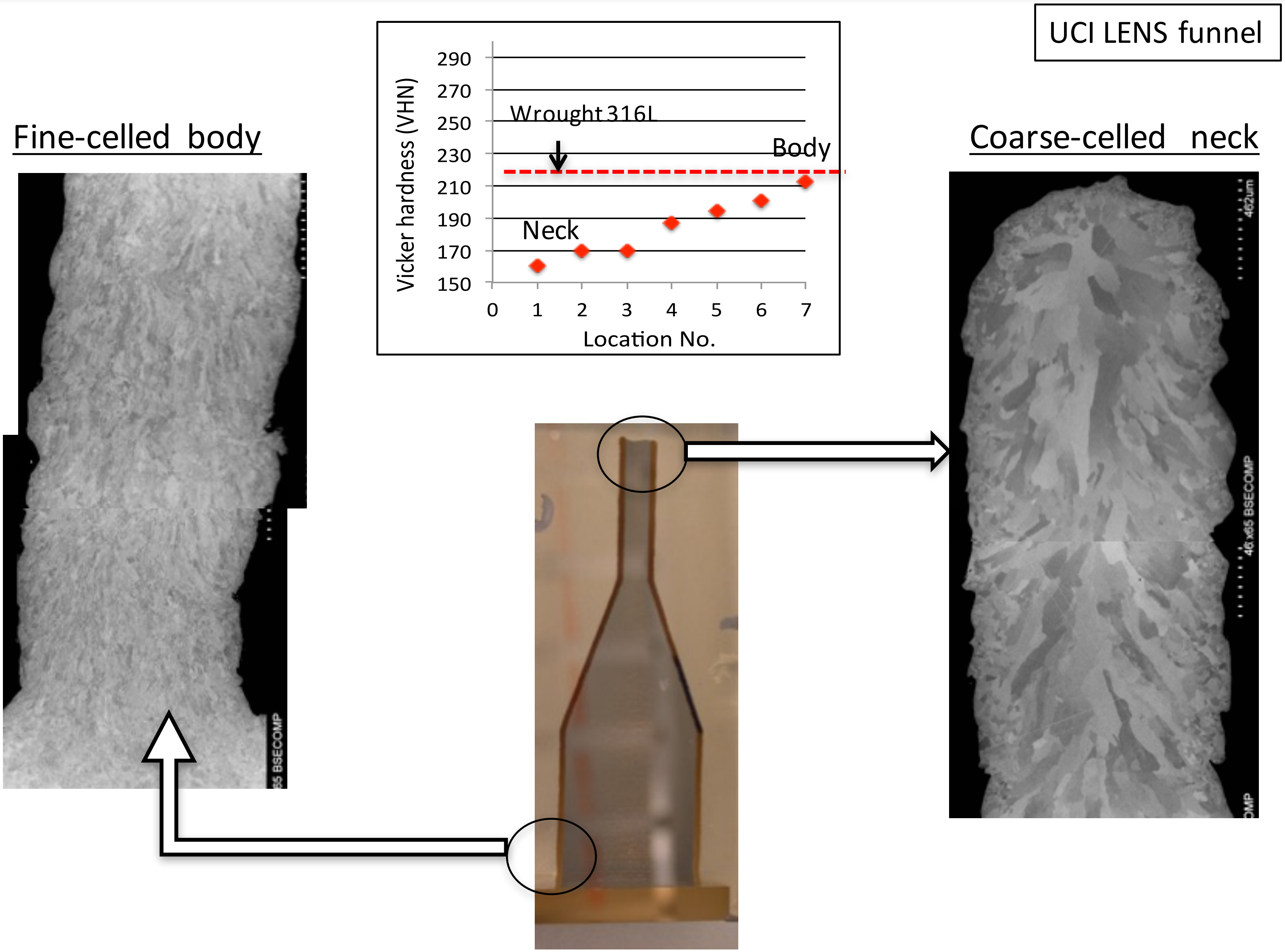


Solidification morphology, revealed by optical-dark field image of the chemically etched funnel, varied with diameter.



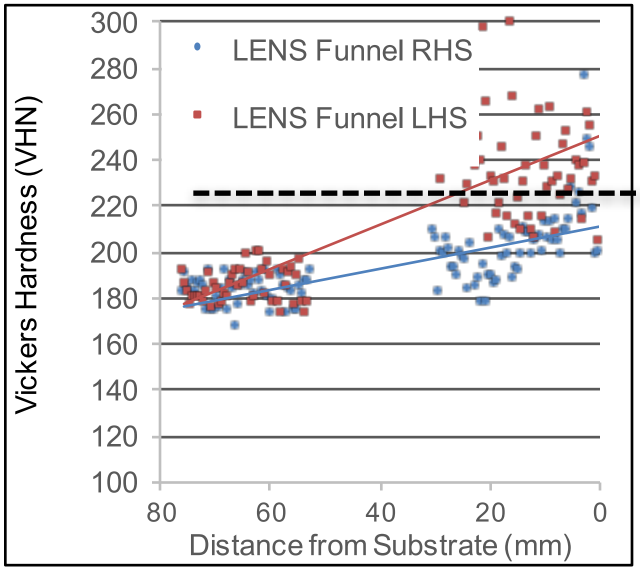
Note: Optical dark field (OM/DF) images obtained from the of the nitric acid etched cross section

Solidification cell coarsening led to the funnel softening at the neck of smaller diameter

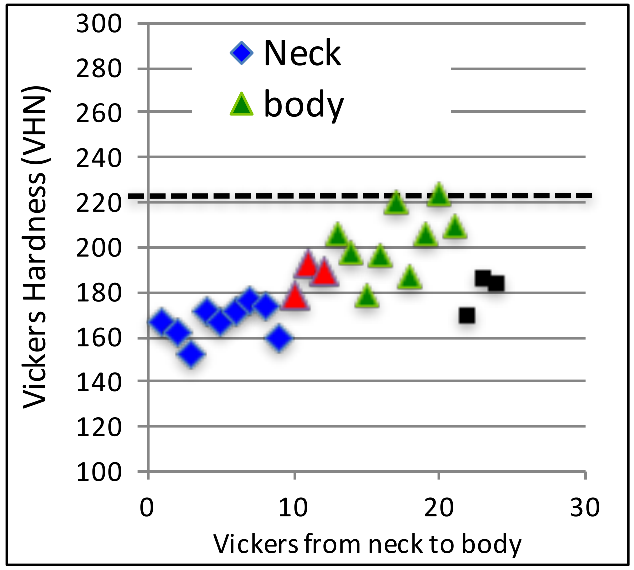


The funnel softening toward the neck observed in all LENS funnels build by the different LENS systems at three facilities

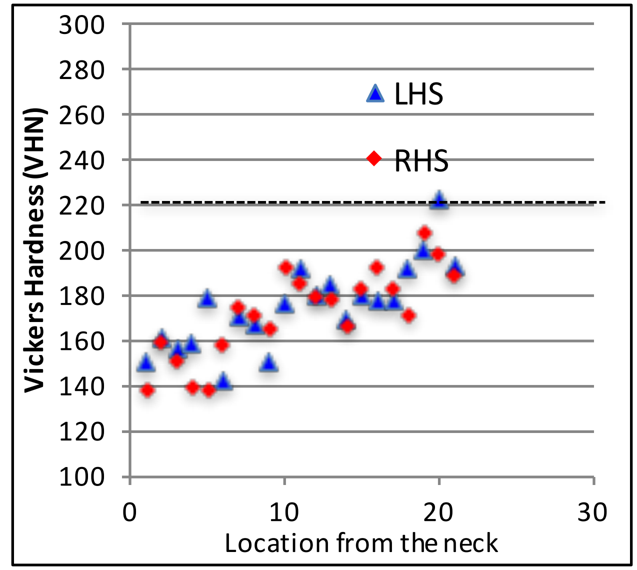
UCD LENS

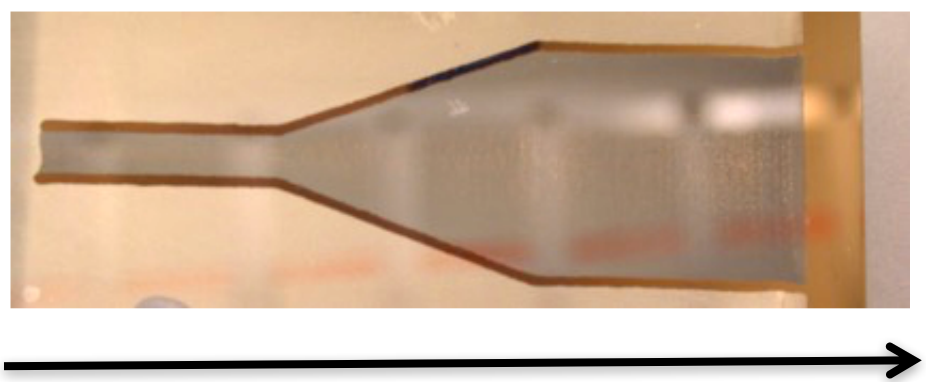


UCI 1KW-FO-LENS



SNL, CA-LENS





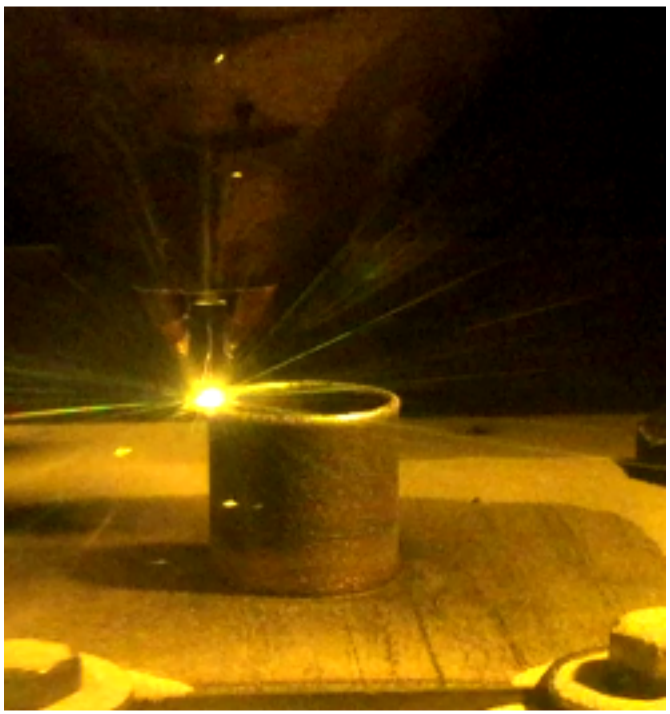
VHN profile Neck to body

The smaller diameter neck is subjected to higher heat intensity and longer heat exposure due to shorter laser travel distance

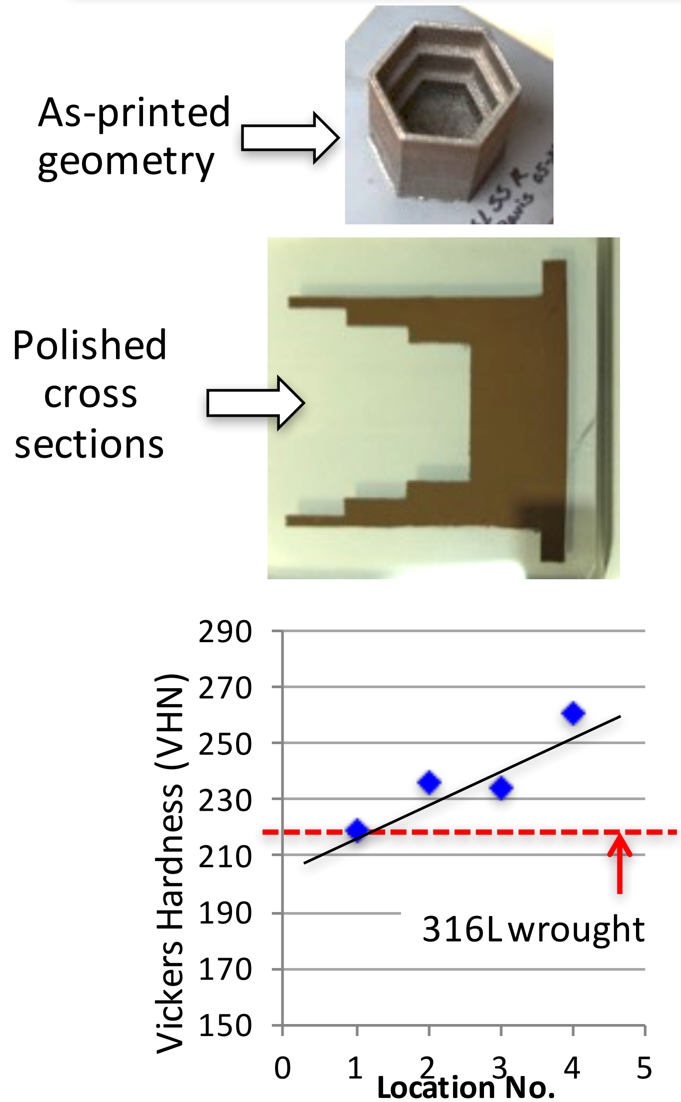
Neck of small diameter

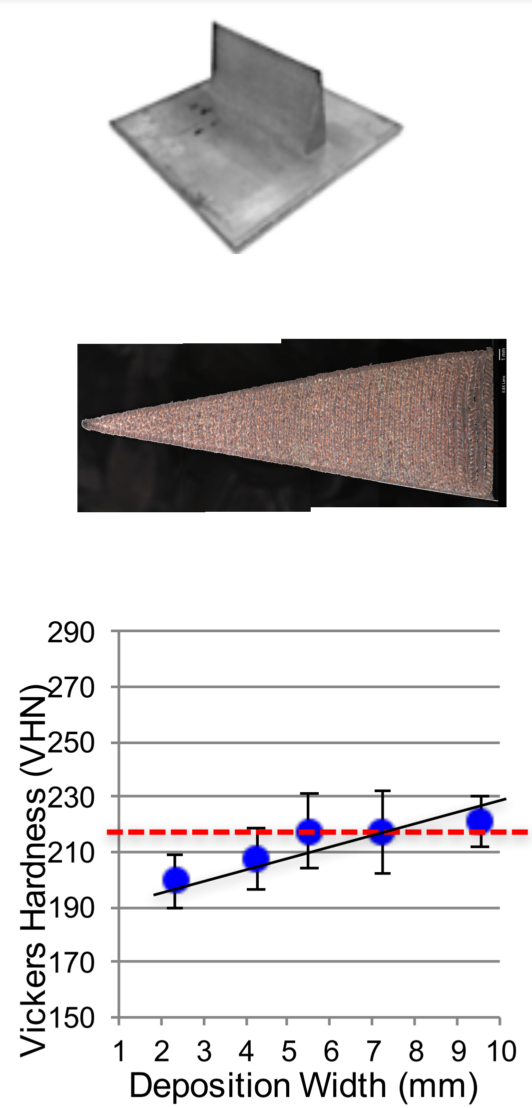
Tapper of reducing diameter

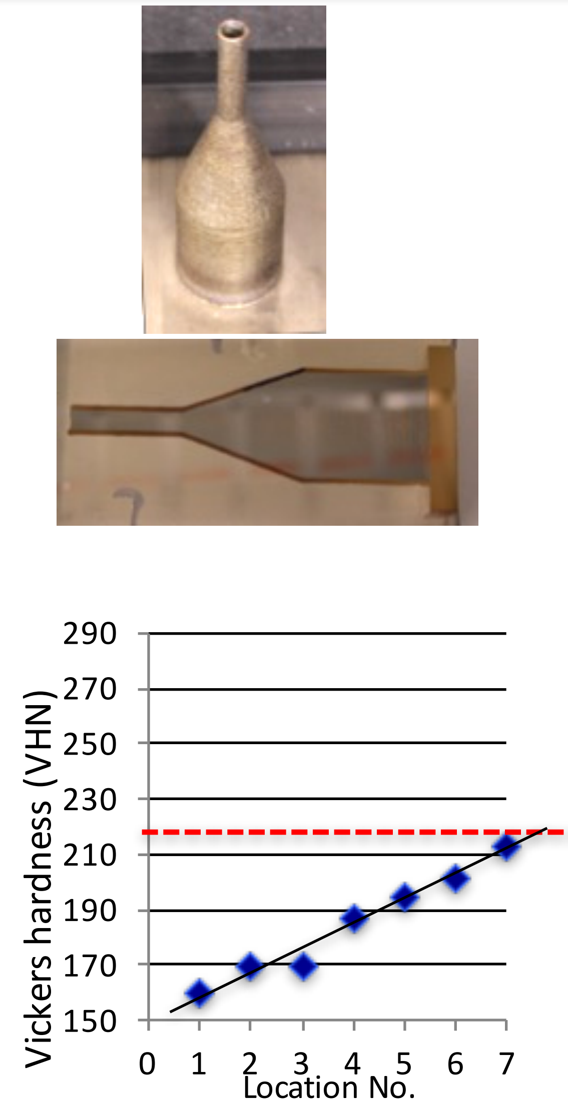
Body of large diameter



The overall Vickers microhardness varies among the prototypes, printed with the same LENS parameter at the same condition

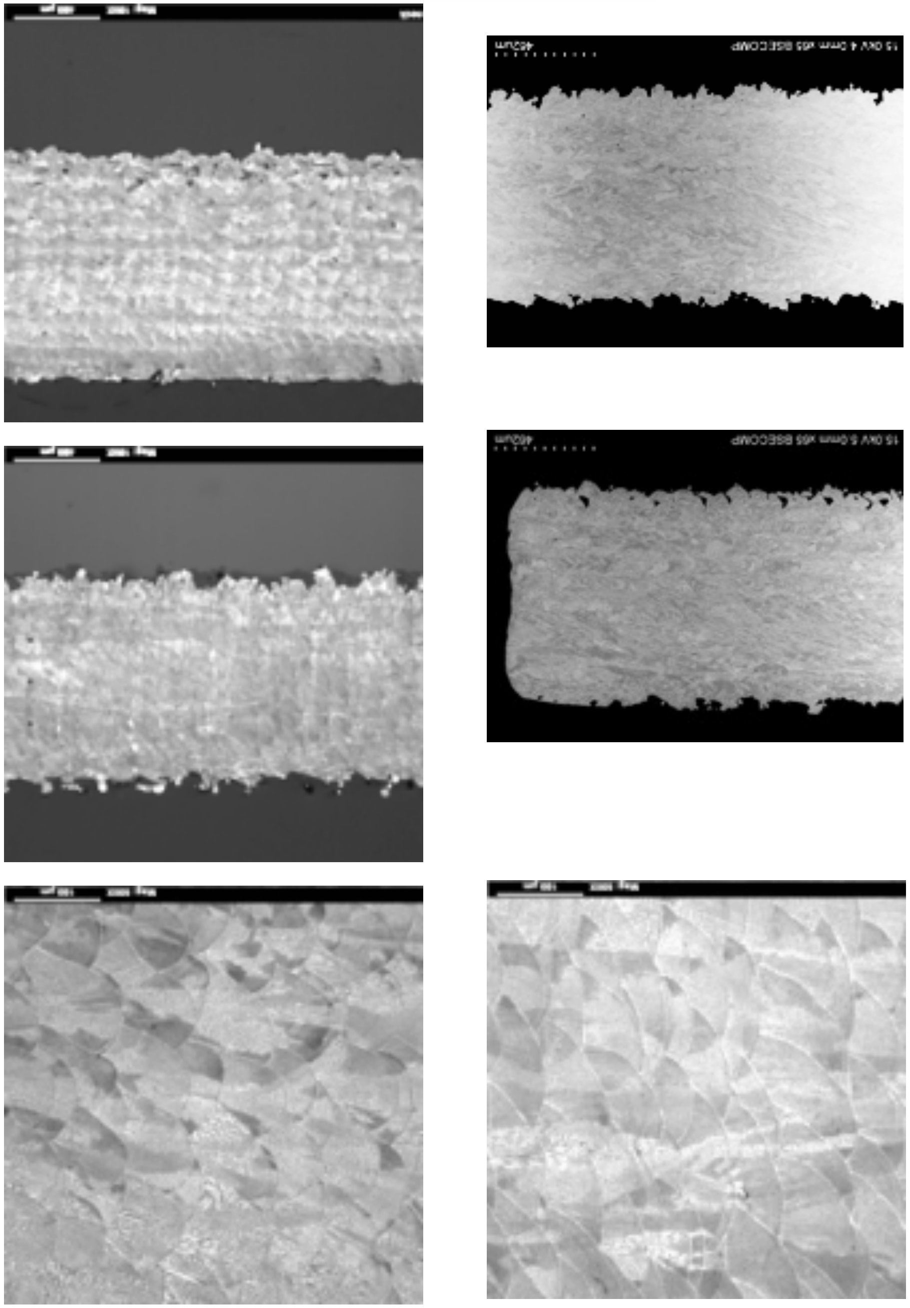


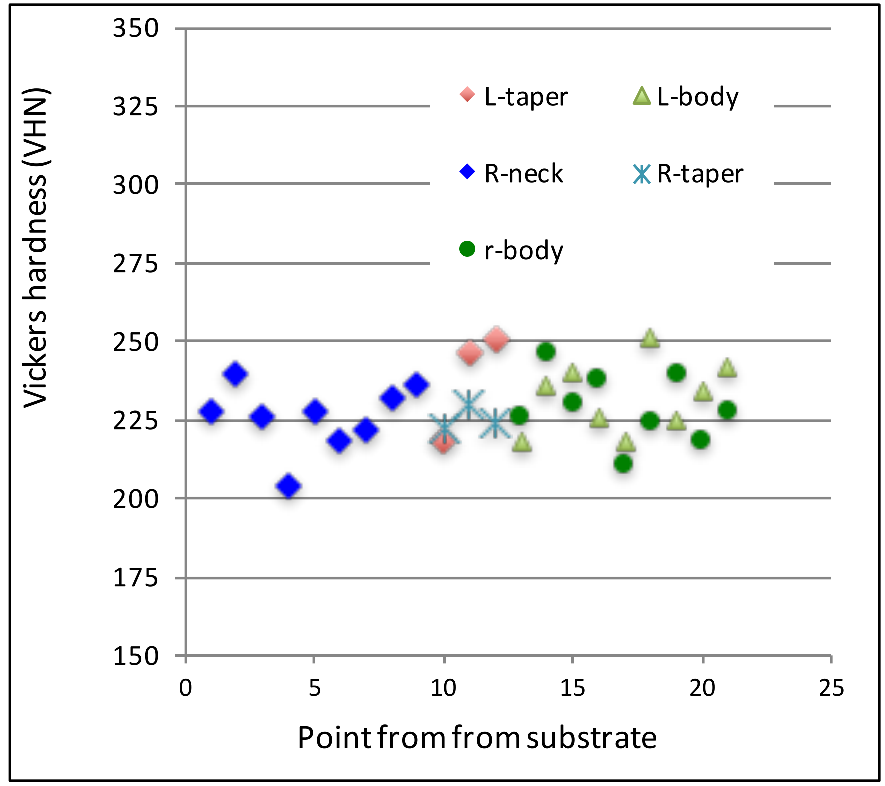


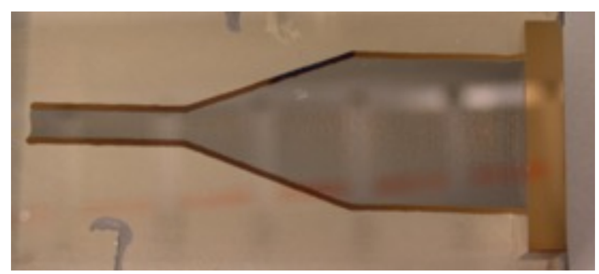


The Vickers hardness increases toward the substrate interface in all cases

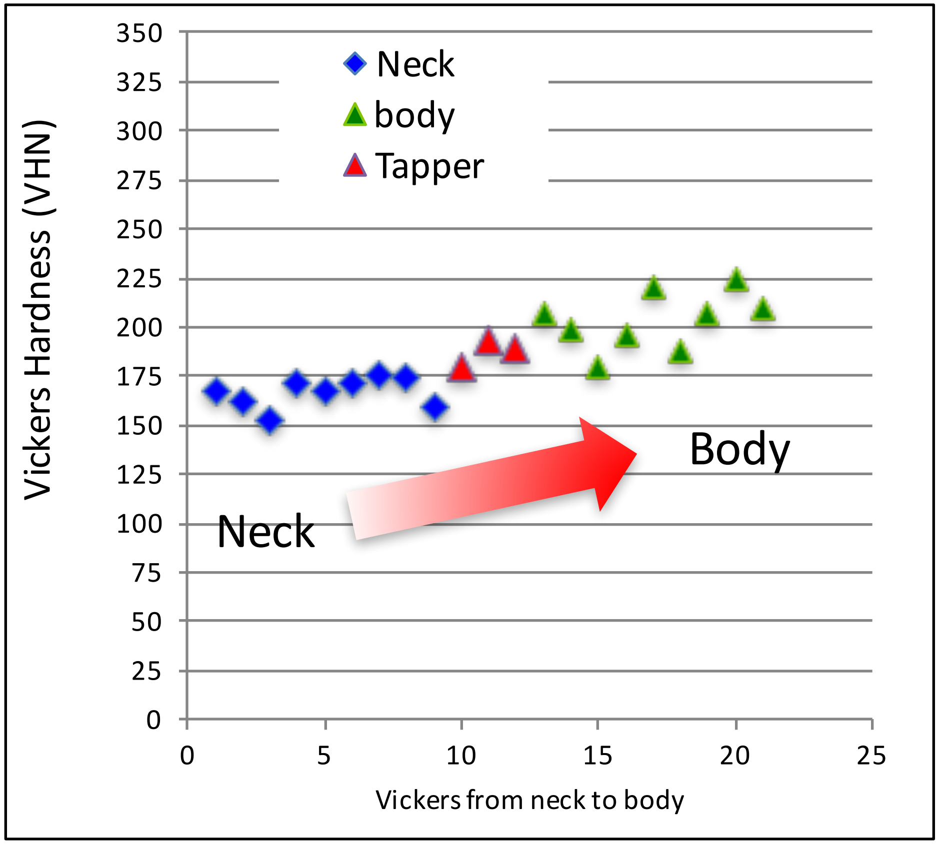
PBF build funnel with flat hardness profile

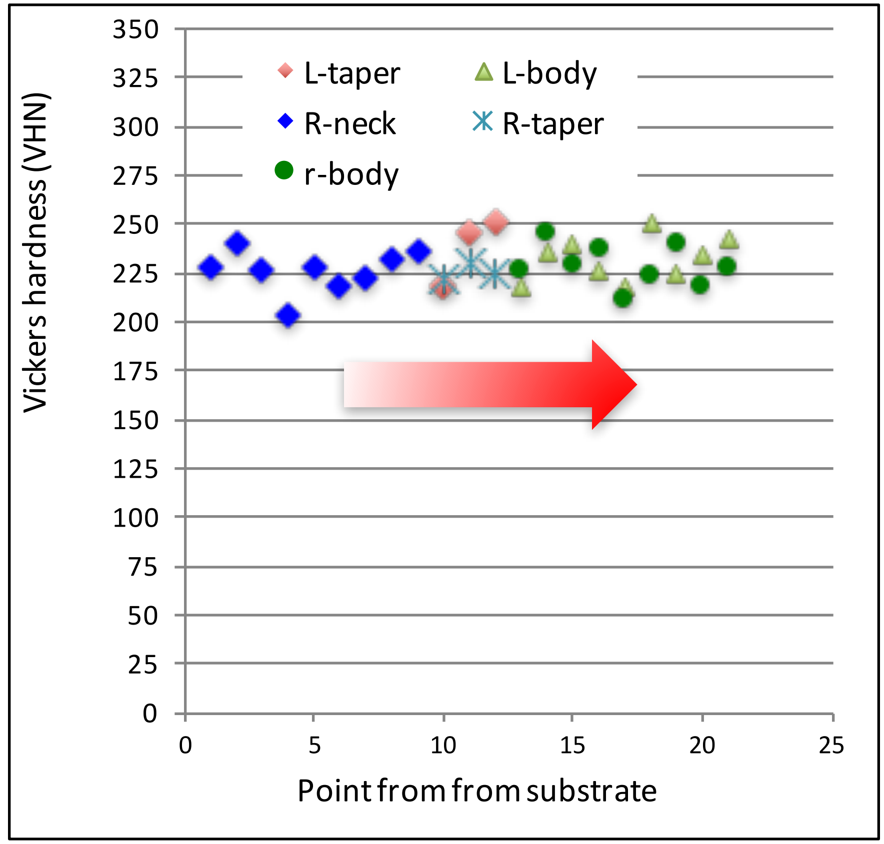


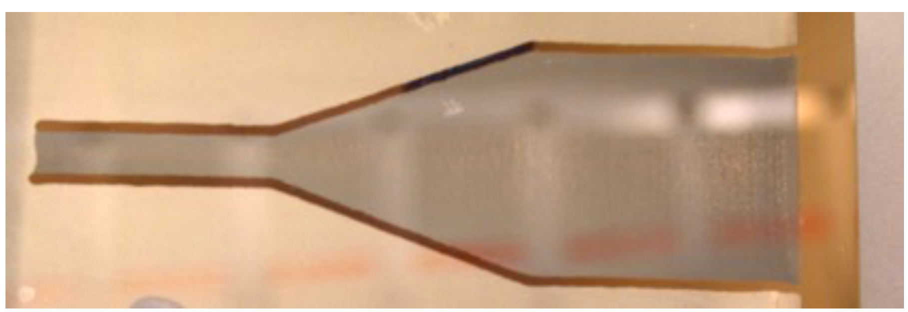




Average Vickers hardness decrease with combination of distance from the substrate and funnel diameter







Summary

- For complex AM engineering components, the geometry and dimensions impact local metallurgy and mechanical behavior as a result of the localized thermal transport and heat distribution.
- Thermal transport and heat distribution is determined by laser-material interactions, of which are AM process parameter and printing condition dependent.
- Process control and optimization must be a integral part of AM S&T maturation for enabling the material property control and material assurance to achieve component qualification.