

Physical Metallurgy and Structural Integrity of the 316L SS 3-D AM prototypes

Nancy Yang, W. Y. Lu, and J. Yee, and T. Reynolds
Sandia National Laboratories, California, USA

Technical team members

- R. Nishimoto, 8341
- J. Chames, 8341
- A. Gardea, 8341
- Enrique Lavernia ,UCI
- Julie Schoenung, UCI
- Baolong Zheng, UCI
- Ryan Hardwick, Summer intern
- Neetika Patel, Summer intern

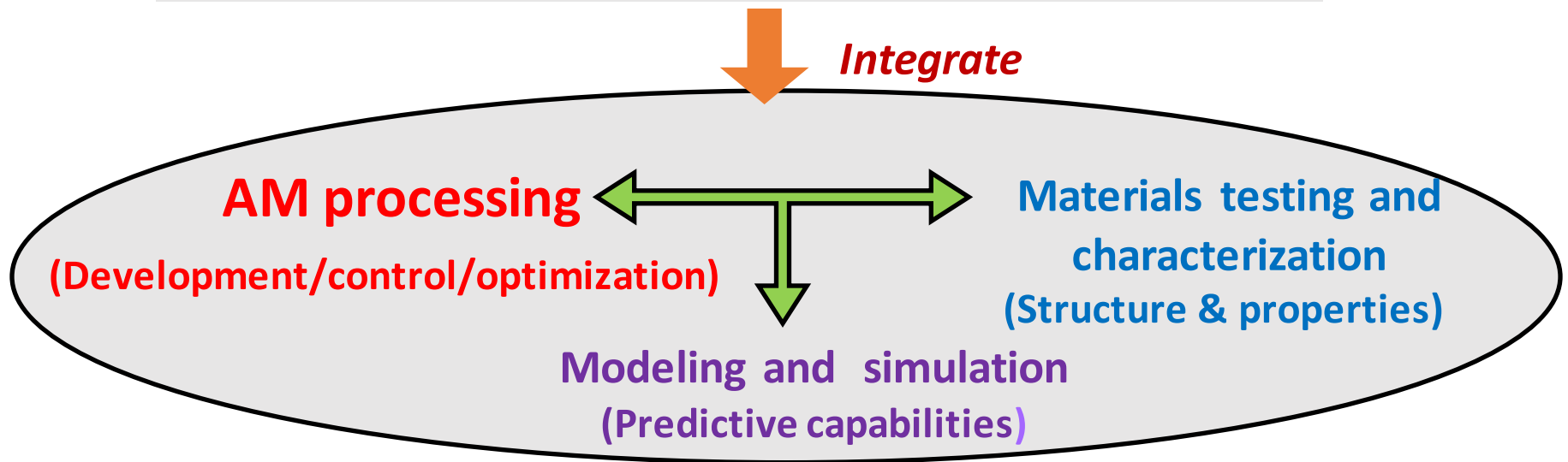
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Outline

- Programmatic objective
- AM fundamentals, 3-D LENS- and PBF- printing
- 3-D LENS & PBF-induced surface characteristics and physical metallurgy
- Structural irregularity and mitigation
- Summary

Programmatic objective: Integrating a robust scientific approach

AM Science and Technology (S&T) Maturation



Discover

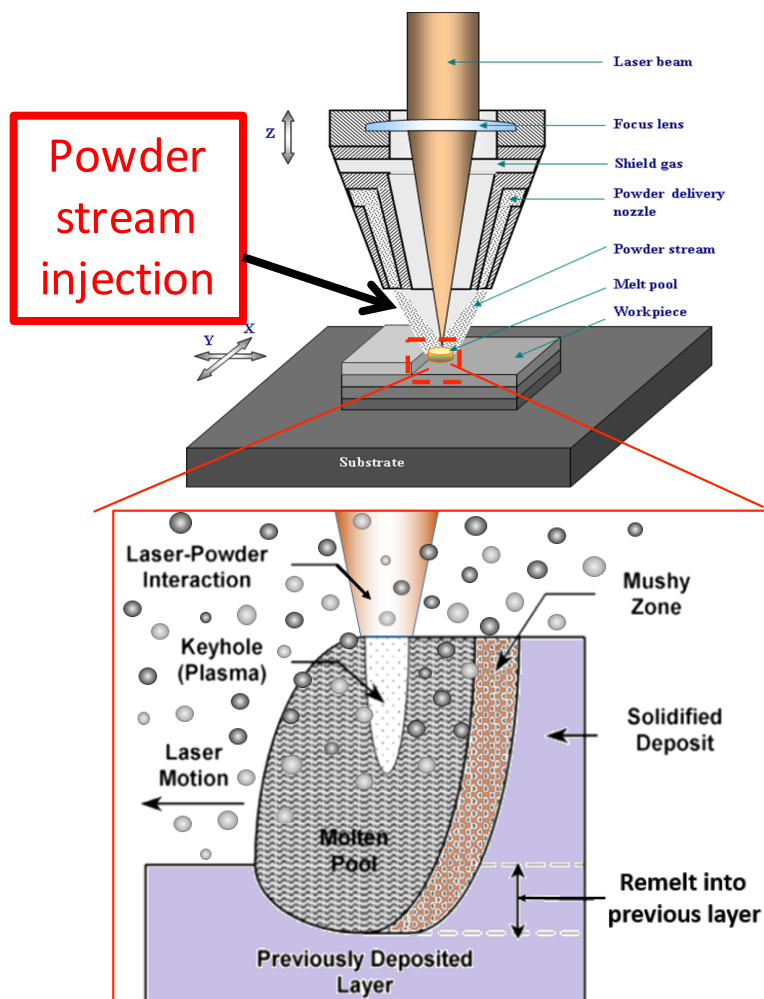
- Process-structure-property-performance relationships
- Geometry/precision & limitation/manufacturing constraints
- Materials properties control and defect mitigation

Enable

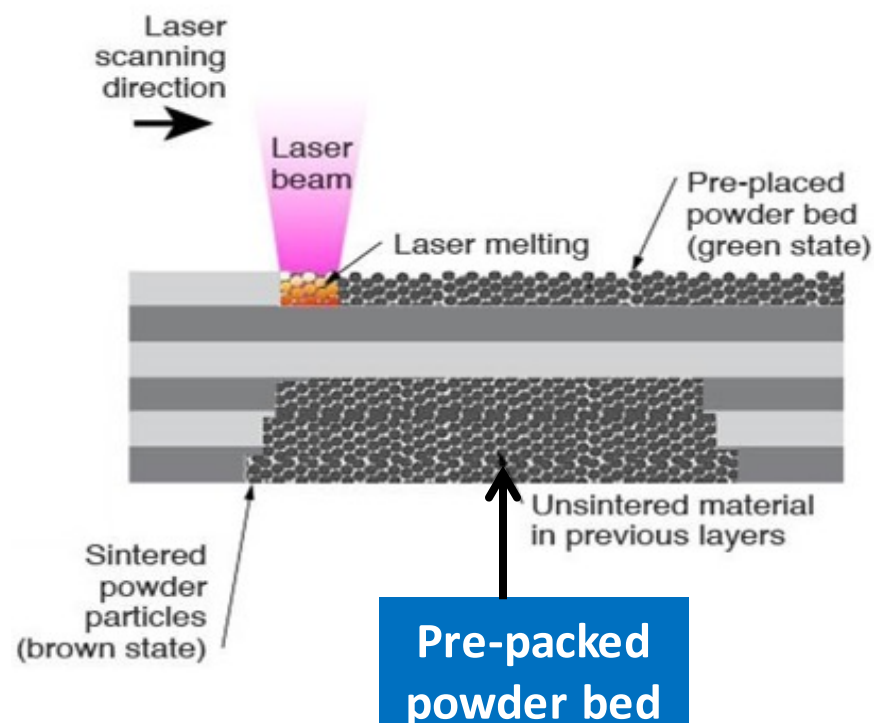
Science-base AM system engineering

Fundamentals of powder-based 3-D LENS and PBF printing

Laser Engineered Net Shaping (LENS)



Powder Bed Fusion (PBF)

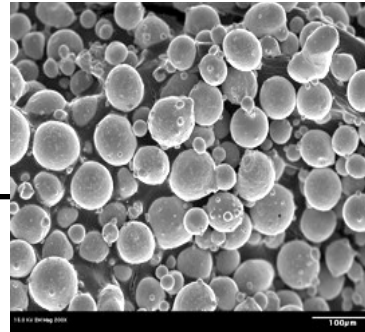


LENS & PBF common steps

- Powder melting
- Molten metal fusion
- Molten metal solidification

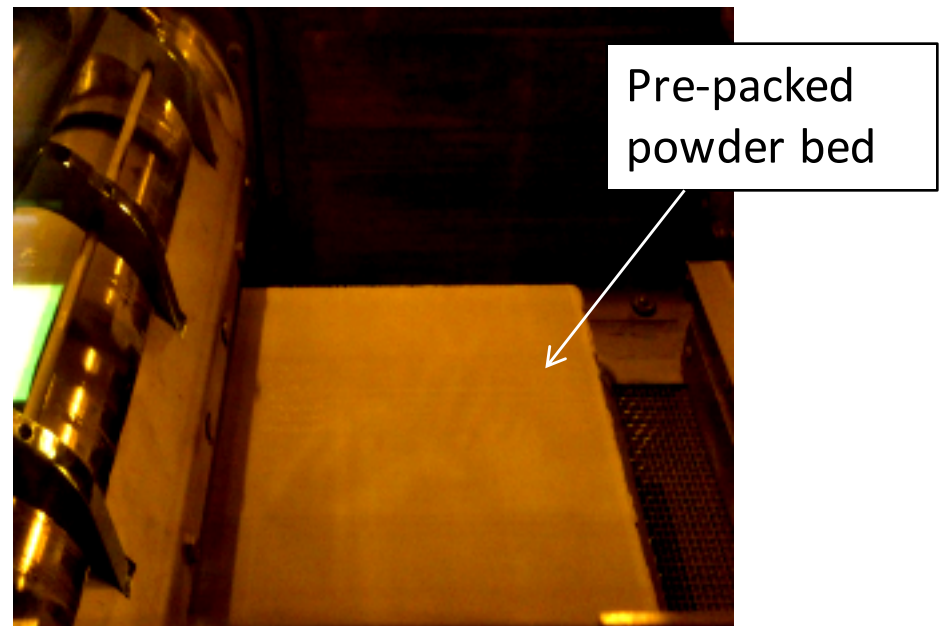
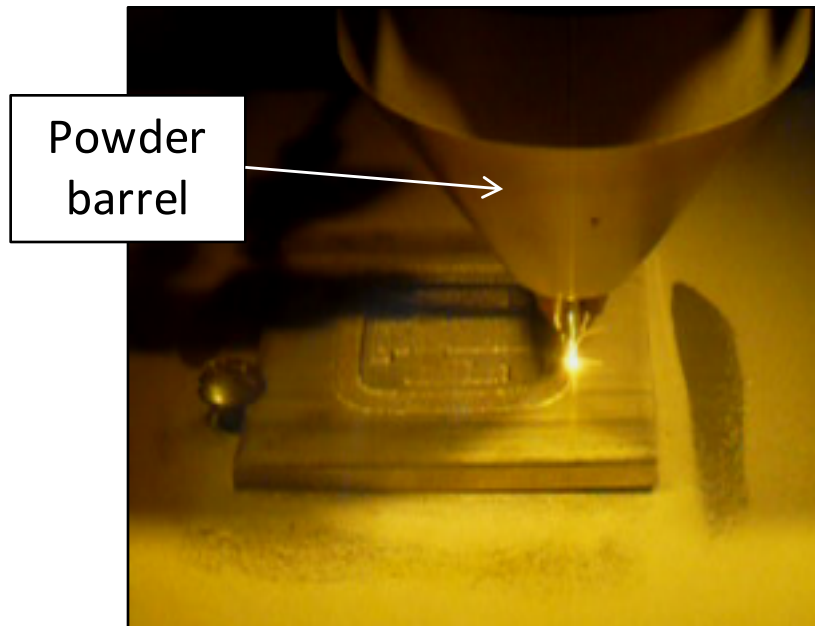
Powder-based 3-D LENS- and PBF- printing process

Starting 316L atomized feedstock powders

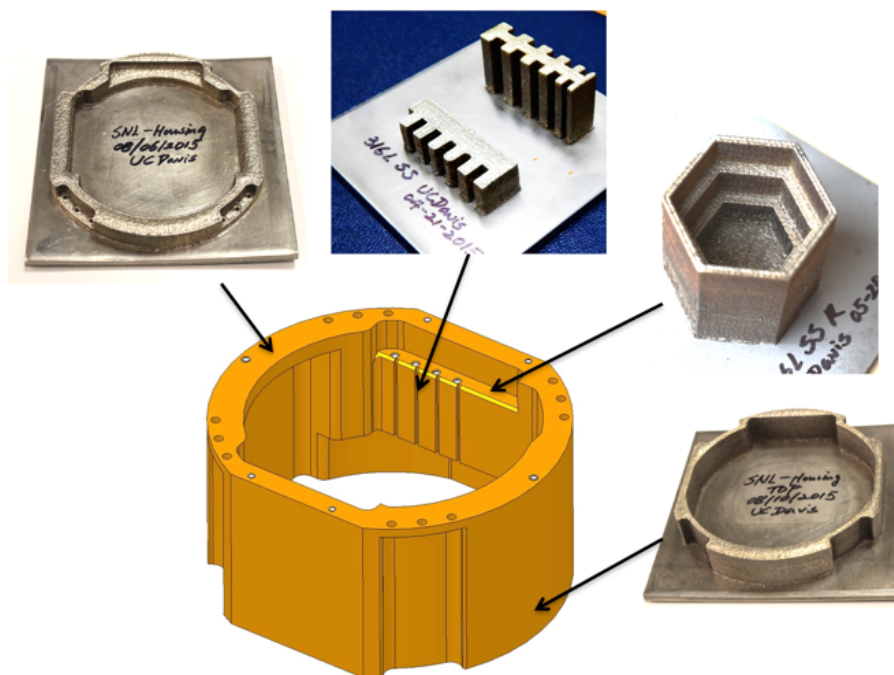
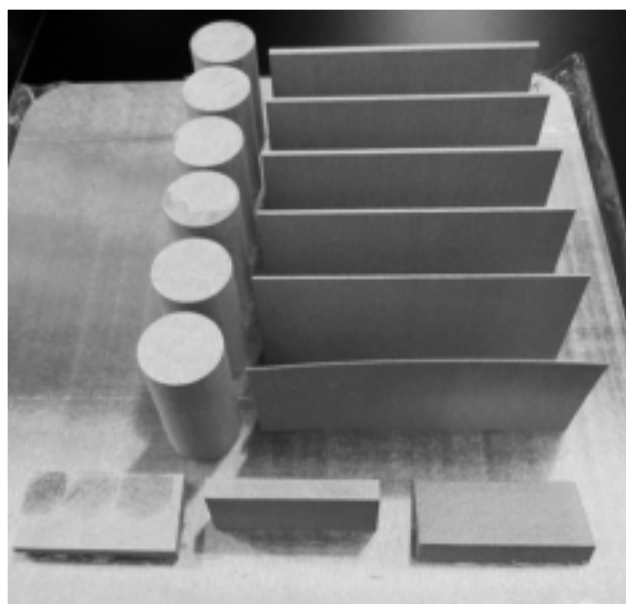
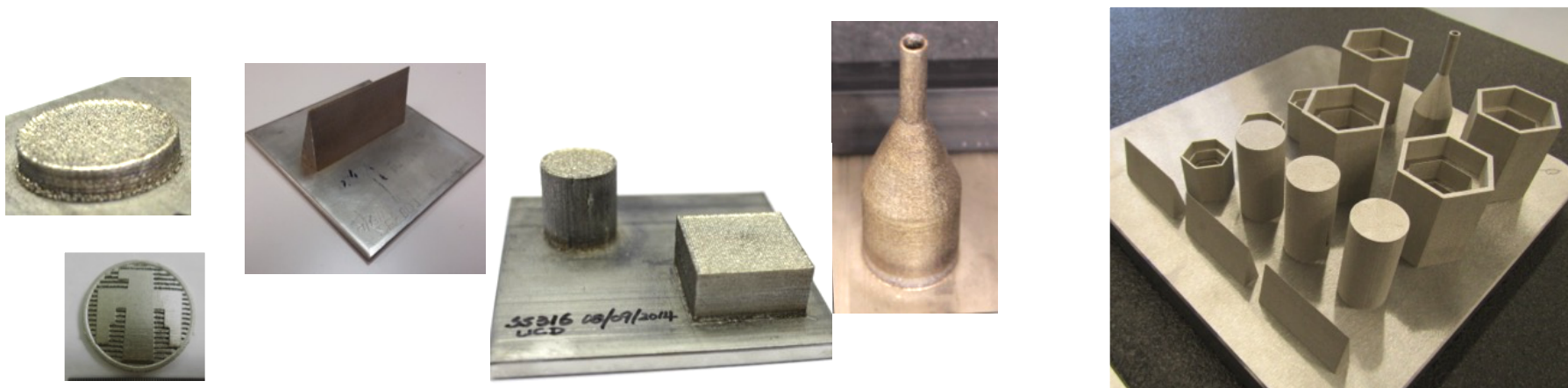


3-D LENS printing

3-D PBF printing



3-D LENS- & PBF- 316L SS prototyping



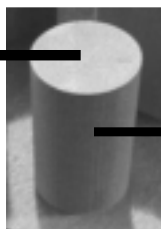
AM induced material characteristics of 316L SS

- Surface morphology
- Solidification Microstructure
- Mechanical behavior
- Structural integrity and defect

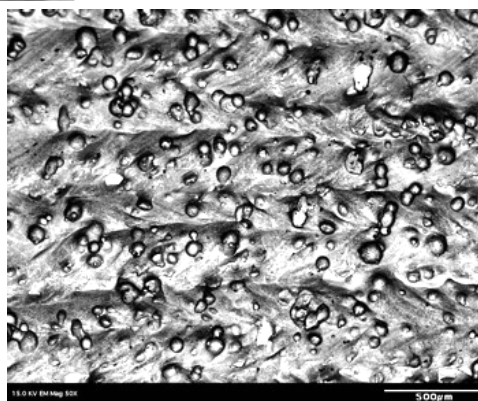
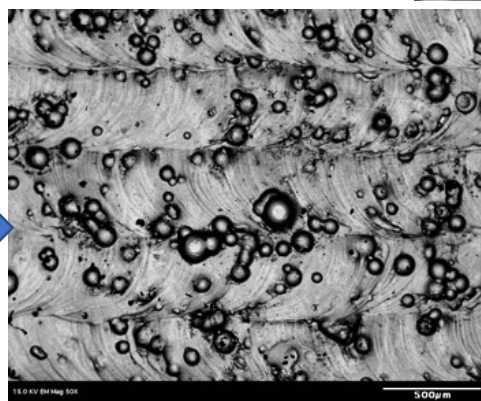
Process-induced unmelted powders are common on LENS top surface and PBF sidewall

Top surface

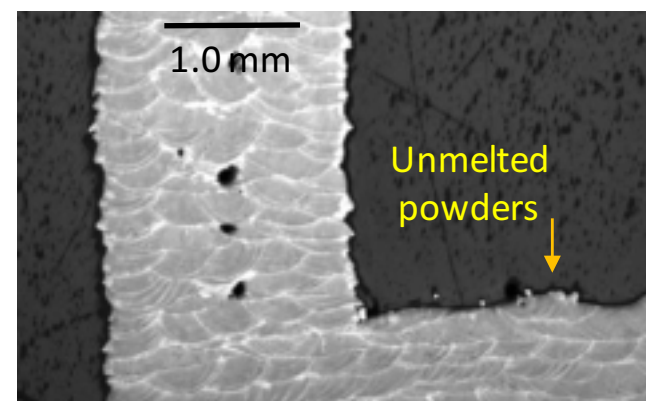
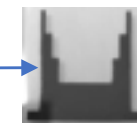
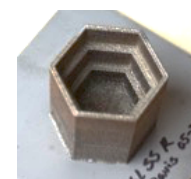
Sidewall



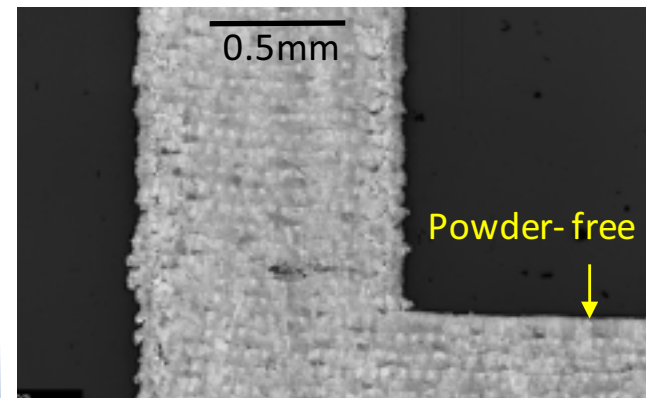
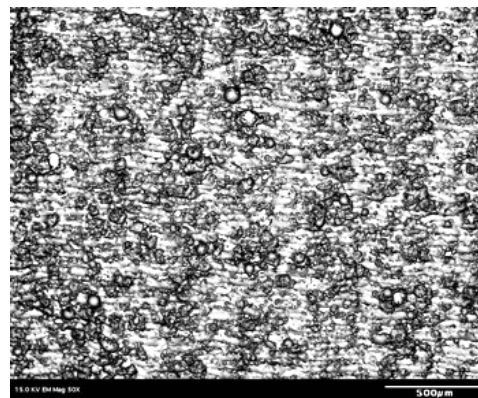
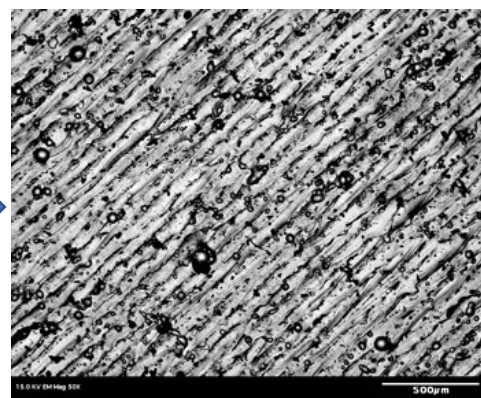
LENS



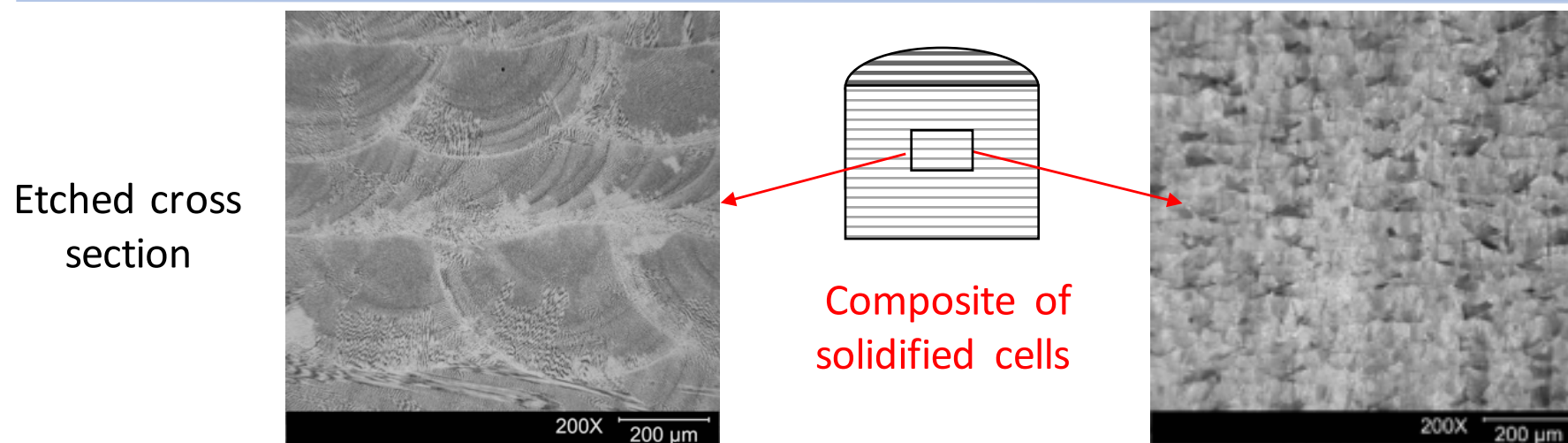
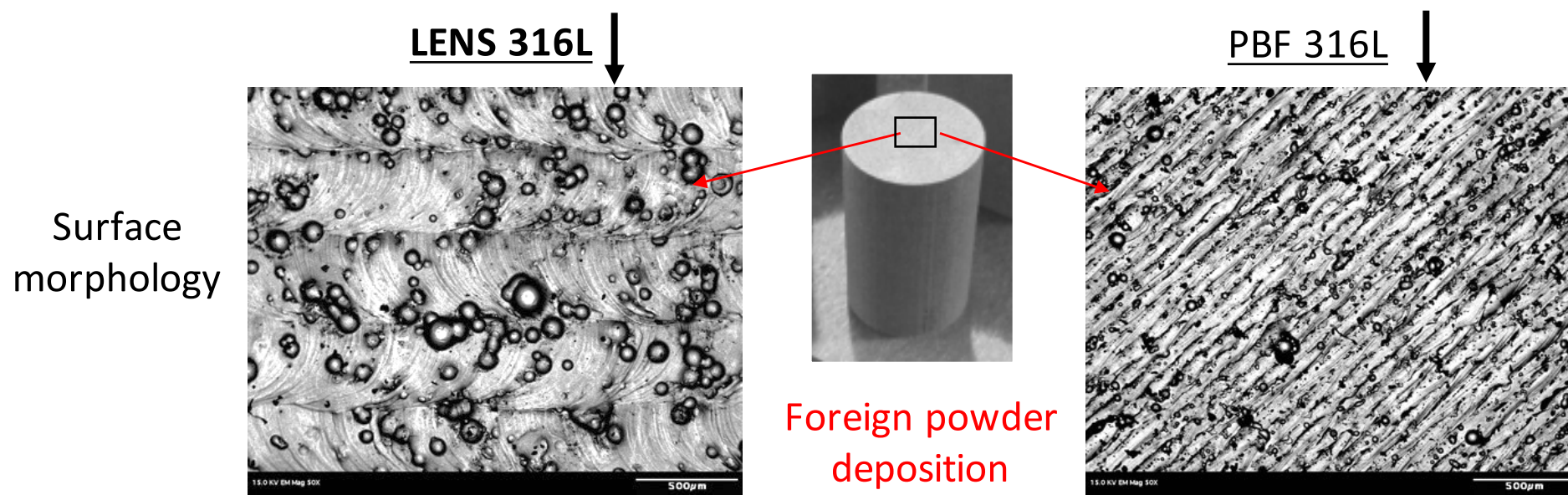
Etched cross section)



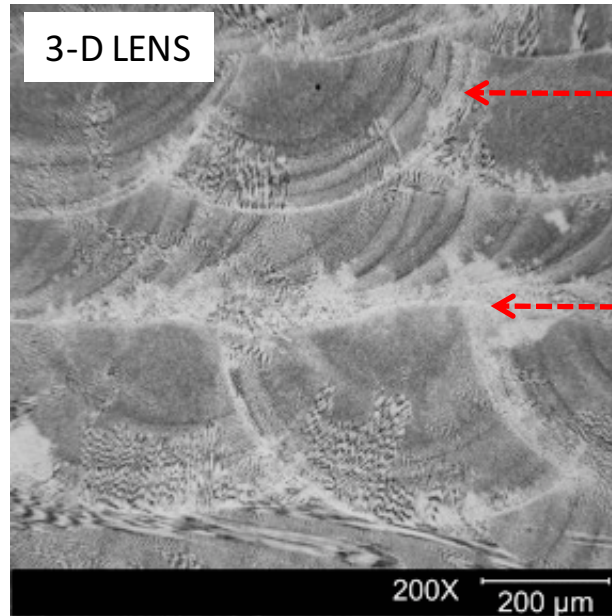
PBF



Different surface morphology and solidification landscape between the 3-D LENS- and PBF- 316L SS

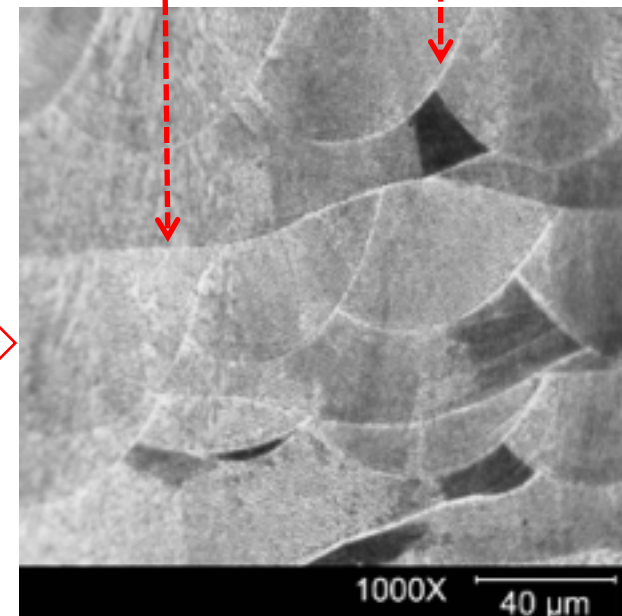
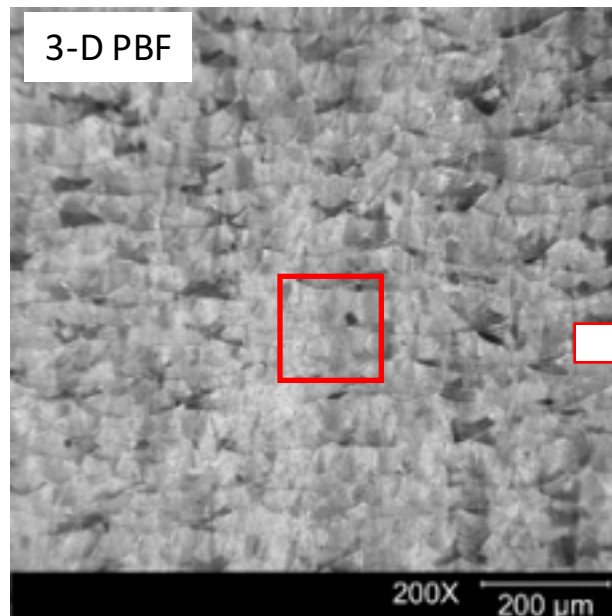


3-D-LENS- & PBF- printed 316LSS exhibit composite structure of solidified cells



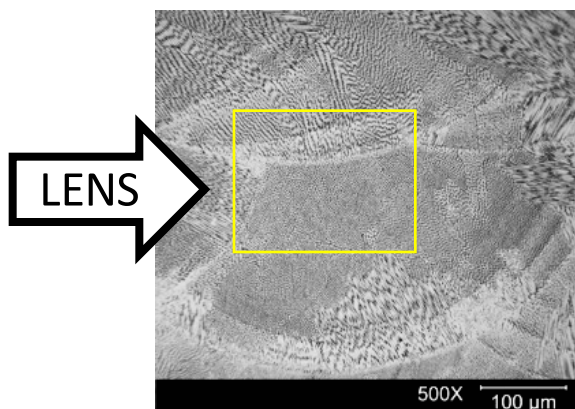
Interface of molten metal interpasses (Horizontal)

Interface of molten metal flow trails interface (Vertical)

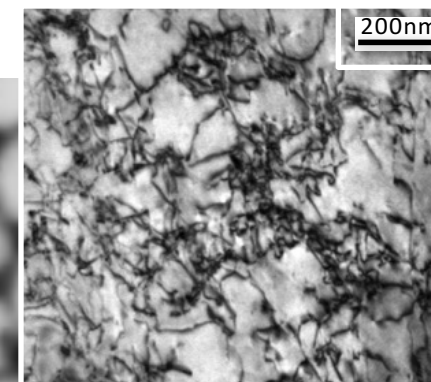
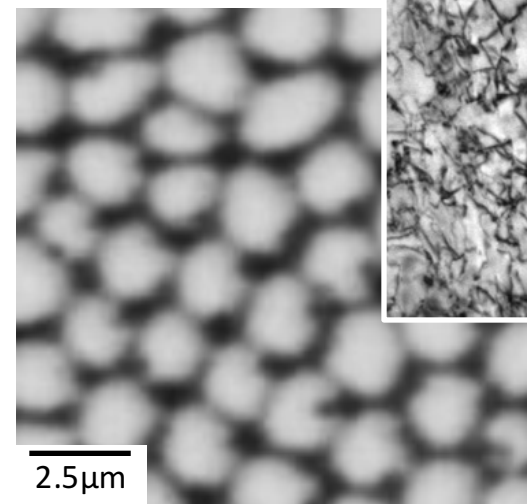
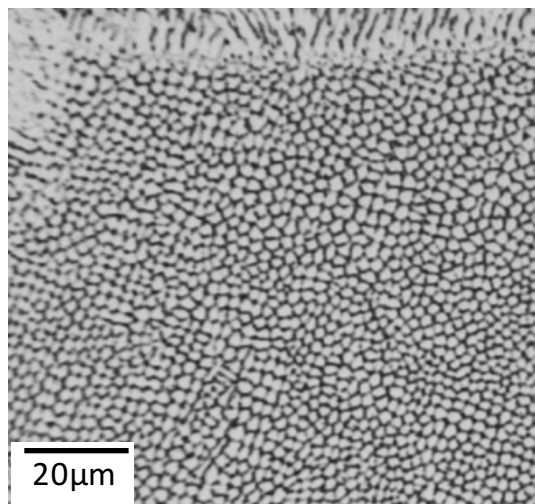


Solidification cell size is coarser and dislocation networks are much more spread in the 316L LENS- than in PBF- cylinder

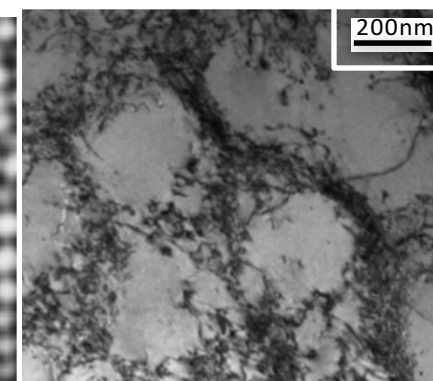
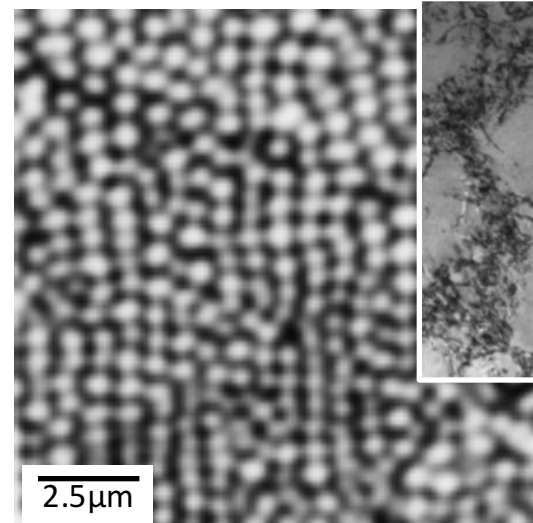
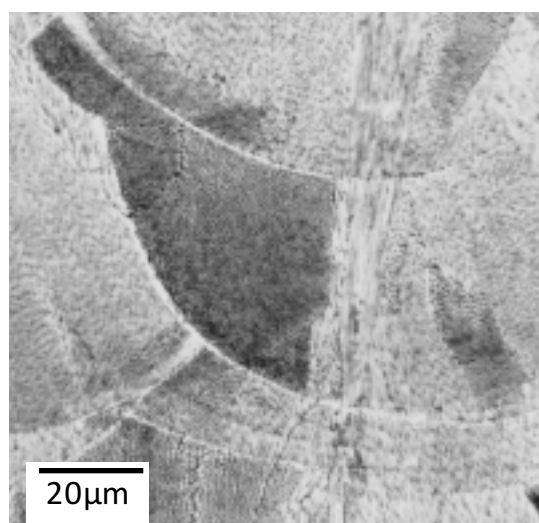
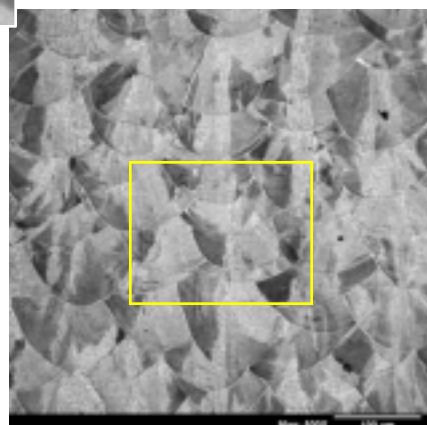
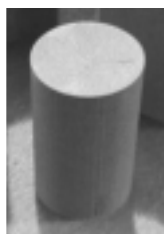
Increasing magnification →



Optical images of
chemical etched
surface



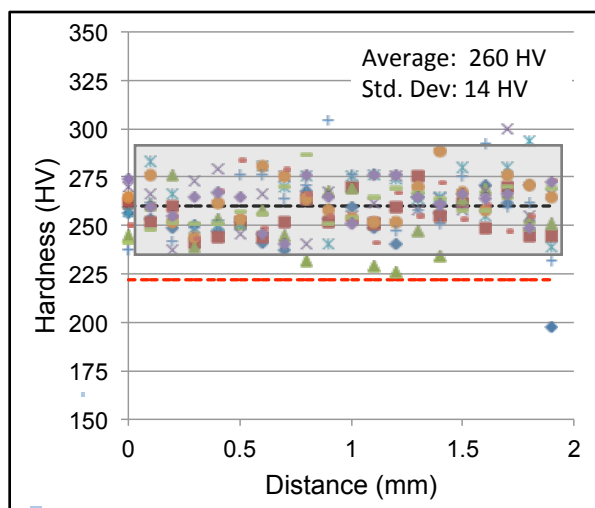
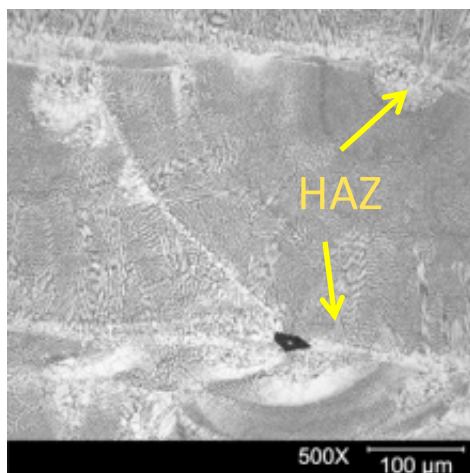
TEM/BF



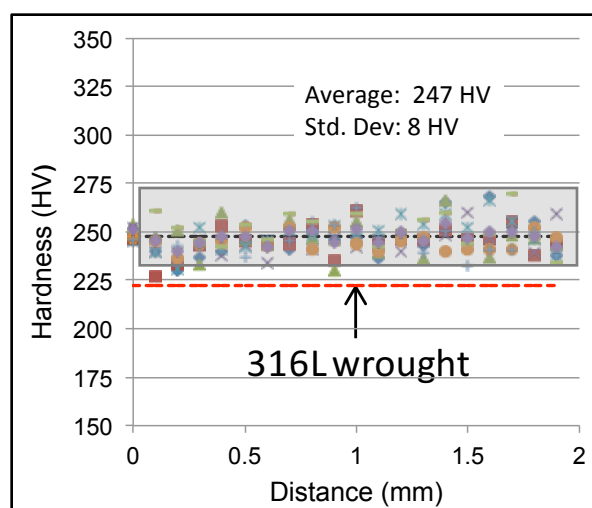
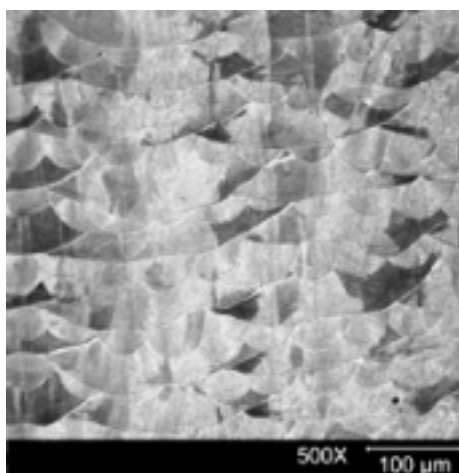
TEM/BF

Local thermal transport & heat distribution dictate solidification microstructure, therefore, mechanical behavior

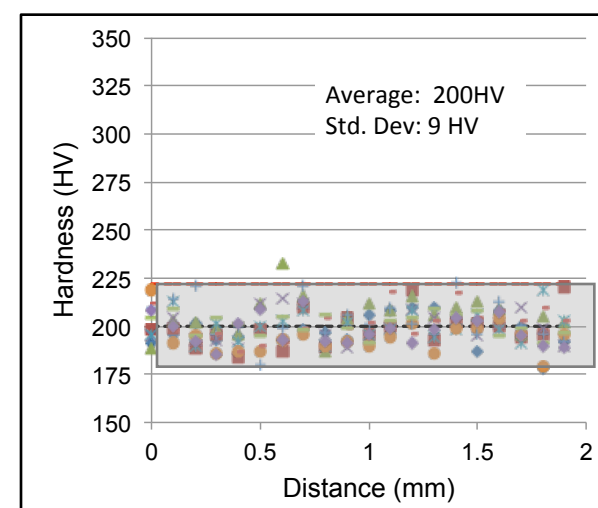
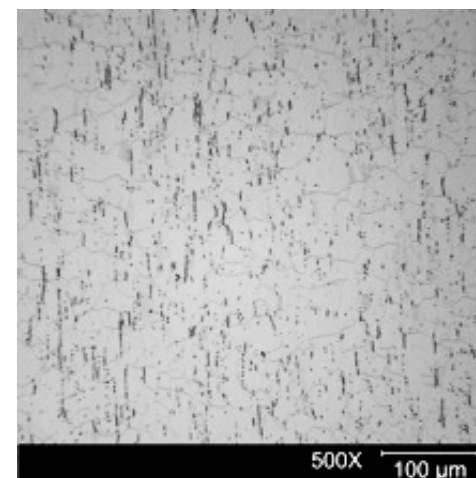
3-D LENS



3-D PBF



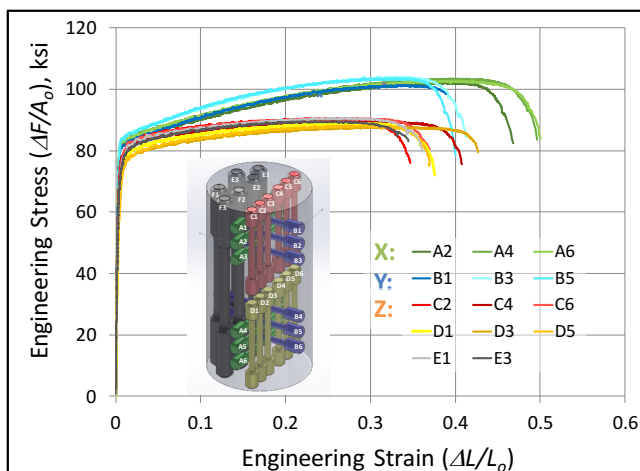
Annealed wrought 304L SS



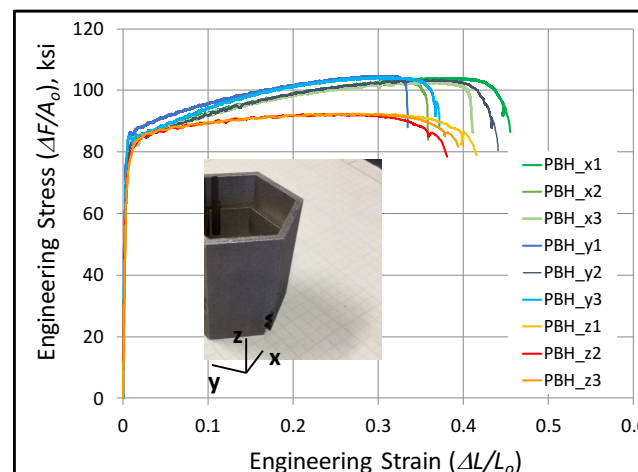
Heat-affect-zone (HAZ) at the interpasses are responsible for the large microhardness variation seen in the LENS hexagon

Engineering properties are anisotropic, i.e., lower along BD, for all the 316L SS LENS- and PBF- prototypes

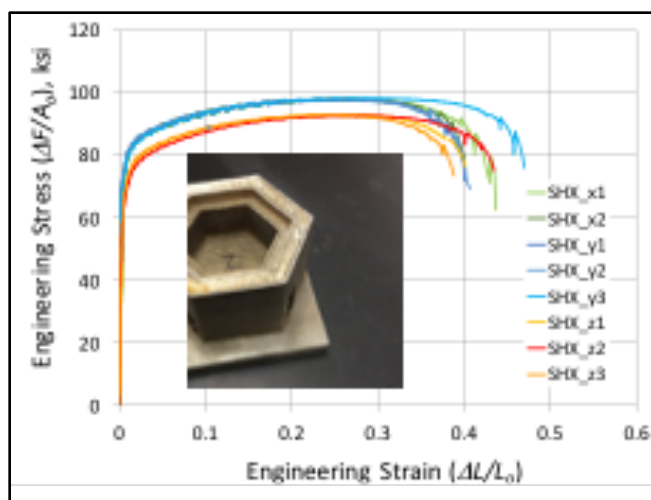
PBF cylinder (SNL)



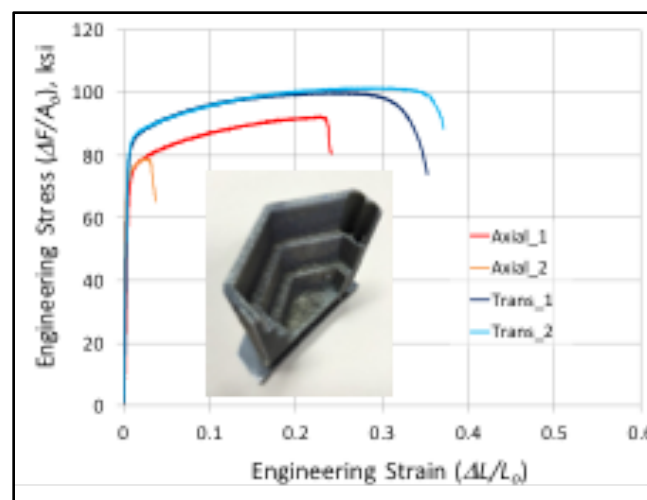
PBF hexagon (SNL)



LENS hexagon (UCI-1/2 length)



LENS hexagon (UCD)

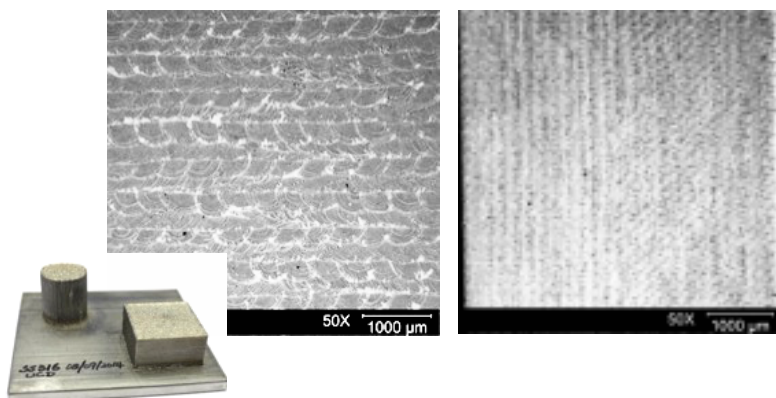


Building direction (BD) ↑

High strength, low ferrite, fine columnar cellular spacing and anisotropic tensile properties are common to all prototypes

Modulated solidification structure

High tensile strength- x-y axis

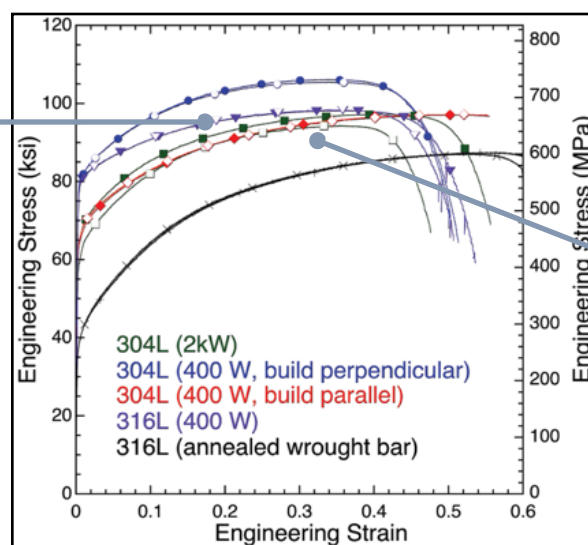
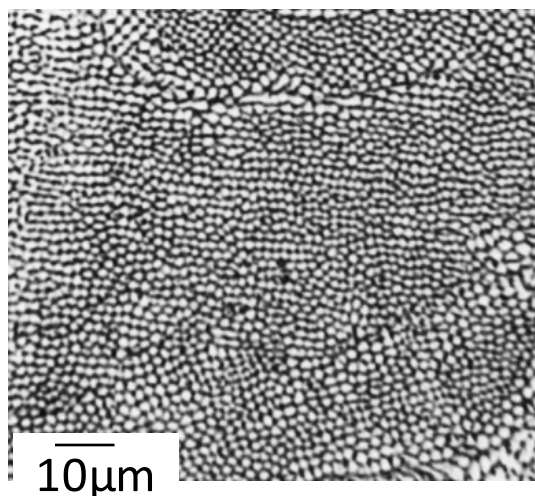


Sample ID	YTS	UTS	Elongation	Vickers HV
	(ksi)	(ksi)	(%)	(VHN)
Annealed 316L wrt	40	80	>50	165
SNLPBF hexagon- T	76	98	34	249 (Base)
LENS hexagon T	69	101	35-38	260 (base)
SNL PBF cylinder	81	103	40-49	247 (Base)

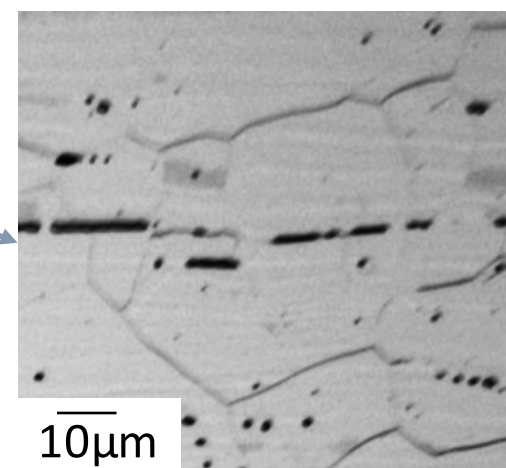
Cellular solidified cell with fine arm spacing

Low Ferrite:

~0.2-0.4 %, for LENS; <<0.2% for PBF; 1-3% for annealed wrought 304L substrate



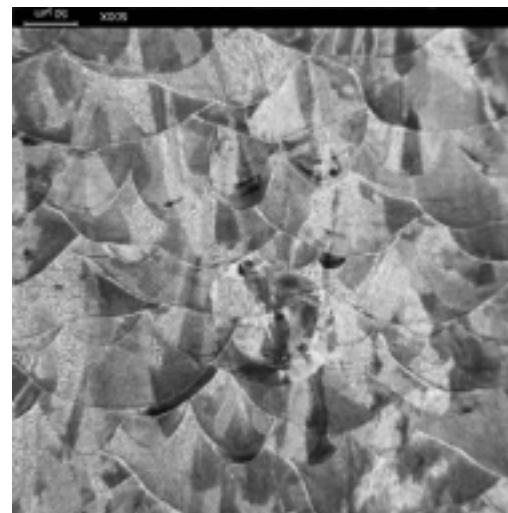
Coarse-grained wrought 316L



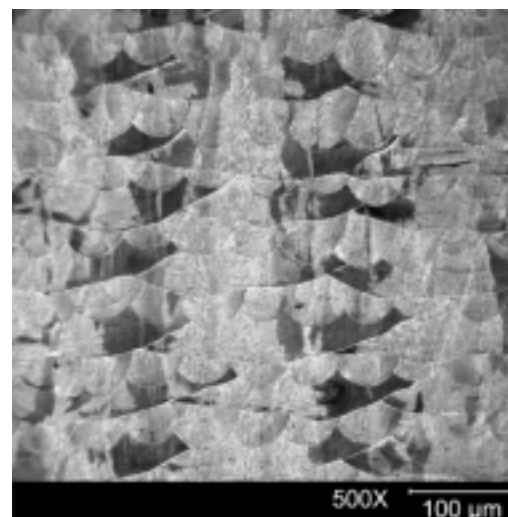
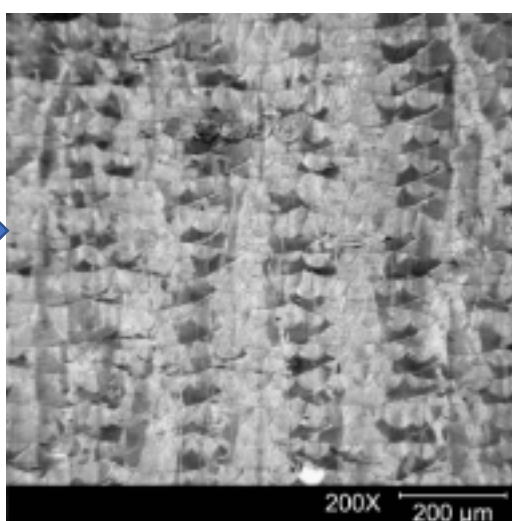
Solidification microstructure varies depending on system hardware as well as printing parameters

Nitric acid etched PBF hexagon

At SNL,CA

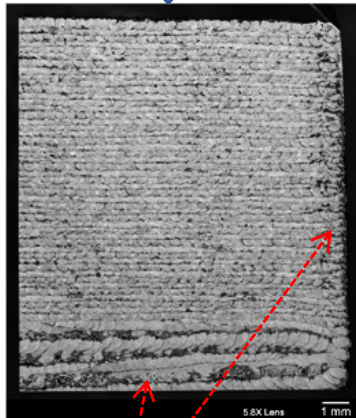
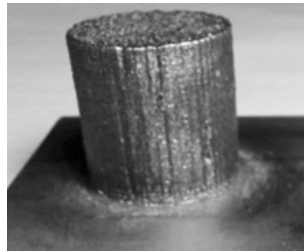


At GPI

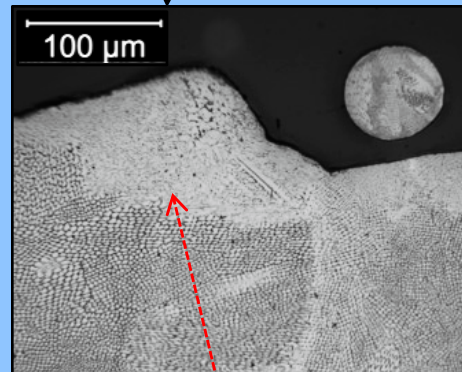
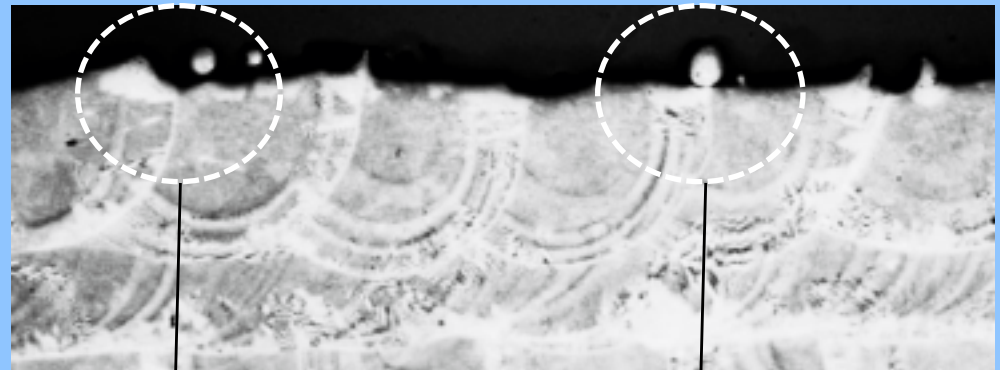
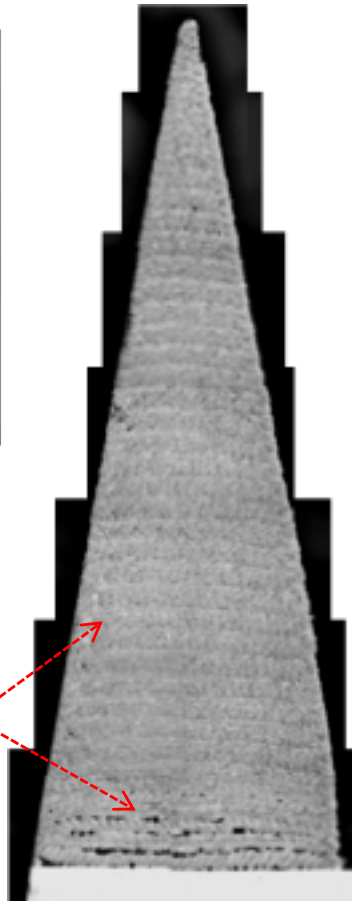
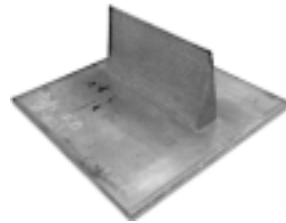


Building direction (BD) ↑

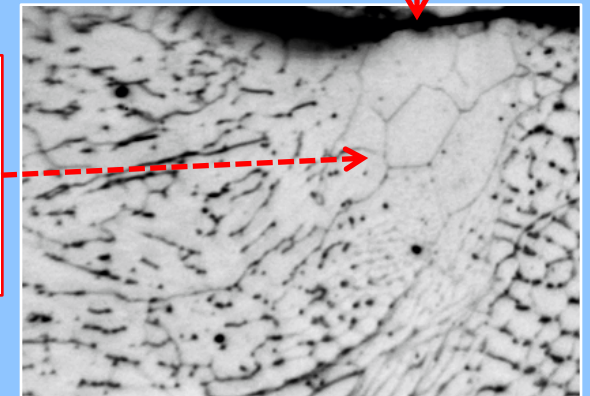
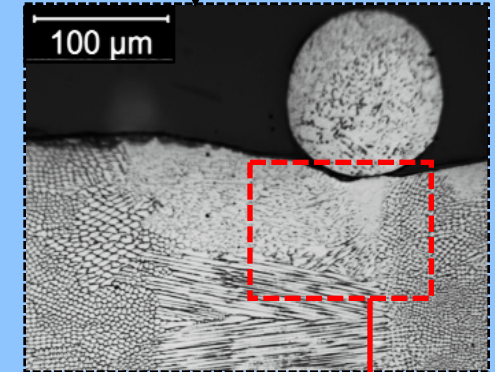
Structure uniformity and defect density in LENS prototype are the results of localized heating and/or ΔT



Structural defect
Gross porosity due
to high ΔT , near
substrate interface
and/or sidewall
surface



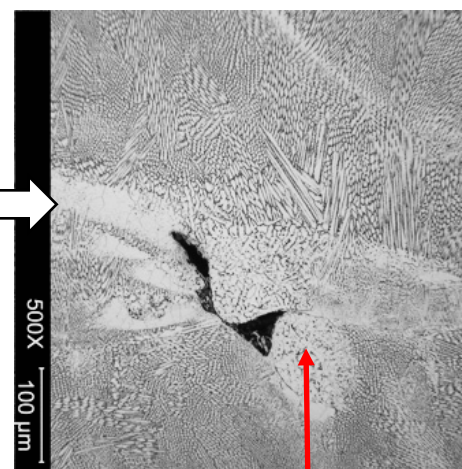
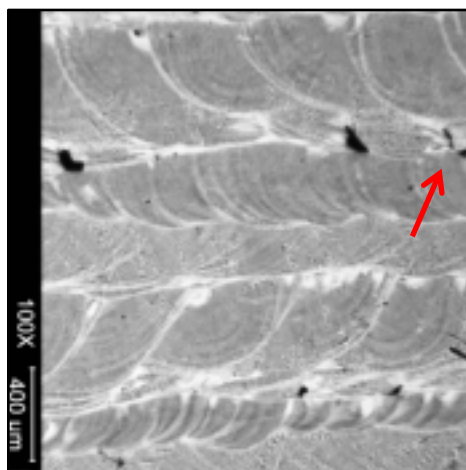
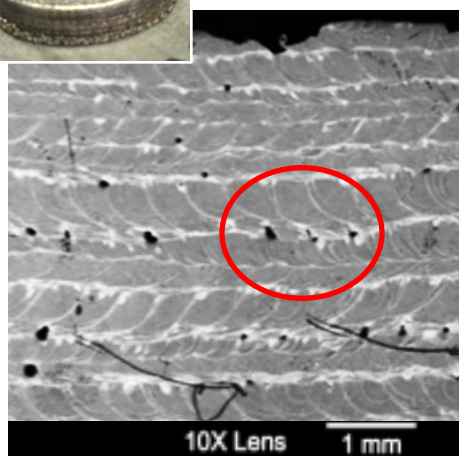
Structural uniformity
Localized heating
yields HAZ and/or
recrystallization



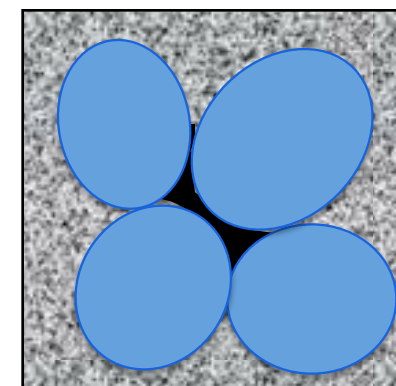
Foreign unmelted powder inclusion disrupts local metal fusion yielding adverse intrinsic structural defect



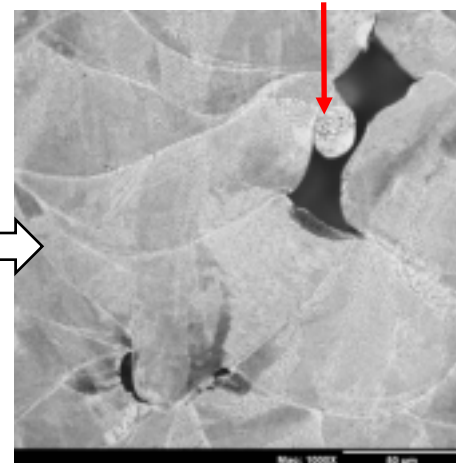
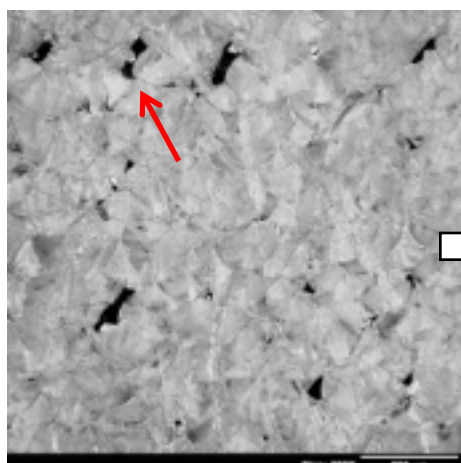
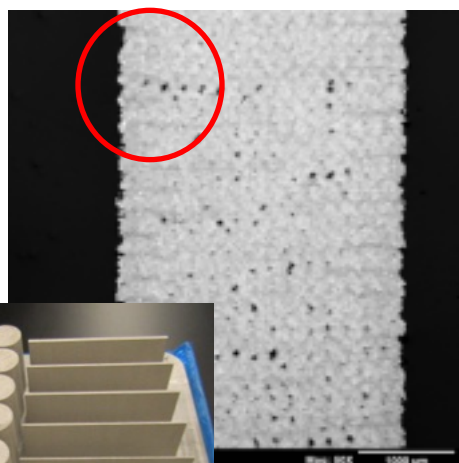
3-D LENS disc



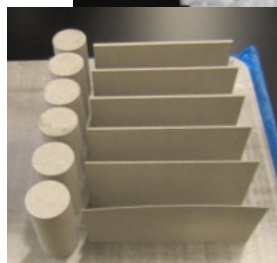
Schematic for
pore formation



Unmelted powder

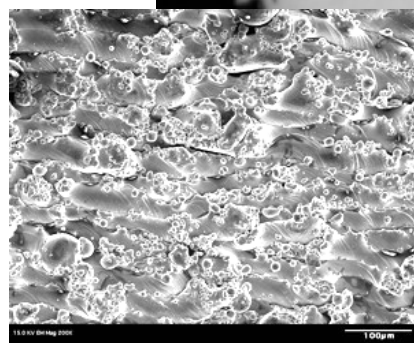
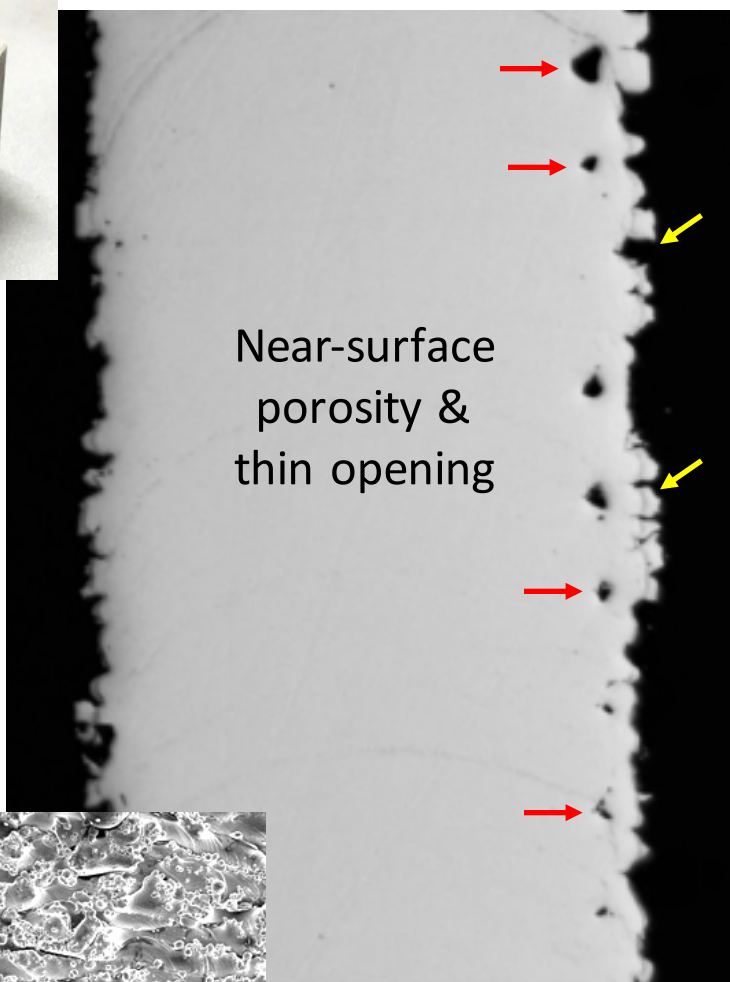


3-D PBF sheet



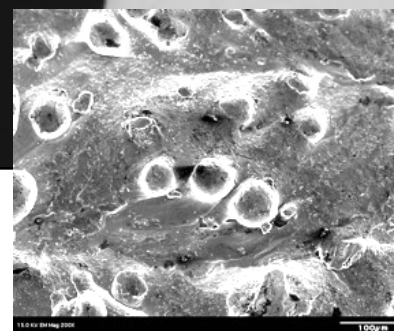
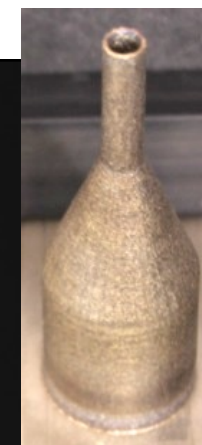
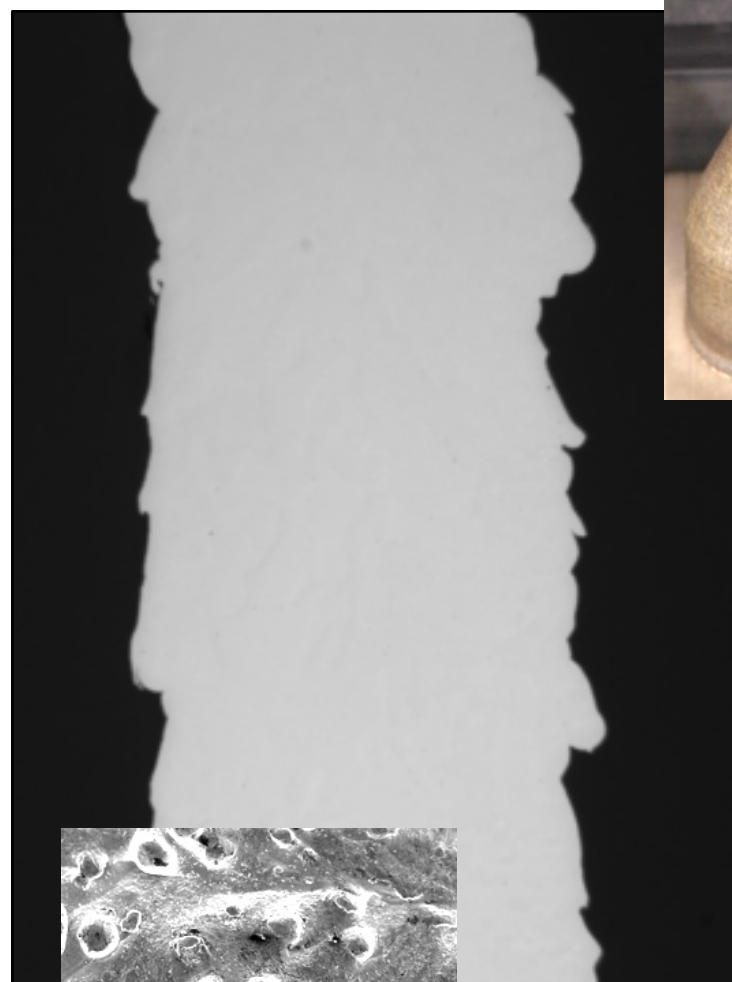
Surface/sidewall irregularities are the results of fused-on unmelted powders and/or molten metal wetting

PBF



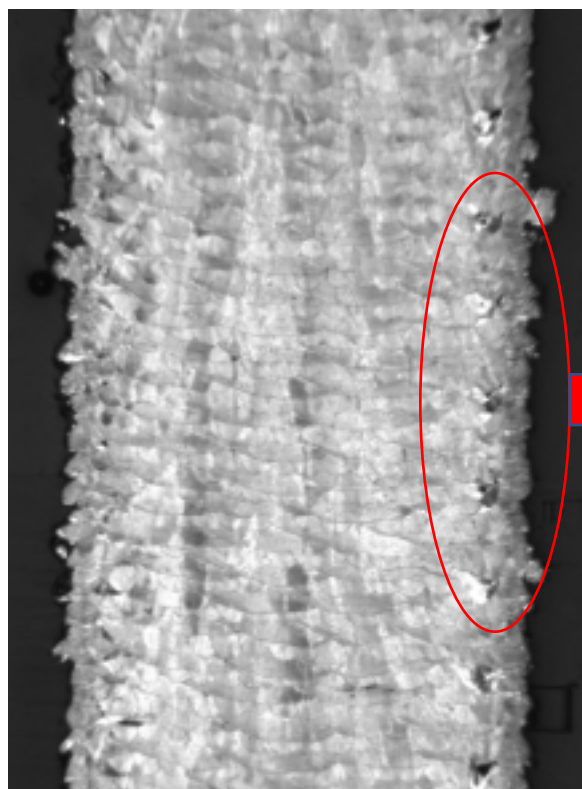
400 μm

LENS

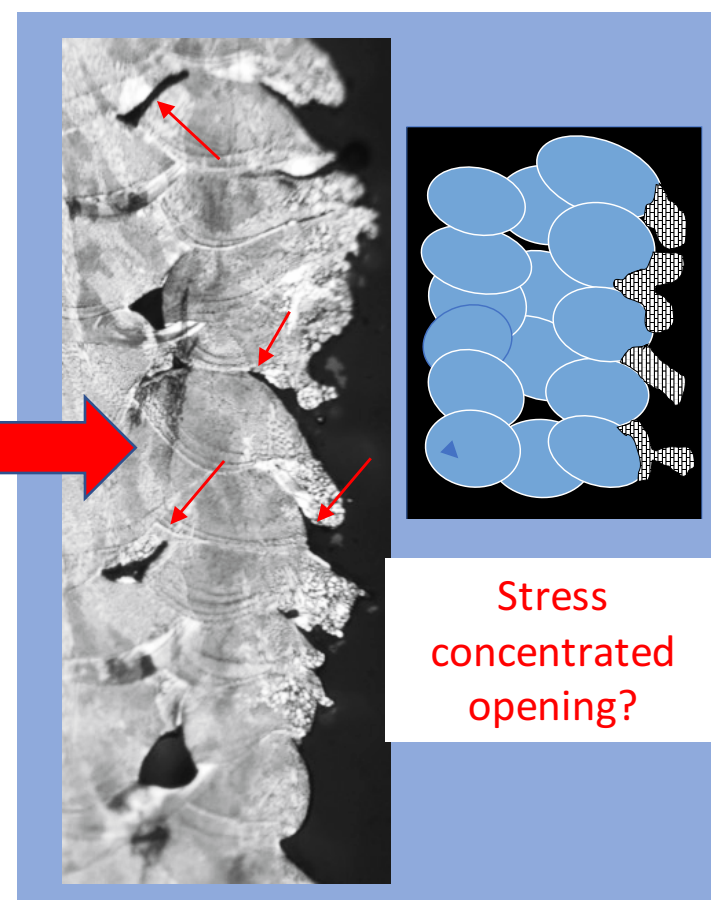


PBF surface with fused-on powders is vulnerable to near-surface porosity and/or stress concentrated sharp openings

As-polished PBF hexagon → Chemical etched

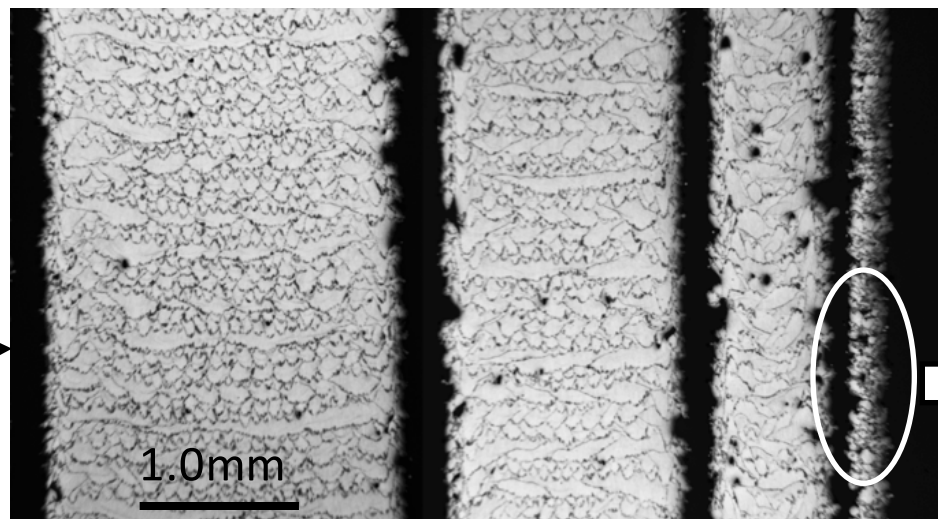


Pore formation schematic



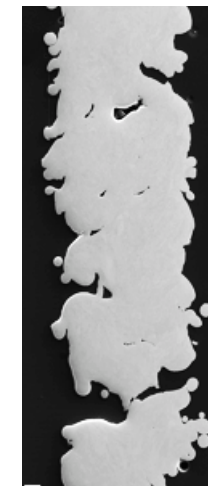
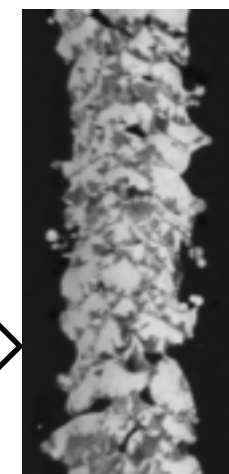
Surface irregularities become bulk property of thin wall feature impacting structure integrity & mechanical behavior

Optical mages of
the PBF printed
304L thin sheets



Etched

As-polished

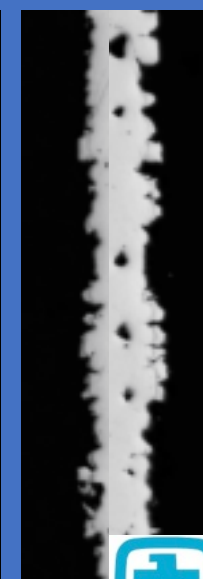
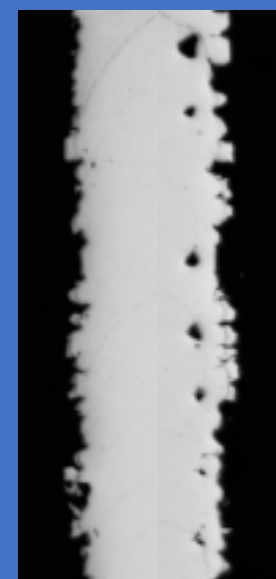
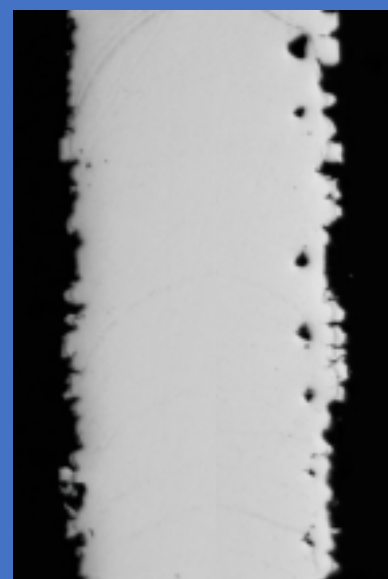


BD
↑

Thickness effect
by optical
images of the
PBF printed
hexagon



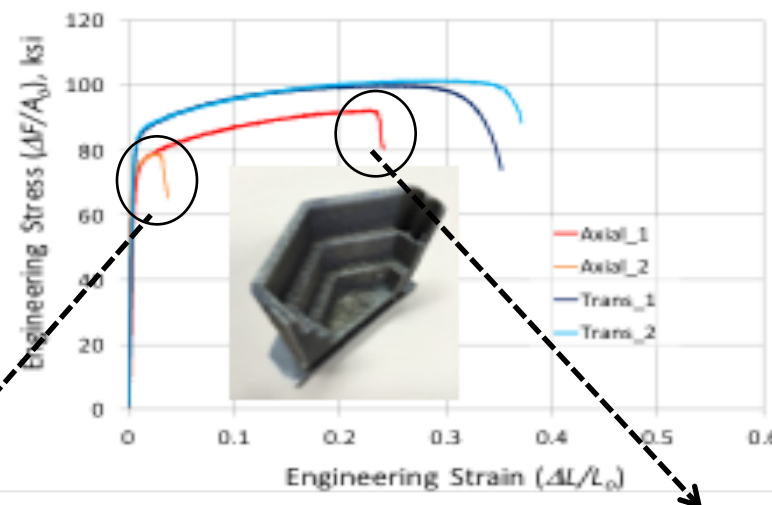
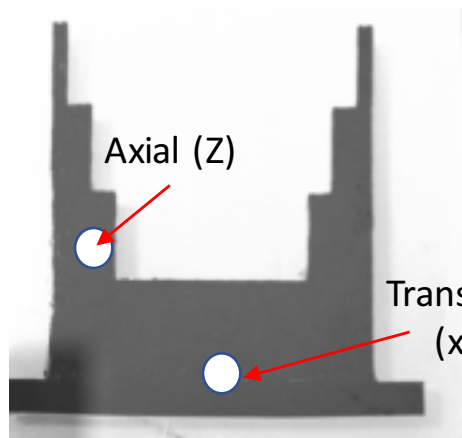
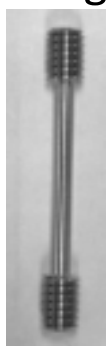
Decreasing sidewall thickness →



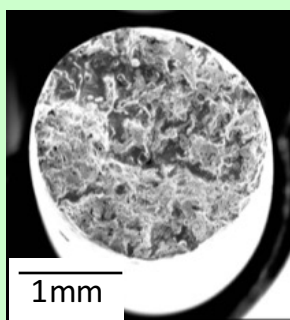
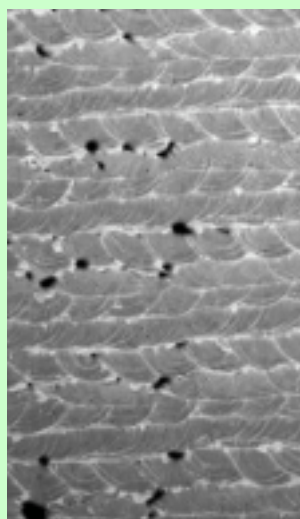
Sandia
National
Laboratories

Gross interpass defect is responsible for the low ductility along BD

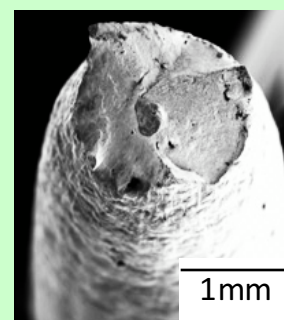
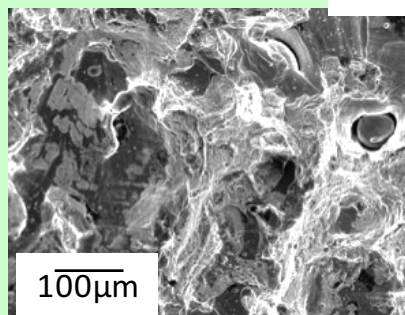
Tensile failure
at mid-length



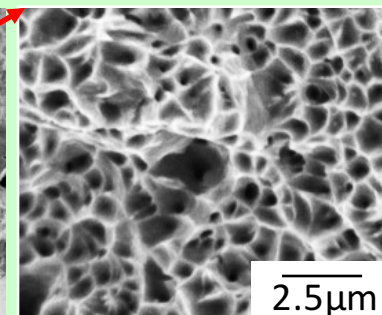
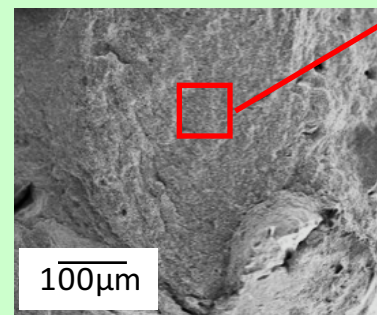
Gross
porosity



Axial un-
necked
premature
failure
(//BD)



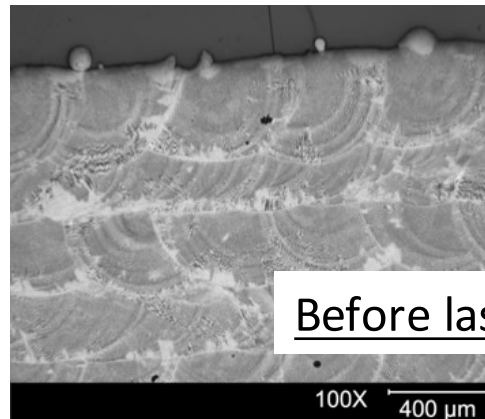
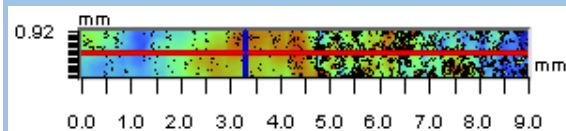
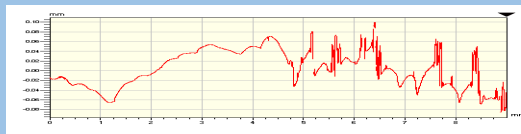
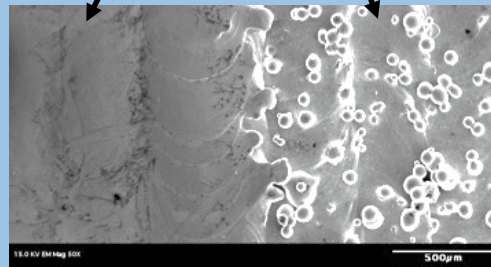
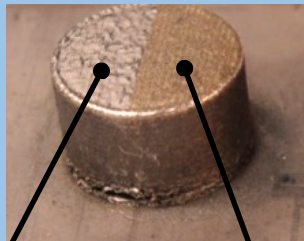
Transverse
necked ductile
dimple failure
(\perp BD)



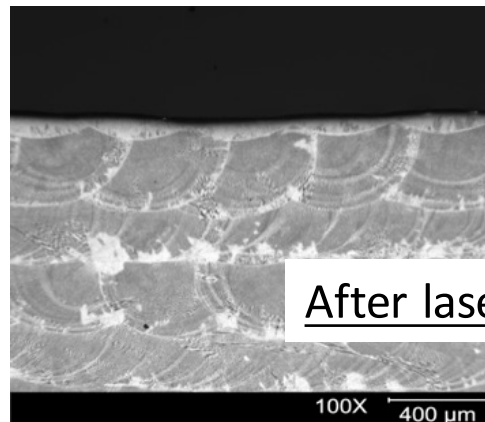
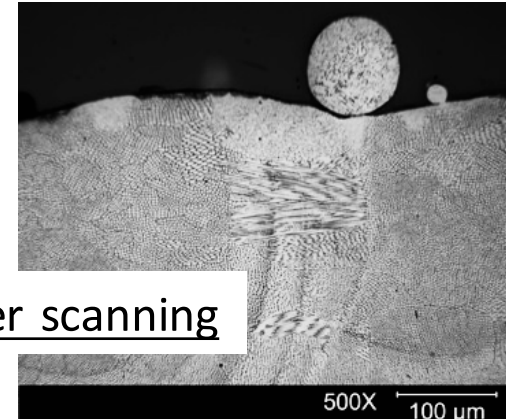
Mitigation strategy:

A blank laser successfully remove unmelted powders, however, yields a distinct surface remelted layer

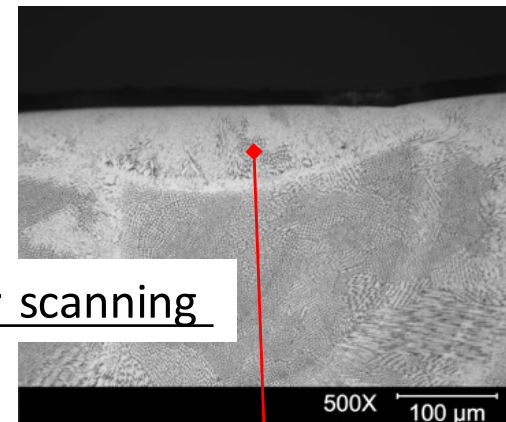
Low power blank beam scanning



Before laser scanning



After laser scanning



Long-term performance implication,
e.g., environmental sensitivity in
particular

Summary

The on-going AM S&T maturation activities

Enable

- ✓ Detect-validate-predict AM-induced metallurgy, structural defect(s) and material reliability
- ✓ Optimize process, control material property and mitigate structural defect(s)

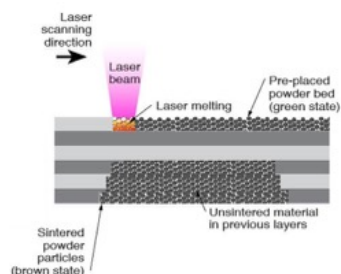
Achieve

Reliable system engineering and engineering performance

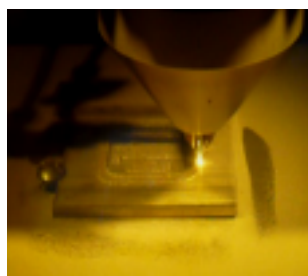
On-going science & technology maturation activities

Process & prototyping

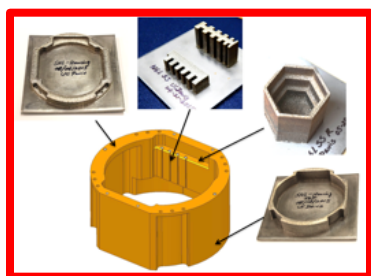
Laser-material interaction



Process optimization

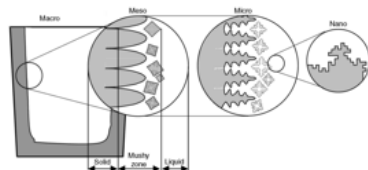


Prototyping feasibility

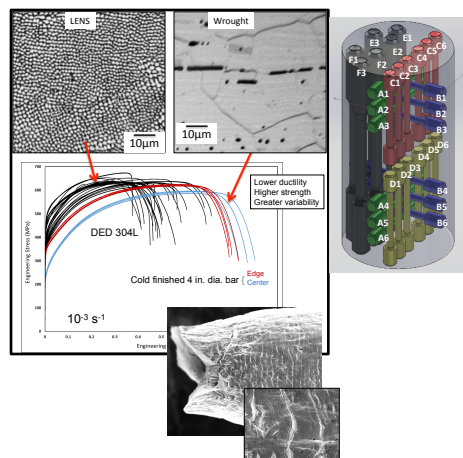


Material science

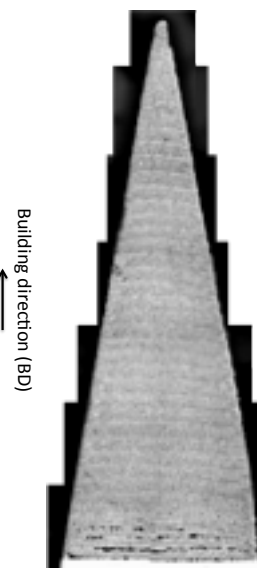
Metal solidification



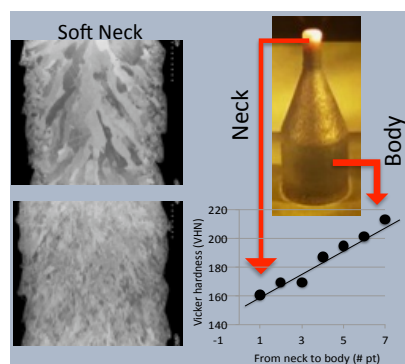
Mechanical behavior



Geometry & structural defect

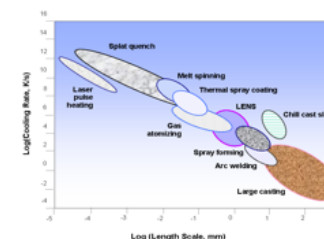


Thermal cooling- Microstructure-Anisotropy

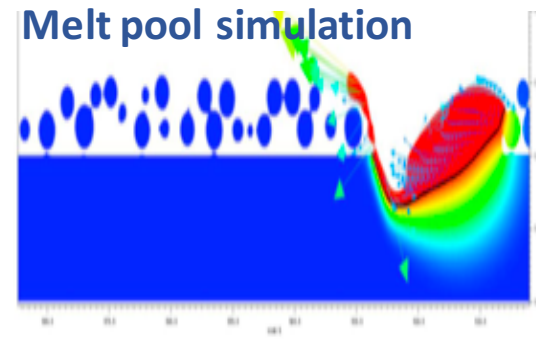


Numerical modeling

Thermal transport & Solidification cooling validation & prediction



Melt pool simulation



External collaborations

- UC Davis/Irvine
- UC Berkeley:
- Stanford
- PolarOnyx INC

Summary

- The understanding of the AM-induced material characteristics are being integrated into our component and system engineering design.
- A better insight into the defect formation mechanism enable us to determine the mitigation strategy
- The advancement of the scientific discoveries ensure reliable science-base AM system engineering.