

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

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Technical team members

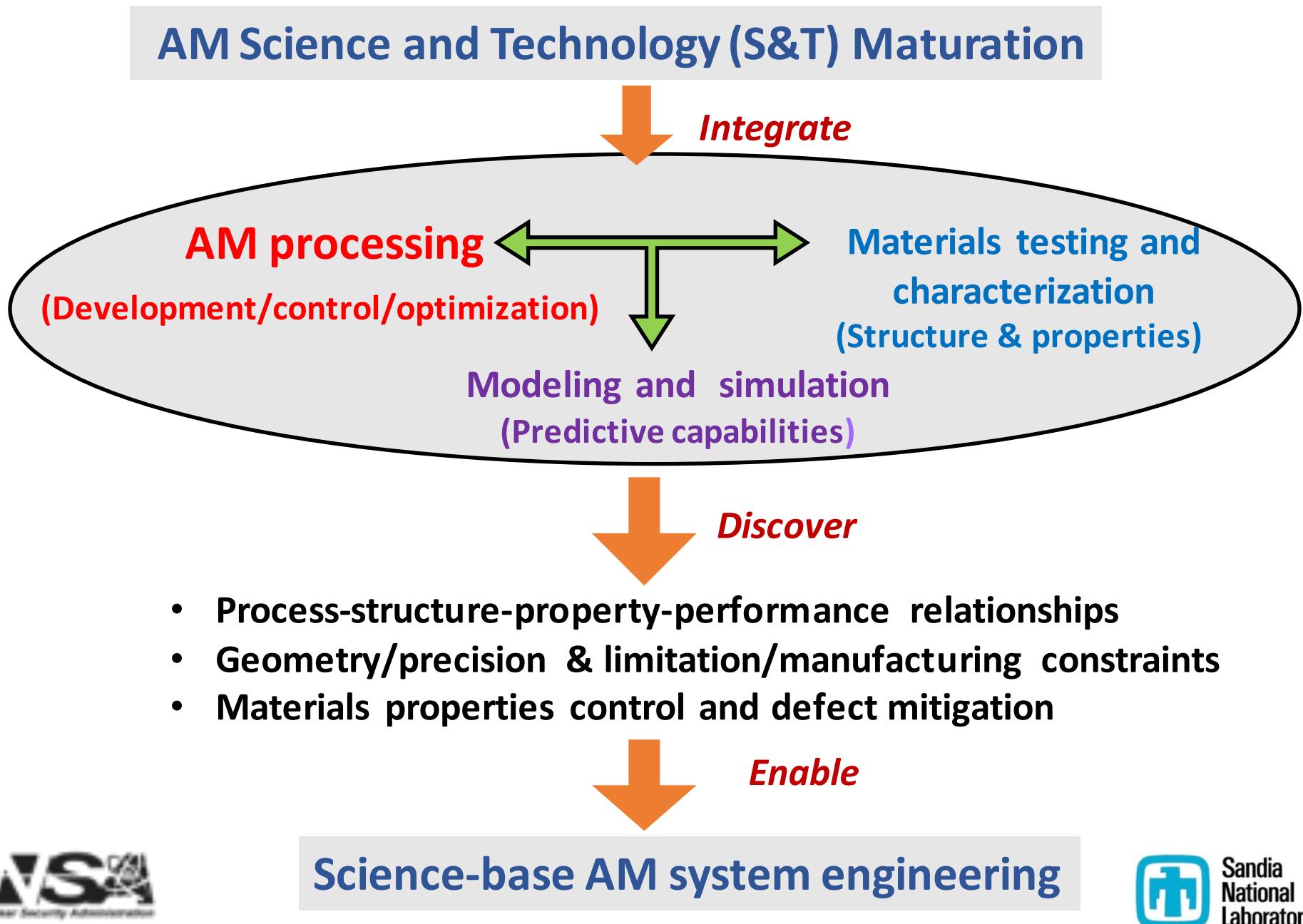
- R. Nishimoto, 8341
- J. Chames, 8341
- A. Gardea, 8341
- Enrique Lavernia ,UCI
- Julie Schoenung, UCI
- Baolong Zheng, UCI
- Ryan Hardwick, Summer intern
- Neetika Patel, Summer intern

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Outline

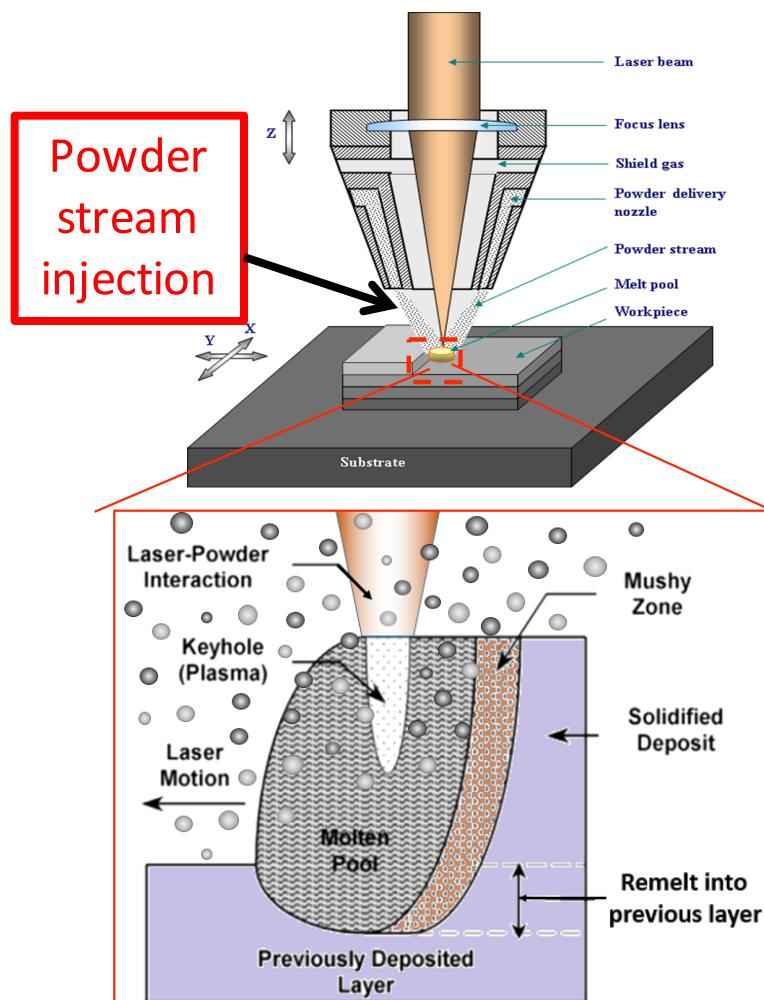
- Programmatic objective
- AM fundamentals, 3-D LEN- and PBF- printing
- 3-D LENS & PBF-induced surface characteristics and physical metallurgy
- Structural irregularity and mitigation
- Summary

Programmatic objective: Integrating a robust scientific approach

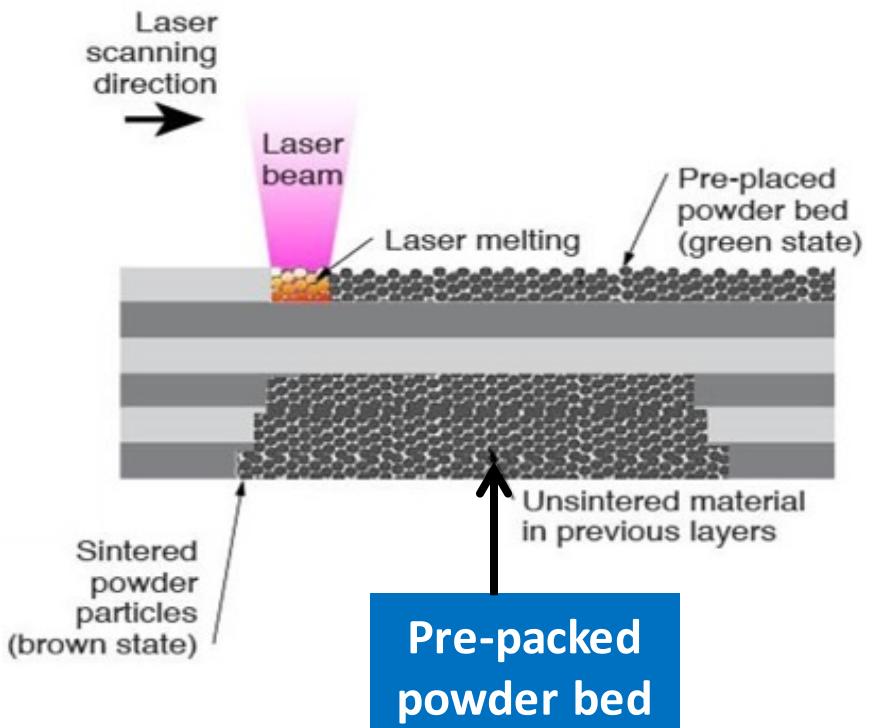


Fundamentals of powder-based 3-D LENS and PBF printing

Laser Engineered Net Shaping (LENS)



Powder Bed Fusion (PBF)

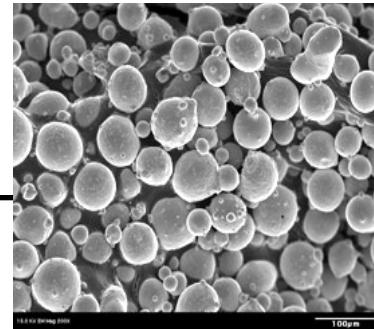


LENS & PBF common steps

- Powder melting
- Molten metal fusion
- Molten metal solidification

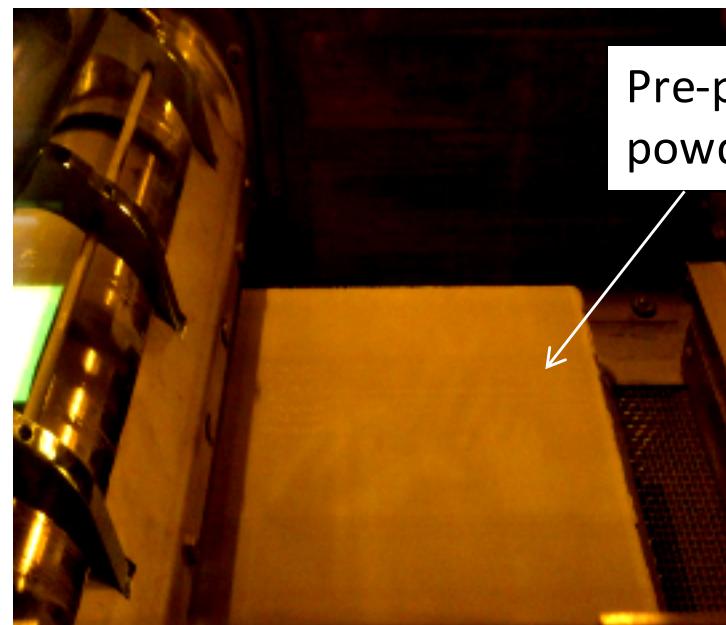
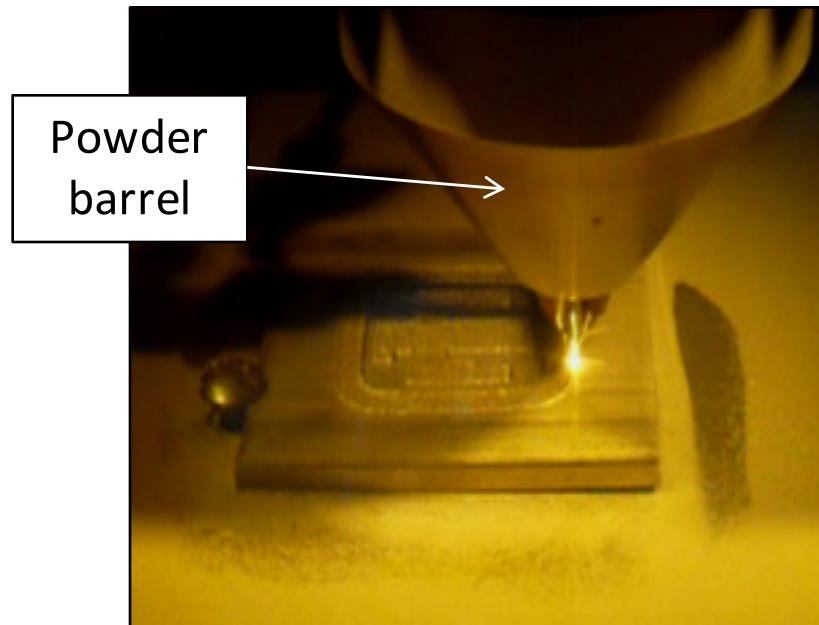
Powder-based 3-D LENS- and PBF- printing process

Starting 316L atomized feedstock powders

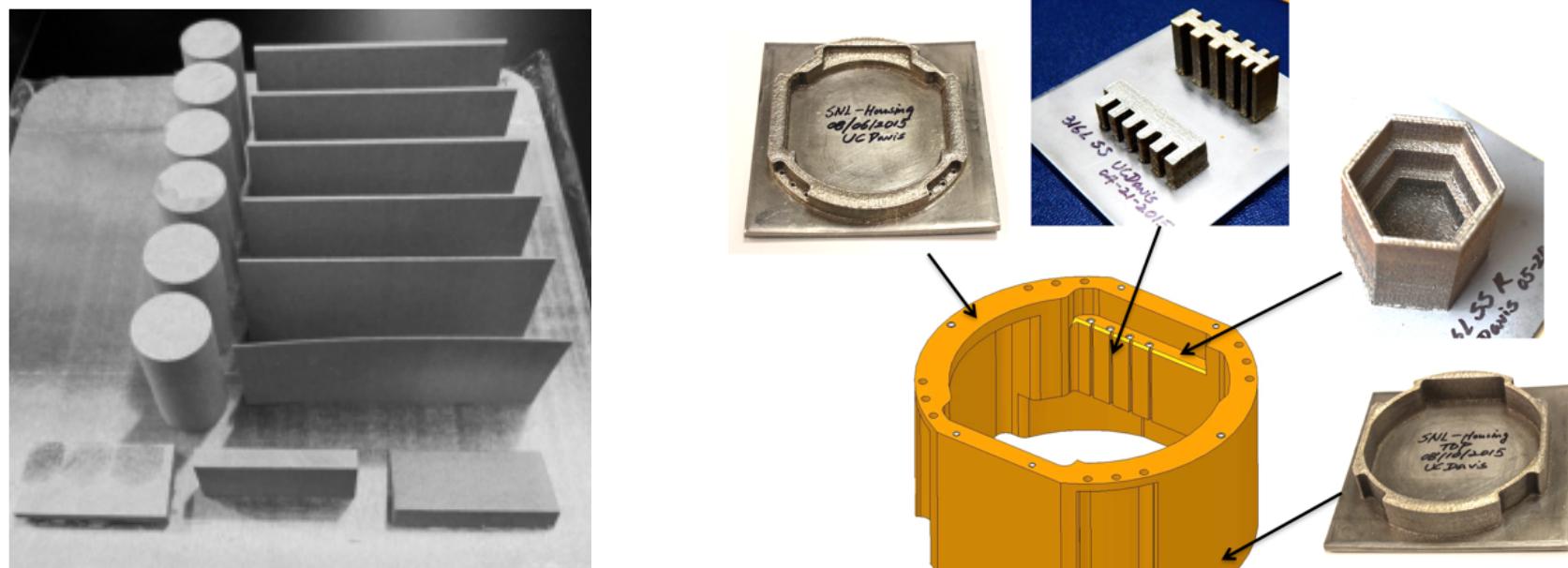
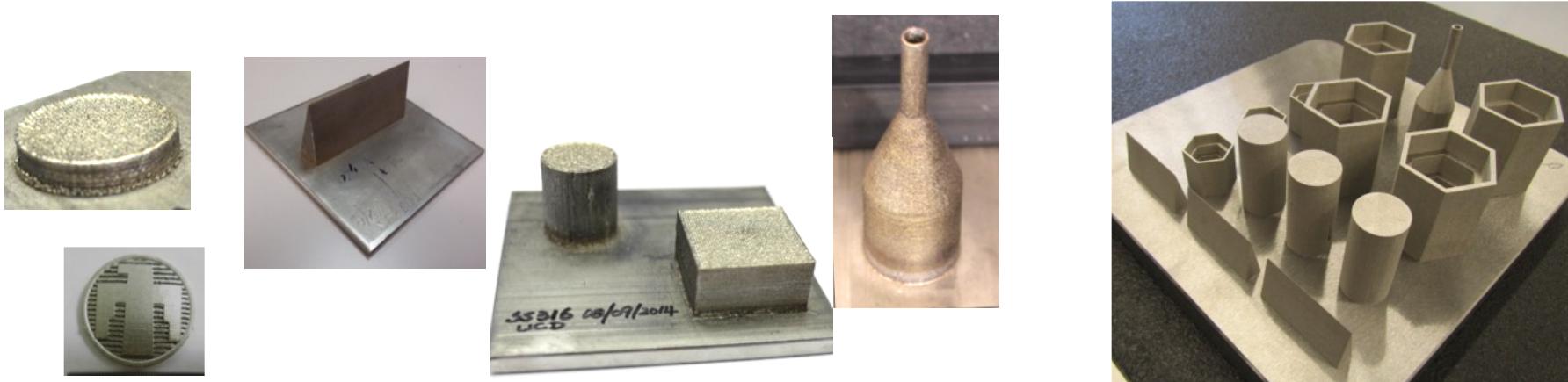


3-D LENS printing

3-D PBF printing



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

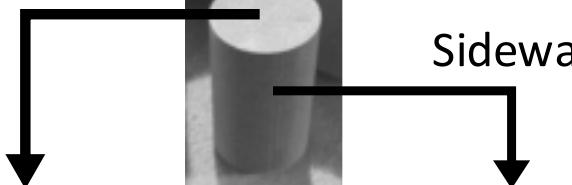


AM induced material characteristics of 316L SS

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

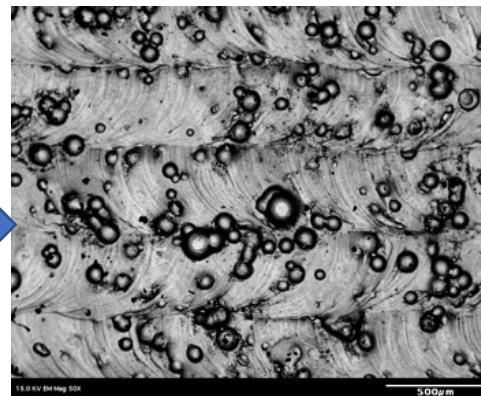
Process-induced unmelted powders are common on LENS top surface and PBF sidewall

Top surface

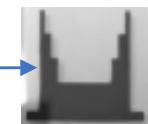
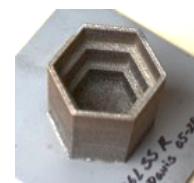


Sidewall

LENS



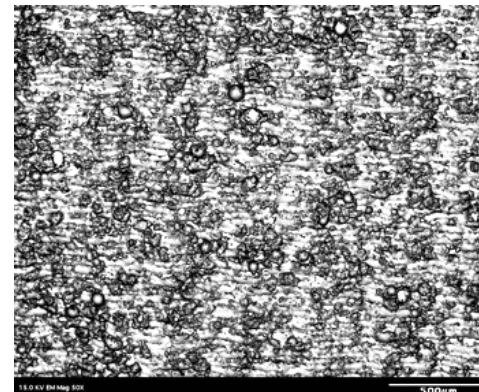
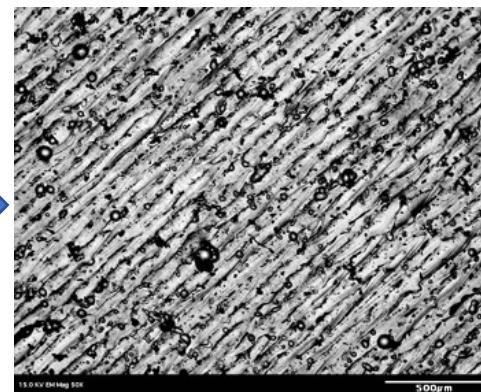
Etched cross section



1.0 mm

Unmelted
powders

PBF

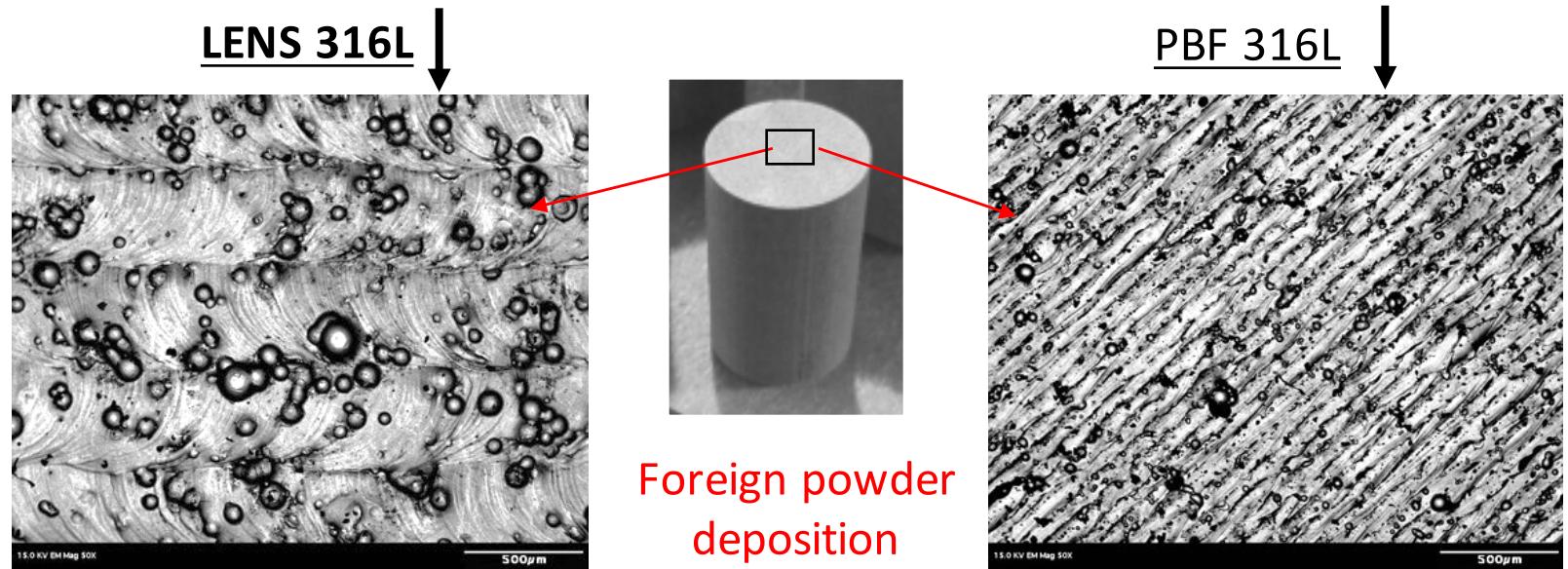


0.5mm

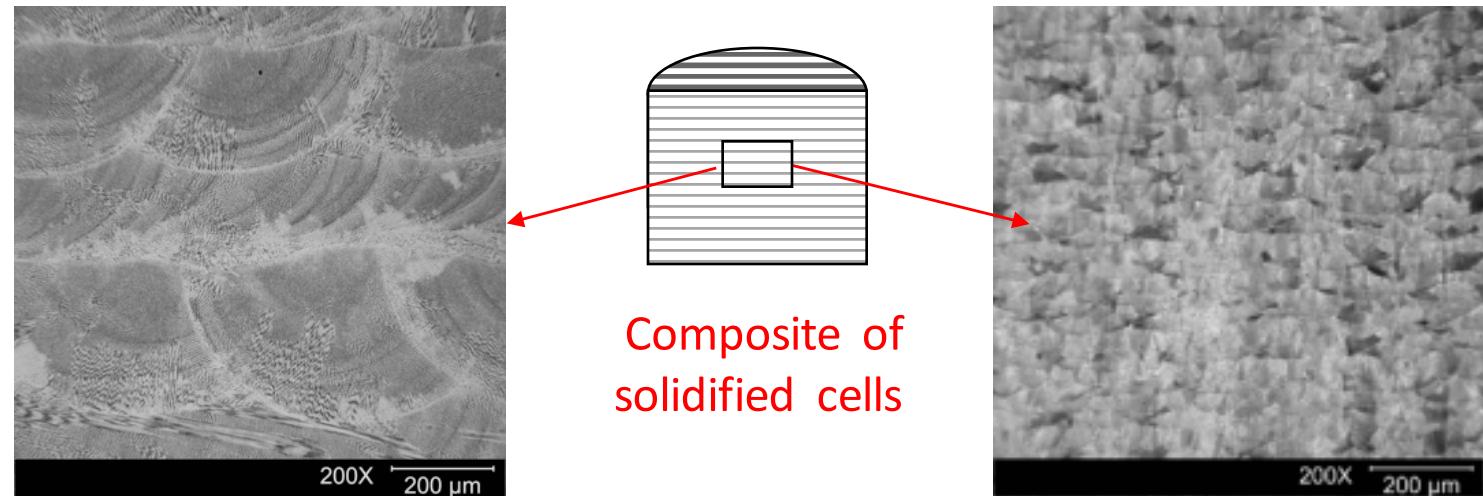
Powder-free

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

Surface morphology



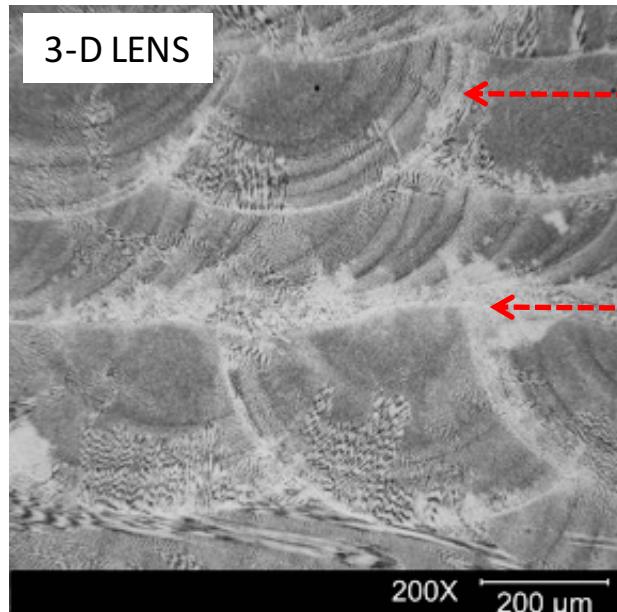
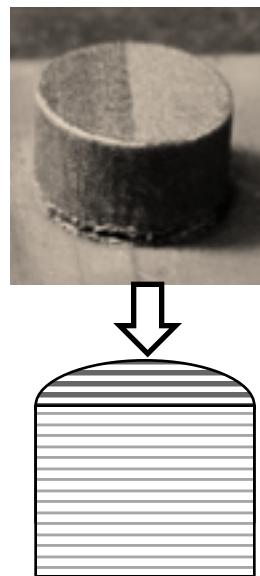
Etched cross section



Composite of solidified cells

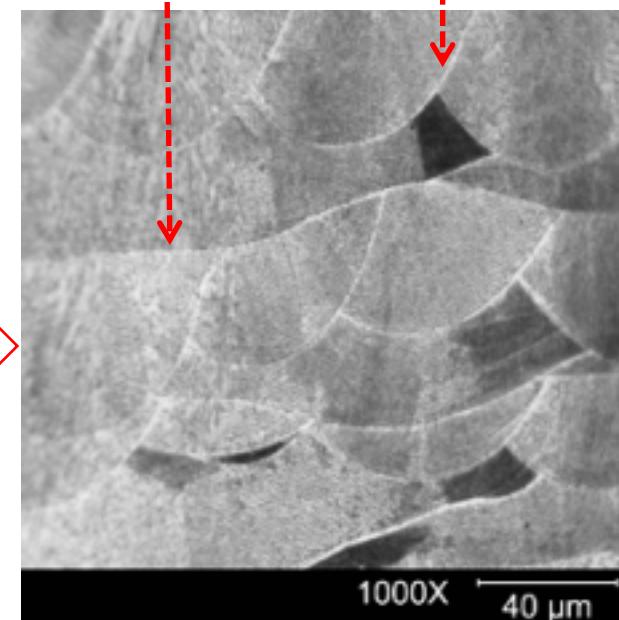
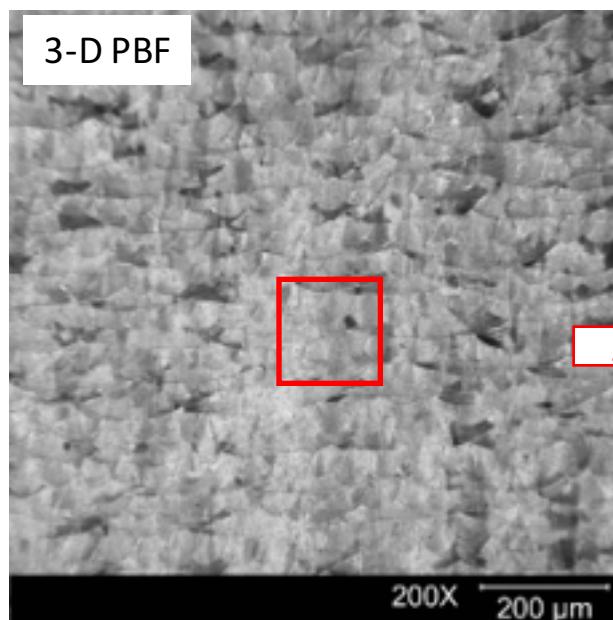
3-D-LENS- & PBF- printed 316LSS exhibit composite structure of solidified cells

Deposit Building
direction (BD)



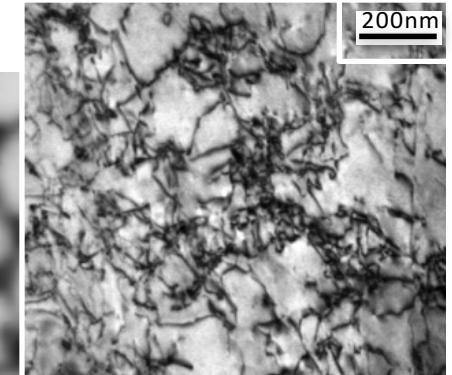
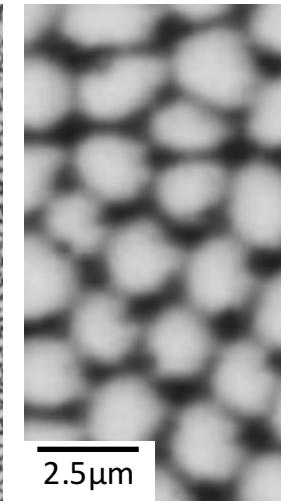
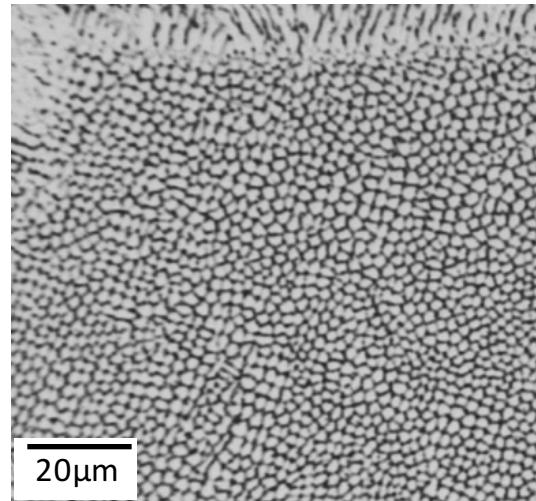
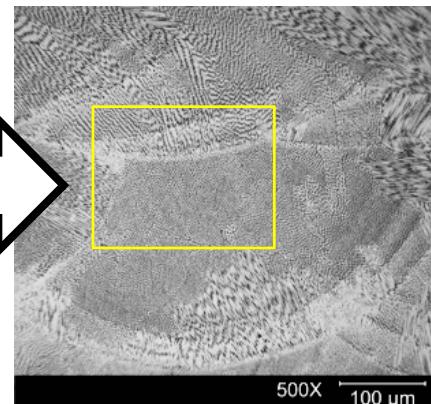
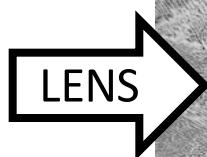
Interface of
molten metal
interpasses
(Horizontal)

Interface of
molten metal
flow trails
interface
(Vertical)

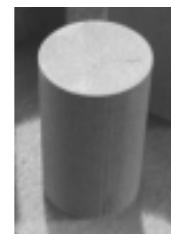


Solidification cell size is coarser and dislocation networks are much more spread in the 316L LENS- than in PBF- cylinder

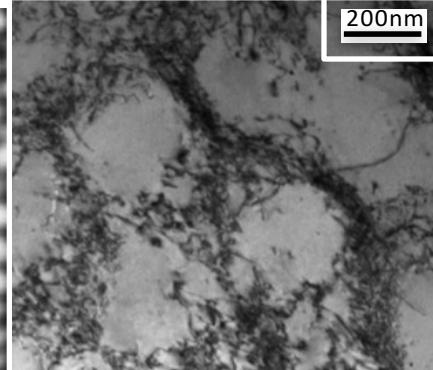
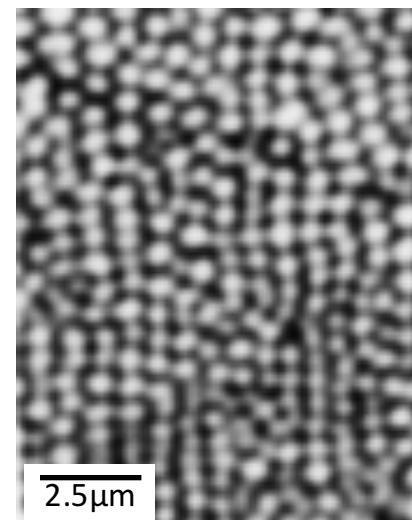
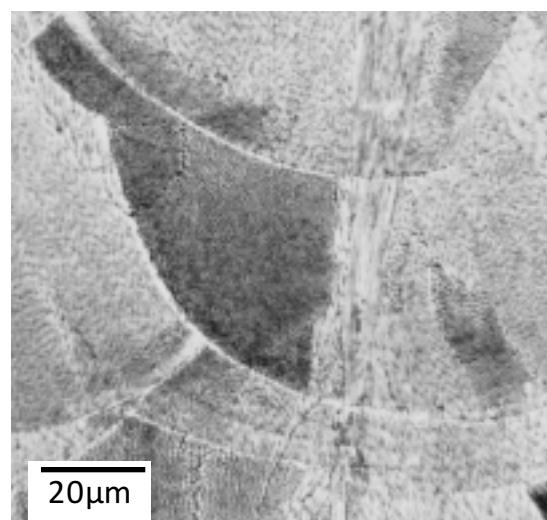
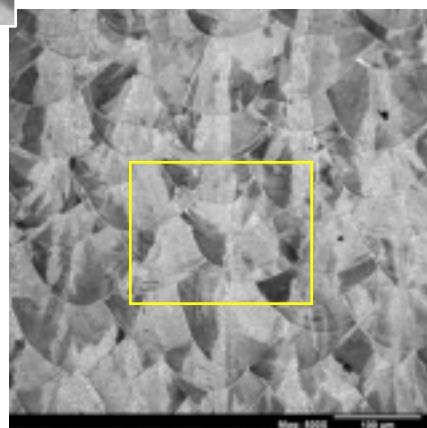
Increasing magnification →



TEM/BF



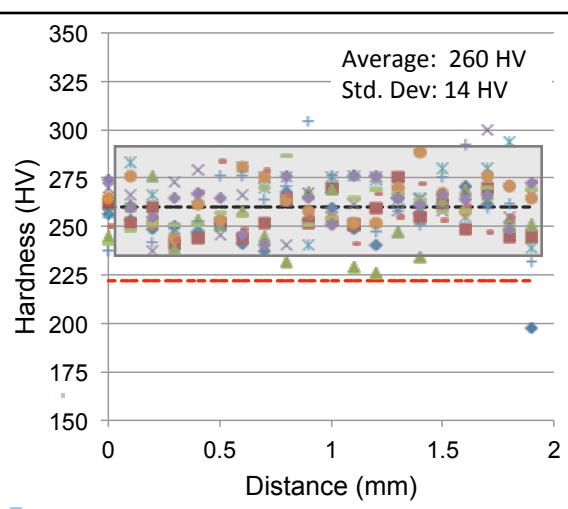
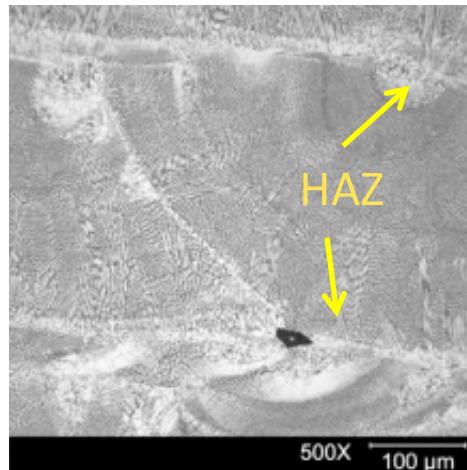
Optical images of chemical etched surface



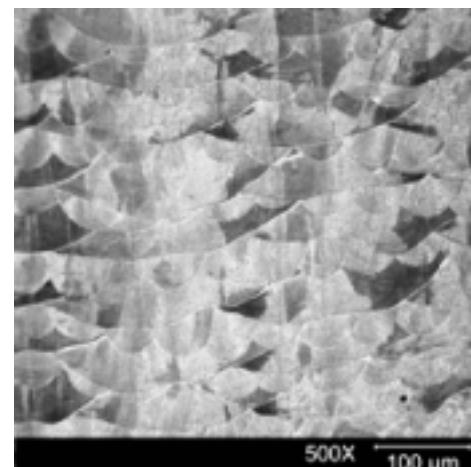
TEM/BF

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

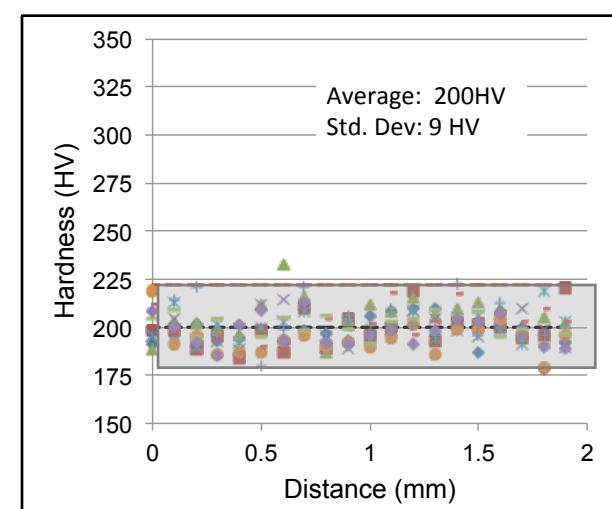
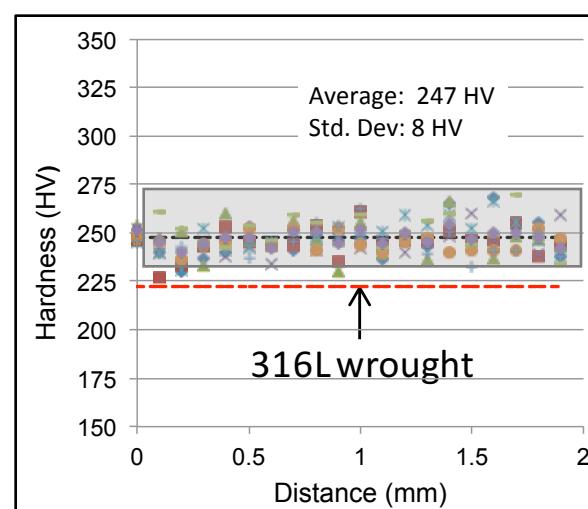
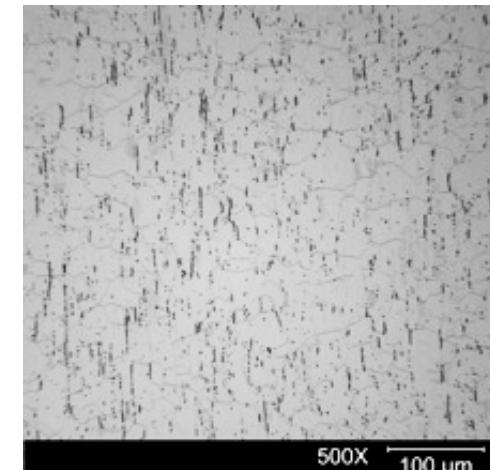
3-D LENS



3-D PBF



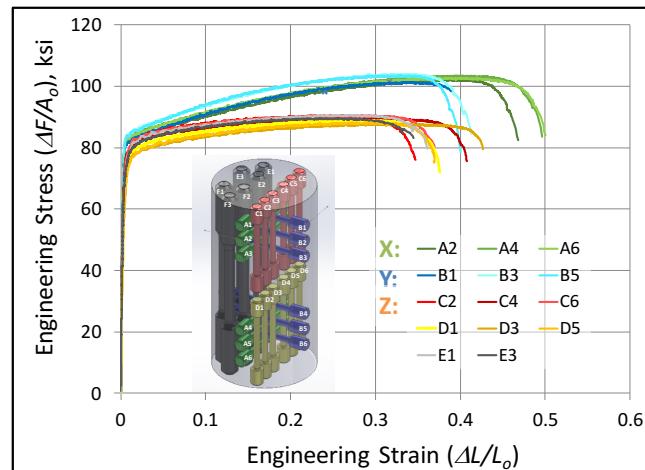
Annealed wrought 304L SS



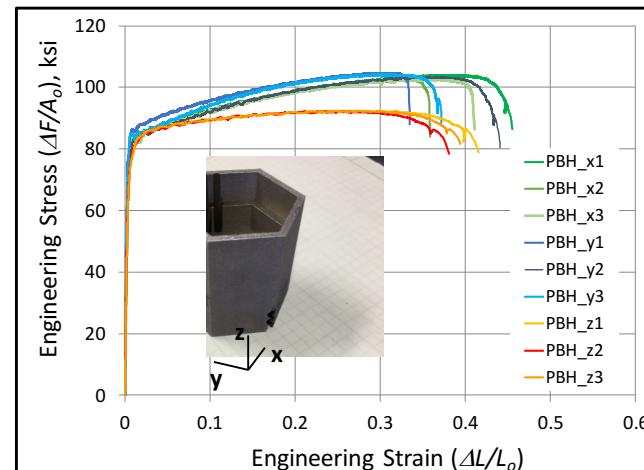
Heat-affect-zone (HAZ) at the interpasseses are responsible for the large microhardness variation seen in the LENS hexagon

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

PBF cylinder (SNL)

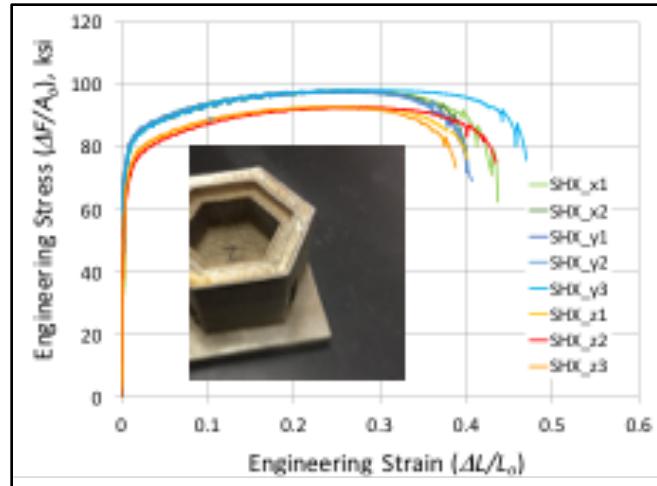


PBF hexagon (SNL)

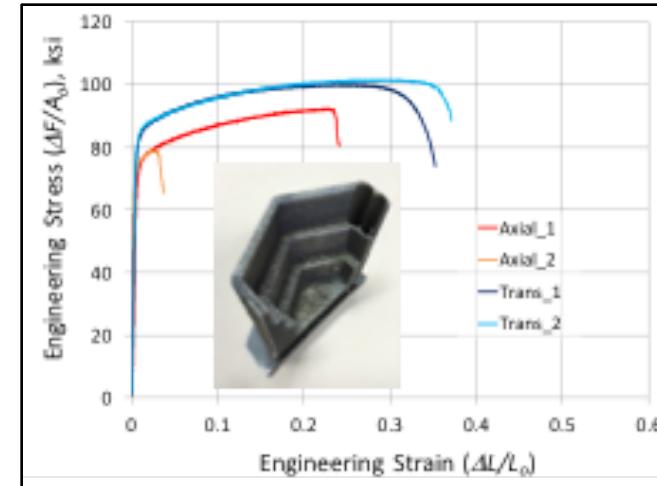


Building direction (BD)

LENS hexagon (UCI-1/2 length)

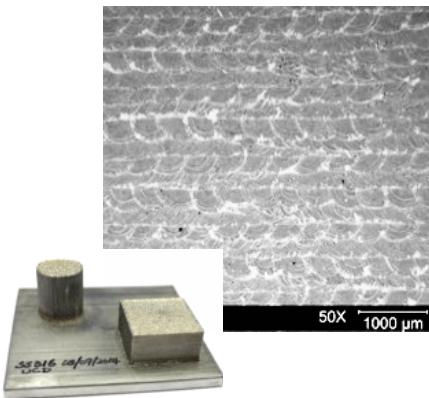


LENS hexagon (UCD)



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

Modulated solidification structure



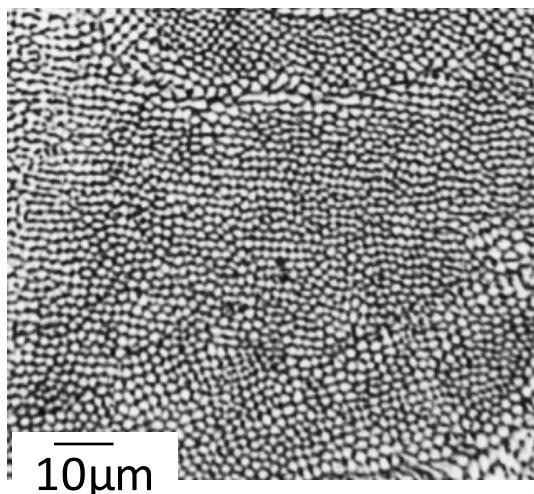
High tensile strength- x-y axis

Sample ID	YTS (ksi)	UTS (ksi)	Elongation (%)	Vickers HV
Annealed 316Lwrt	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)

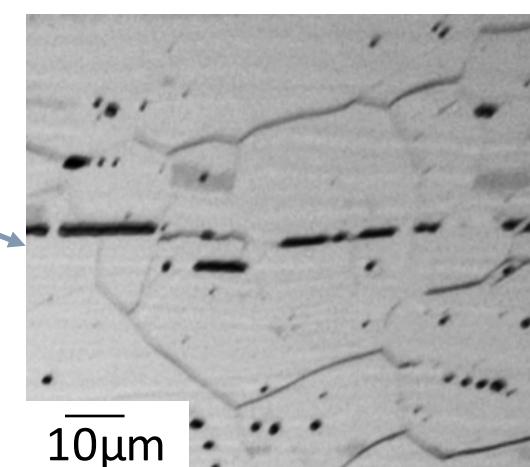
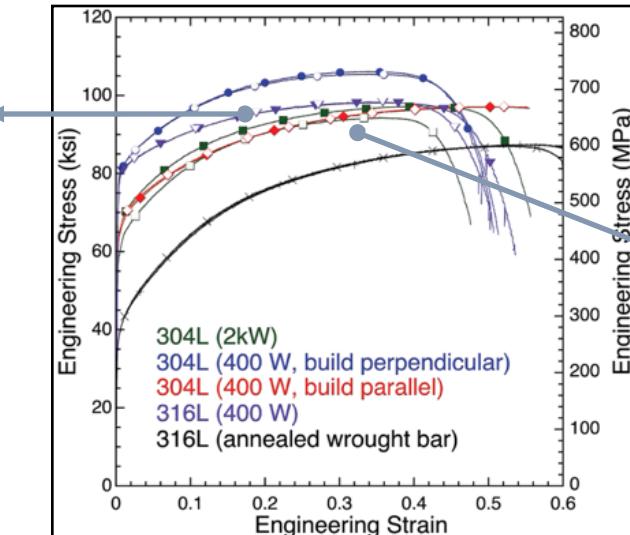
Low Ferrite:

~0.2-0.4 %, for LENS; <<02% for PBF; 1-3% for annealed wrought 304L substrate

Cellular solidified cell with fine arm spacing



Coarse-grained wrought 316L

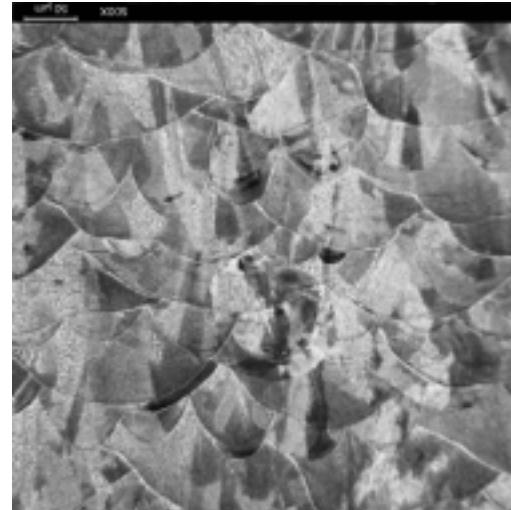
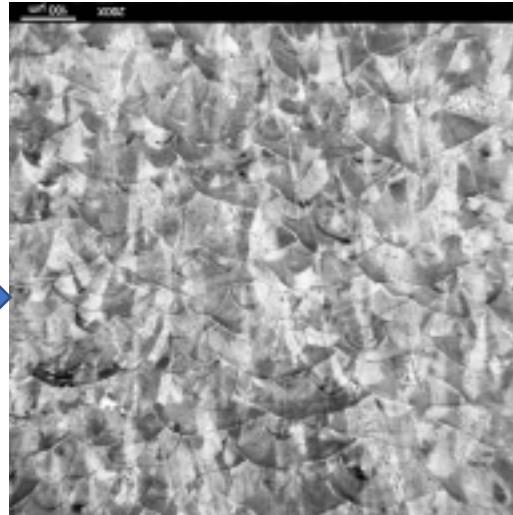


Courtesy of M. Maguire

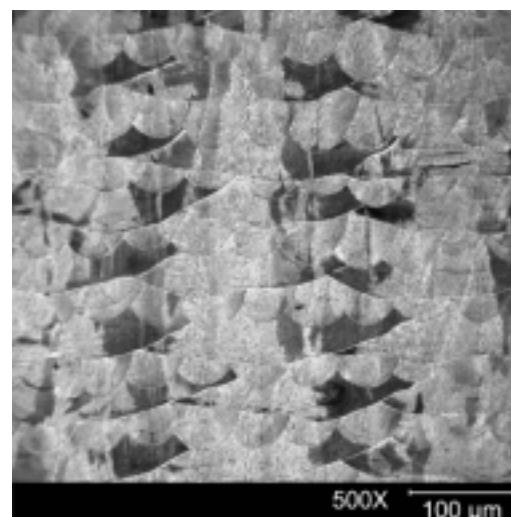
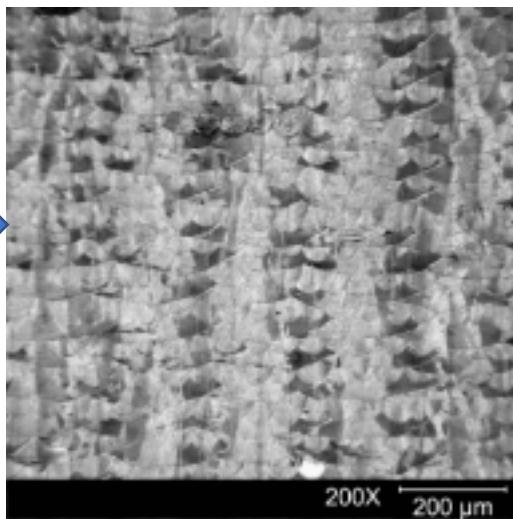
Solidification microstructure varies depending on system hardware as well as printing parameters

Nitric acid etched PBF hexagon

At SNL,CA

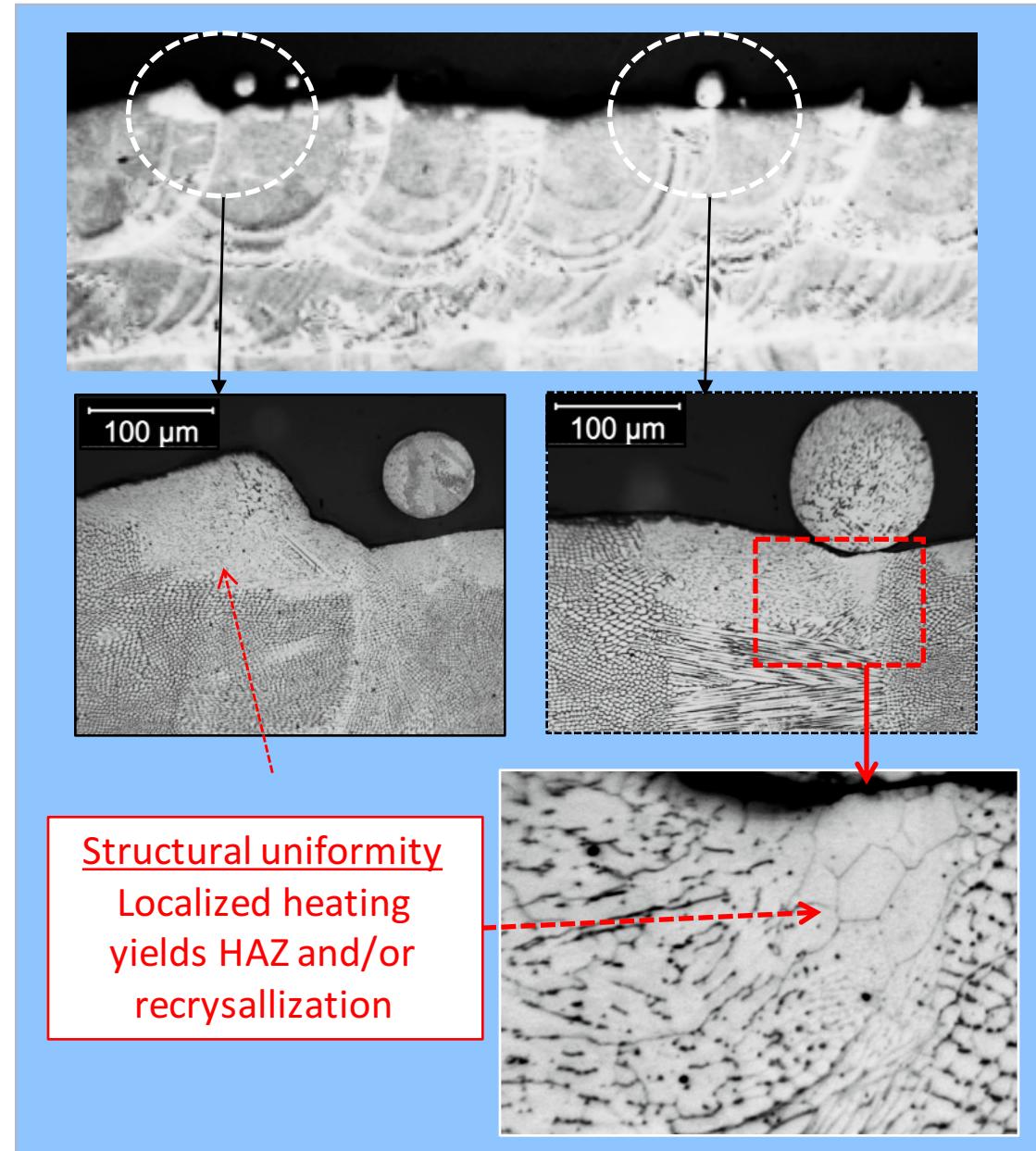
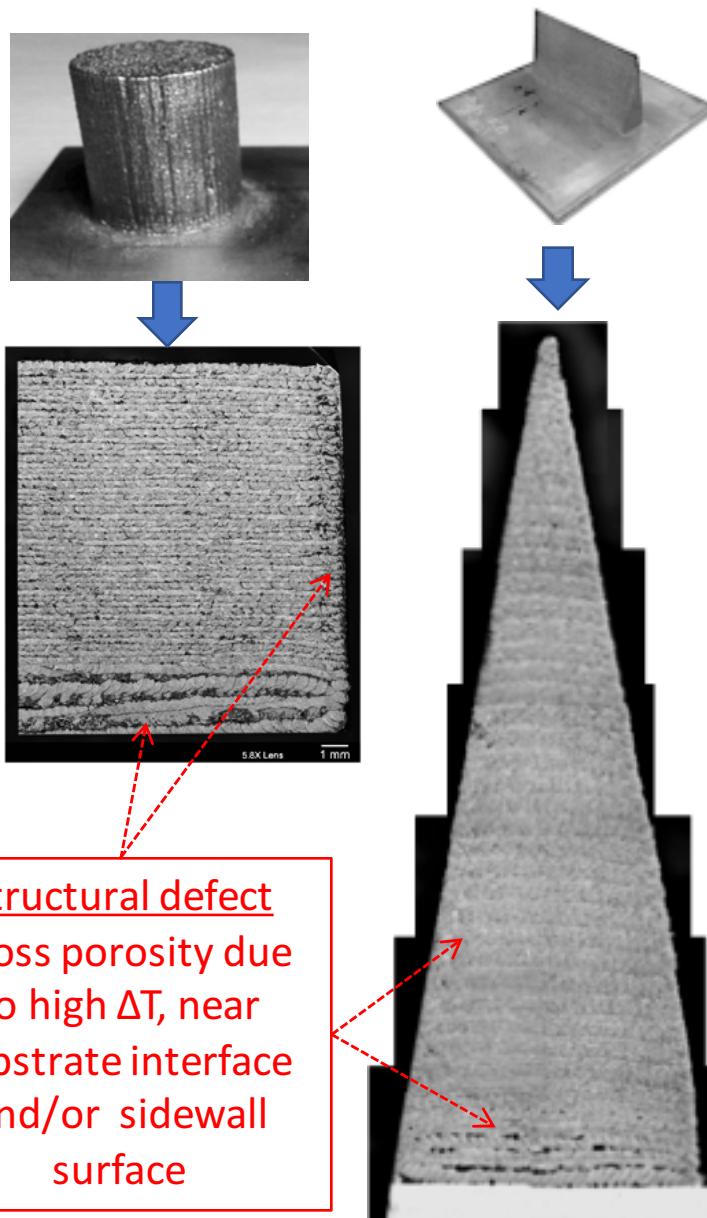


At GPI

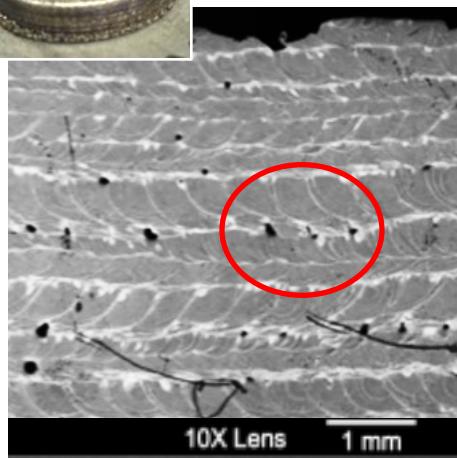


Building direction (BD) →

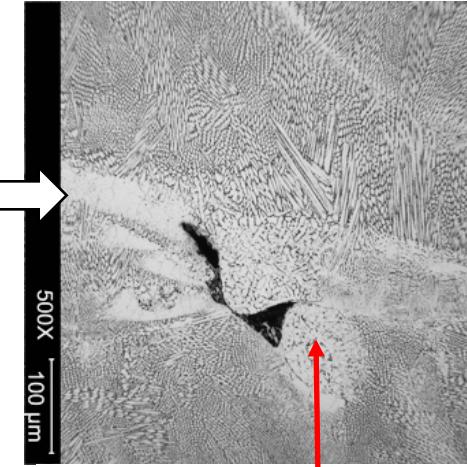
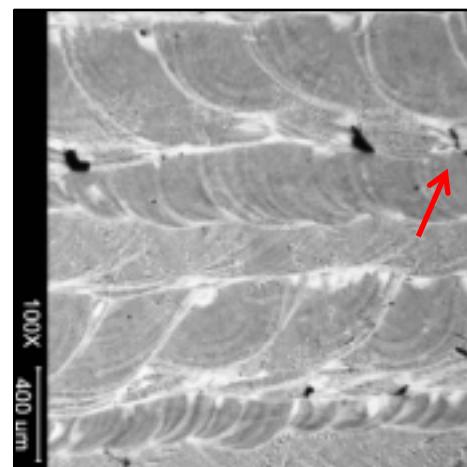
Structure uniformity and defect density in LENS prototype are the results of localized heating and/or ΔT



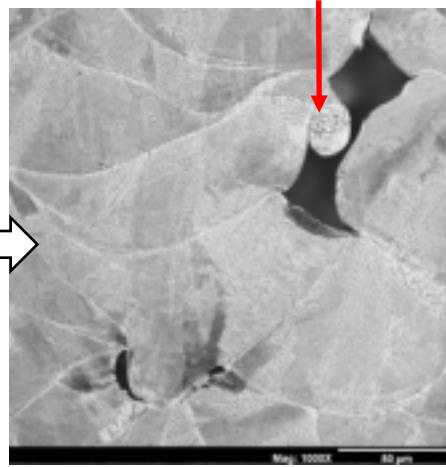
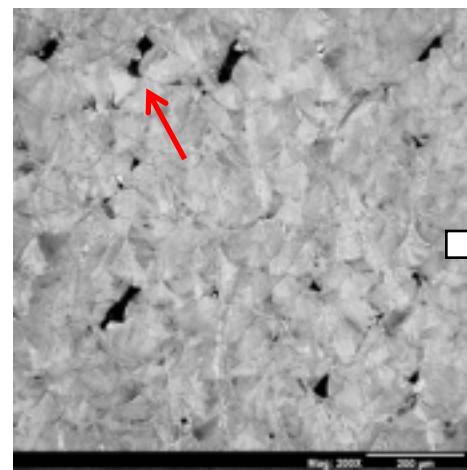
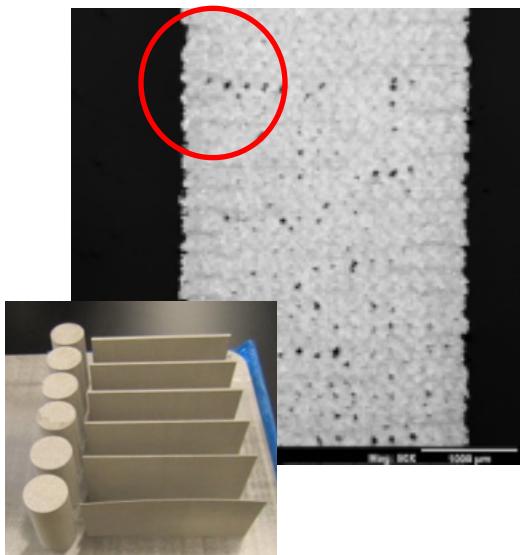
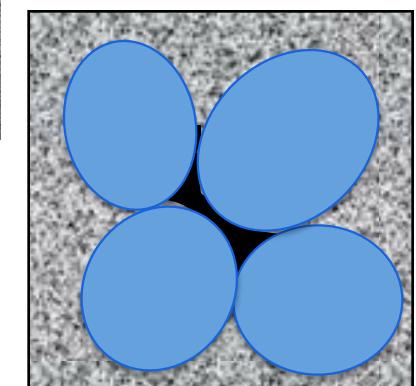
Foreign unmelted powder inclusion disrupts local metal fusion yielding adverse intrinsic structural defect



3-D LENS disc



Schematic for pore formation

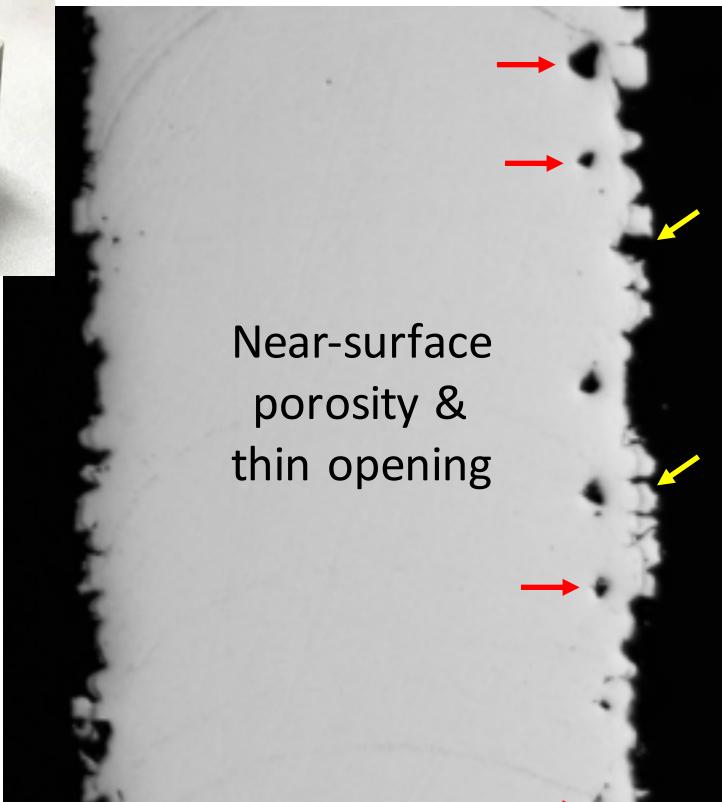


3-D PBF sheet

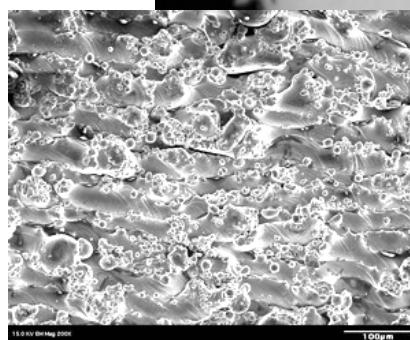
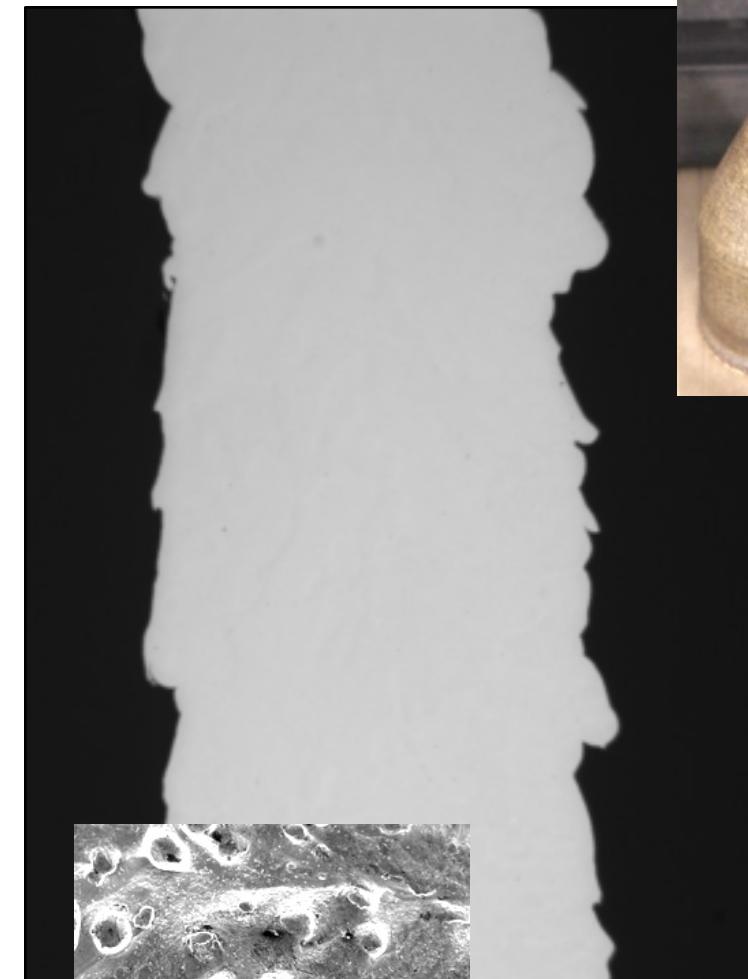
Surface/sidewall irregularities are the results of fused-on unmelted powders and/or molten metal wetting



PBF



LENS



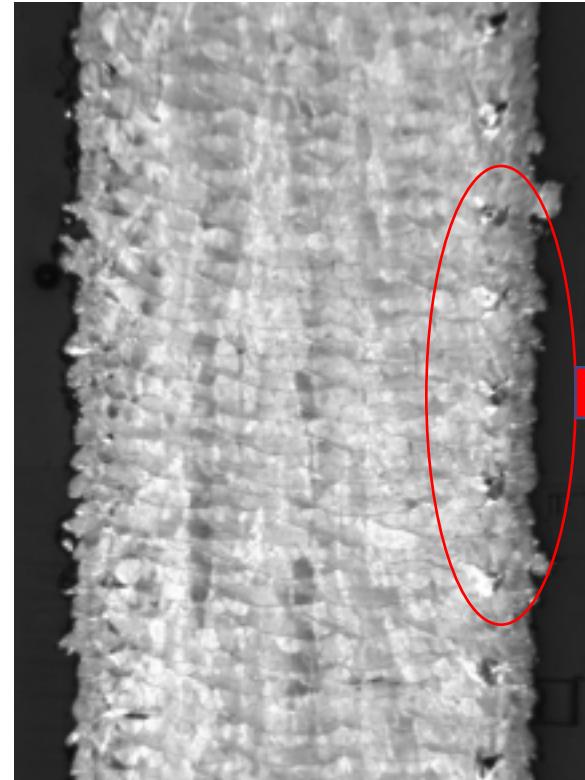
400 µm



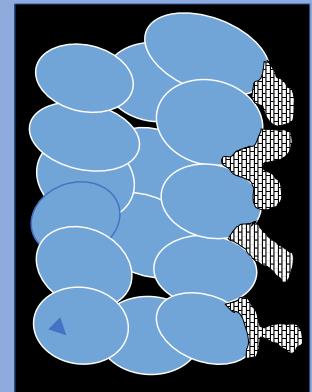
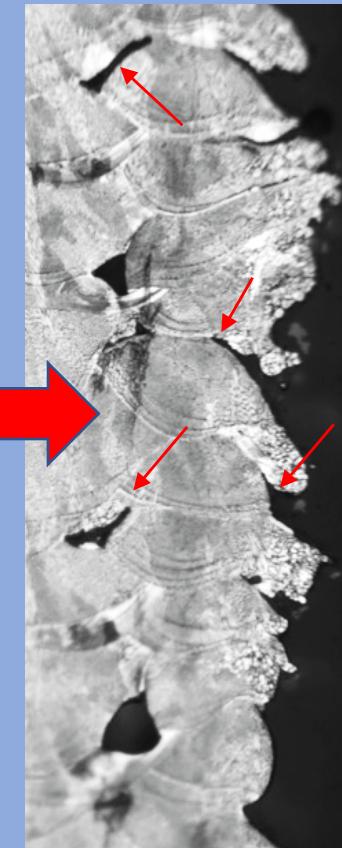
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PBF surface with fused-on powders is vulnerable to near-surface porosity and/or stress concentrated sharp openings

As-polished PBF hexagon → Chemical etched



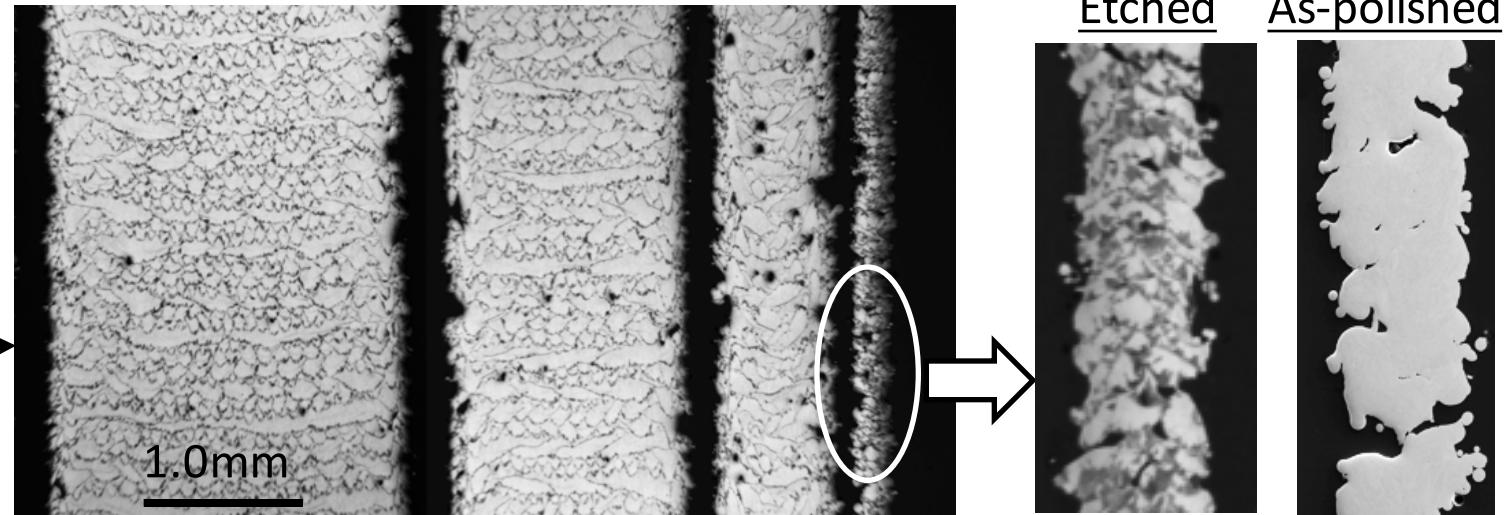
Pore formation schematic



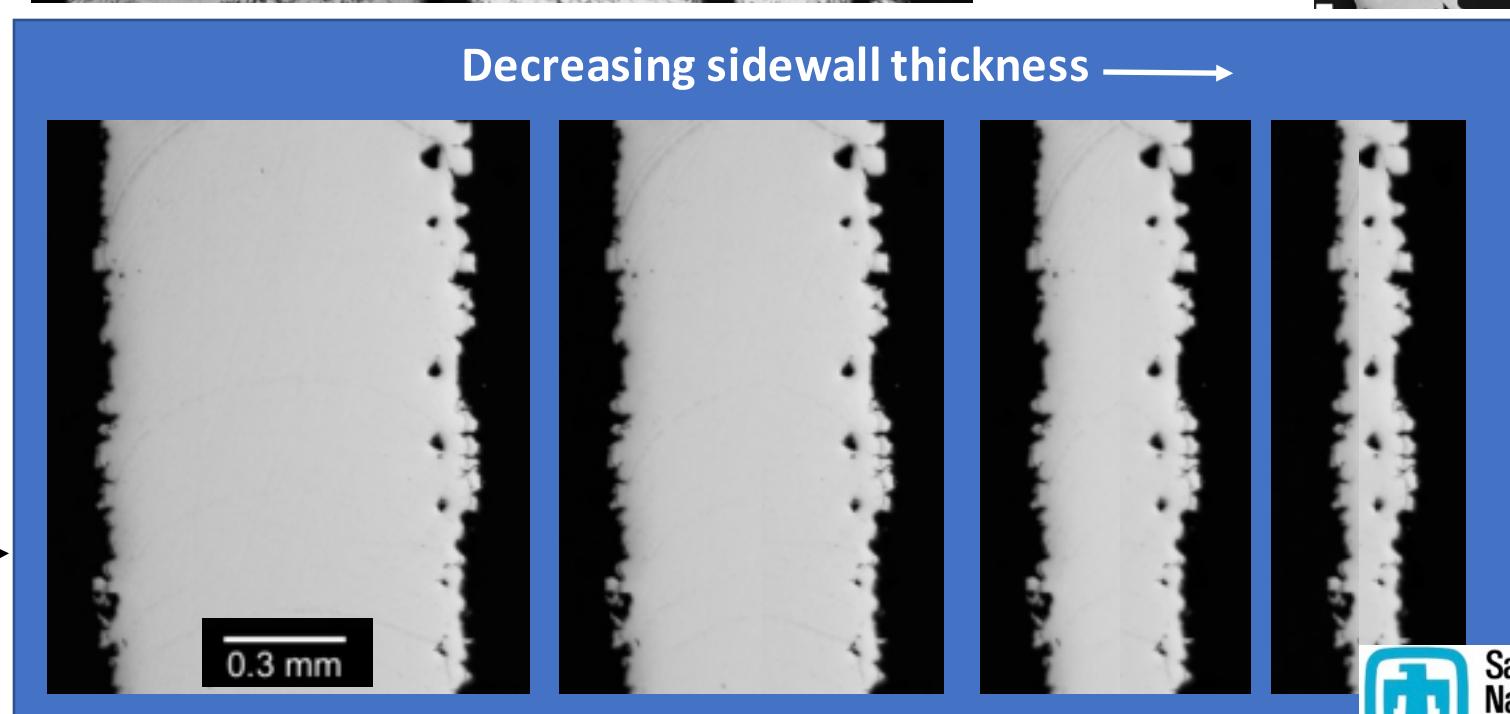
Stress concentrated opening?

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

Optical mages of the PBF printed 304L thin sheets



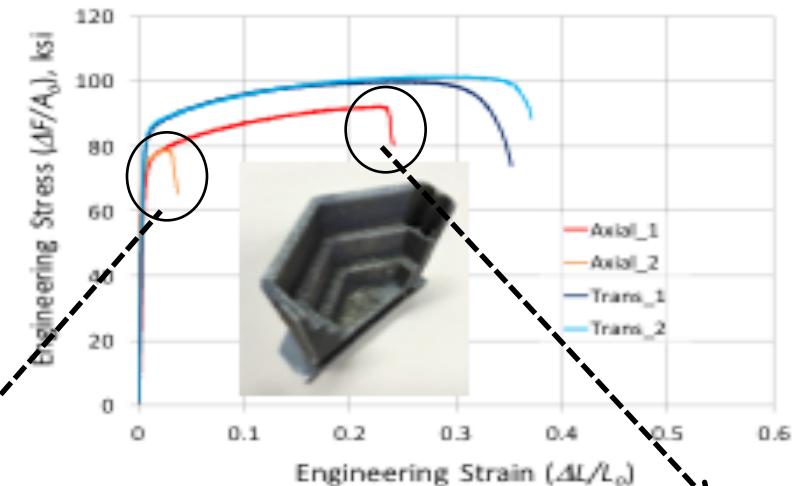
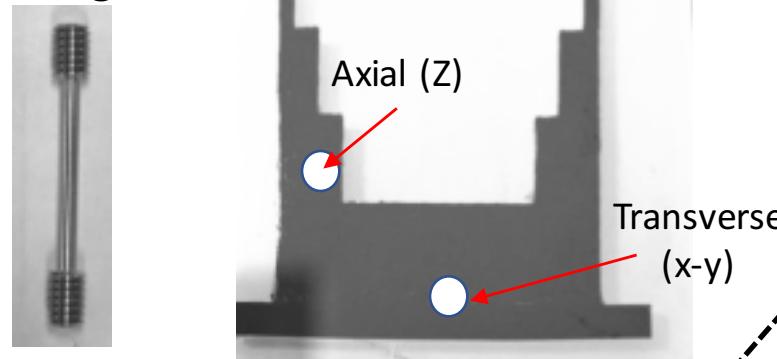
Thickness effect by optical images of the PBF printed hexagon



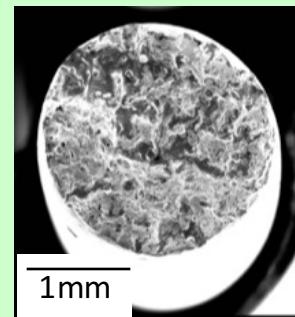
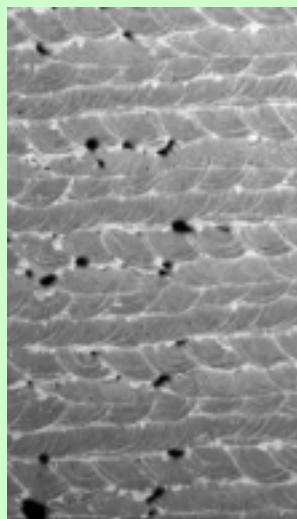
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Gross interpass defect is responsible for the low ductility along BD

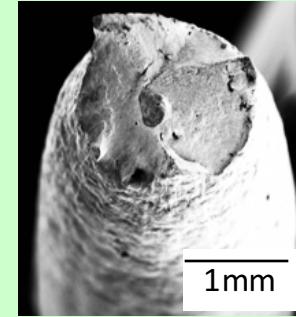
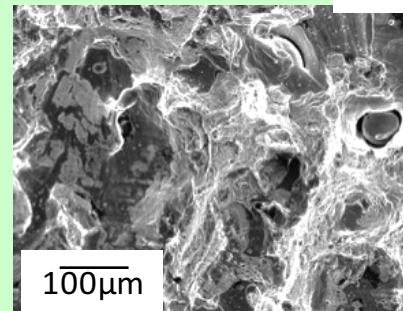
Tensile failure at mid-length



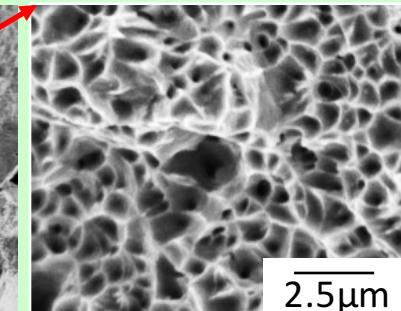
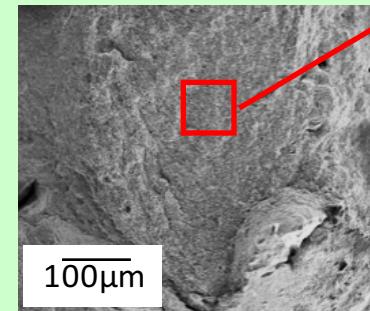
Gross porosity



Axial un-necked premature failure (//BD)



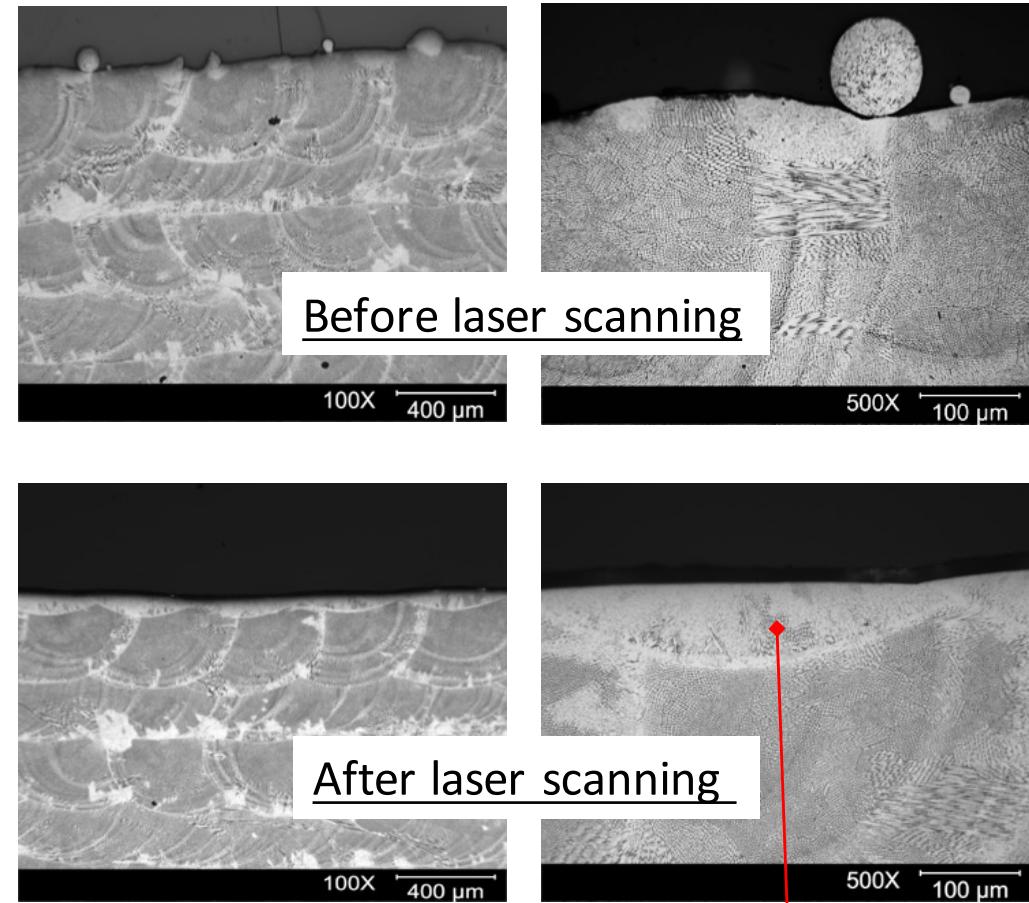
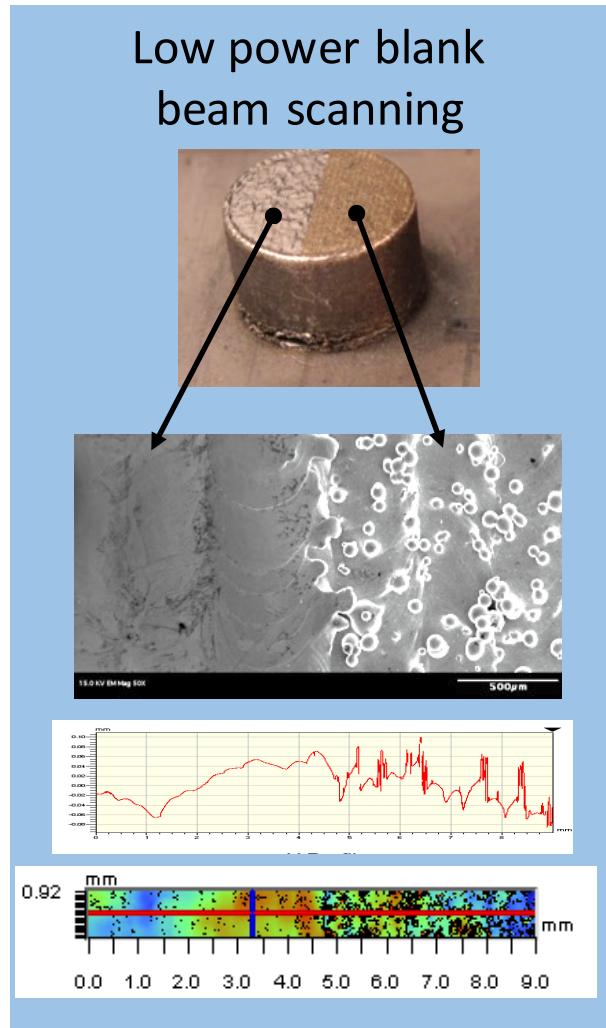
Transverse necked ductile dimple failure (⊥BD)



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Mitigation strategy:

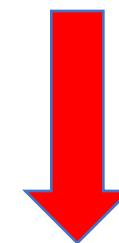
A blank laser successfully remove unmelted powders, however, yields a distinct surface remelted layer



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

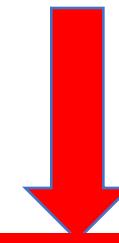
Summary

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)



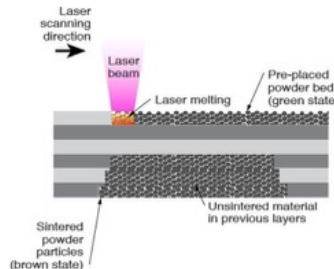
Achieve

Reliable system engineering and engineering performance

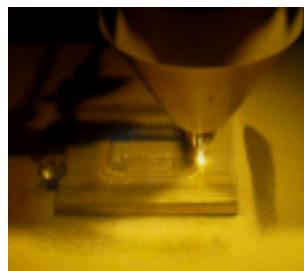
On-going science & technology maturation activities

Process & prototyping

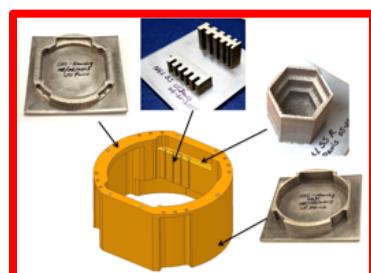
Laser-material interaction



Process optimization

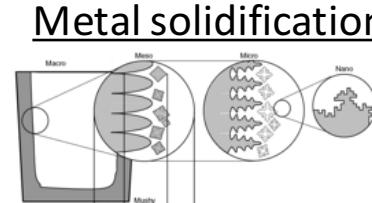


Prototyping feasibility

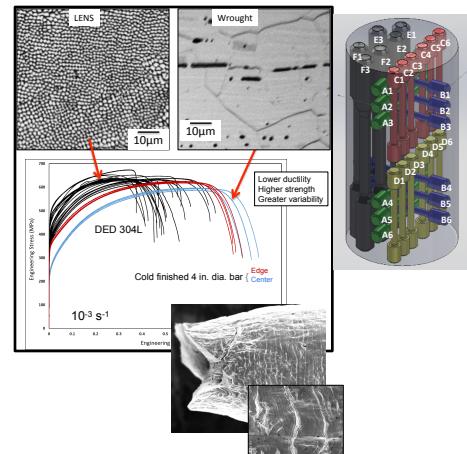


Material science

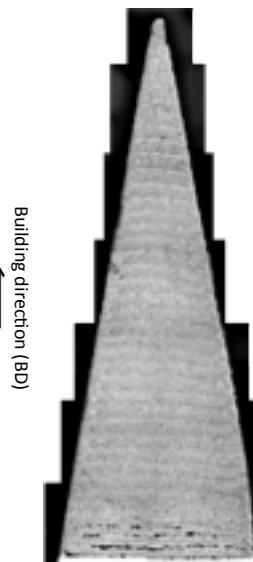
Metal solidification



Mechanical behavior

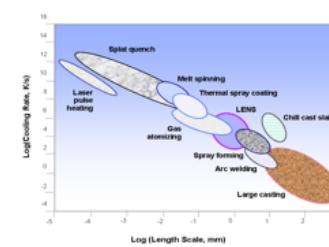


Geometry & structural defect

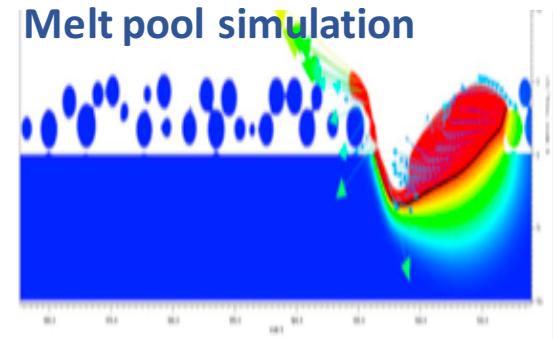


Numerical modeling

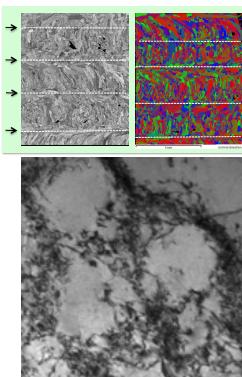
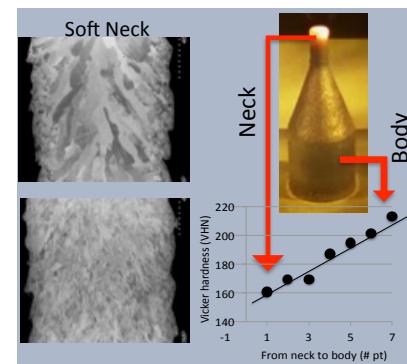
Thermal transport & Solidification cooling validation & prediction



Melt pool simulation



Thermal cooling- Microstructure-Anisotropy



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.