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Process-Structure-Property Relationship for Additive Manufacturing, 3-D LENS Printing

Nancy Y. C. Yang[1], Josh Yee[1], Kyle Gaiser[1], W. Y. Lu, Lee Clemon[1], Baolong Zheng[2], Yizhang Zhou[2], Enrique J. Lavernia[2], and Julie M. Schoenung[2]

[1] Sandia National Laboratories, Livermore, CA 94551-0969

[2] Department of Chemical Engineering and Materials Science
University of California at Irvine, Irvine, CA 95616

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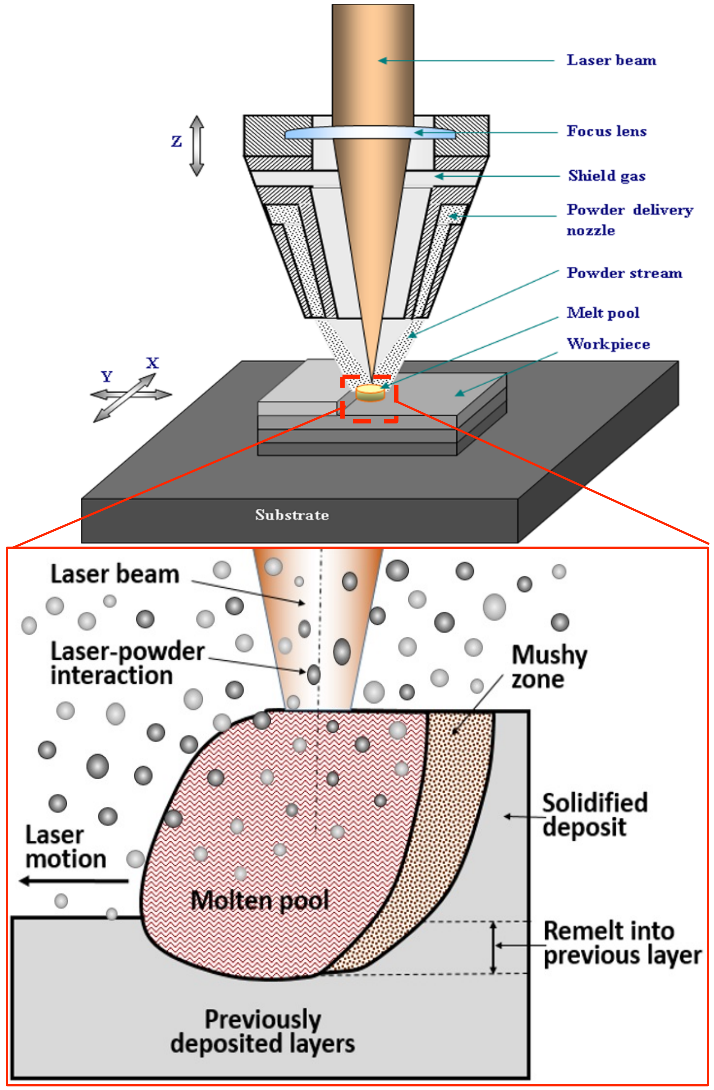
Outline

- Introduction and Programmatic Goals
- Science and Technology (S&T) undertakings
- S&T maturation for 3-D LENS Prototyping of 316L Stainless Steel
- Summary

Introduction

- The emerging additive manufacturing (AM) such as Laser-Engineering-Net-Shaping (LENS) is capable of printing a component with complex shape and dimension to its final finishing.
- The instantaneous powder melting, molten metal deposition and liquid metal solidification of LENS printing often yields the part with inconsistent properties.



Programmatic Goals

SNL's strategic AM thrust areas:

- *Compelling Applications*
- *Materials Assurance*
- *Design & Analysis Tools*
- *Multi-materials AM*
- *Product Realization*

Current Focus

Science & Technology (S&T) maturation
(UC Irvine collaboration)

Enable

AM materials assurance for component engineering

Science and Technology (S&T) Undertakings

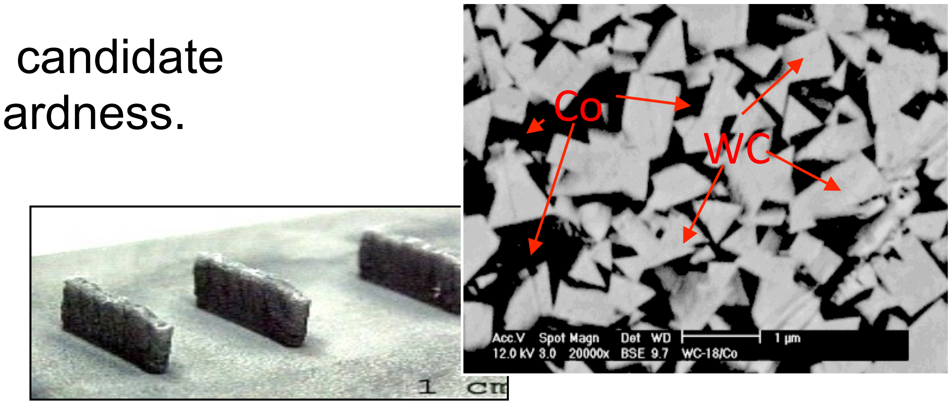
- Al/Al_3Ni low density composite foam
- WC+Co cermet wear resistant composite
- S&T maturation and prototyping of 316L stainless steel for SNL's missions application

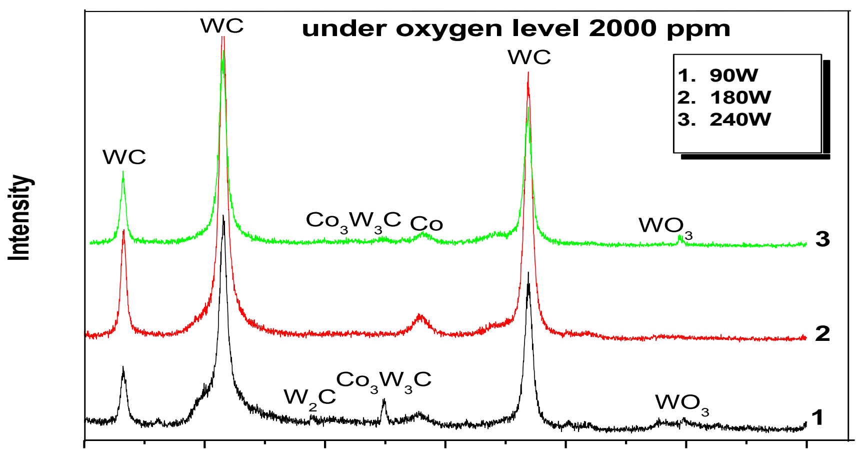
Today's discussion

Developed Thermally Stable WC+Co Cermet

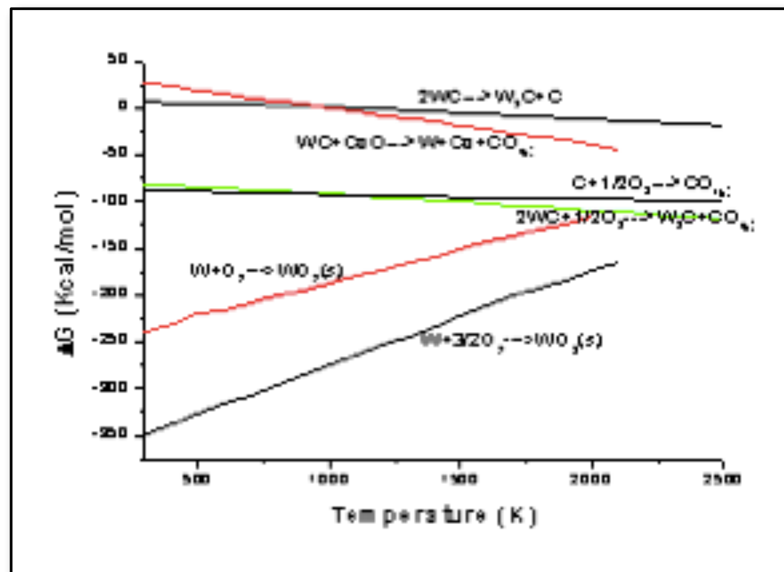
Tungsten carbide (WC) is a well-known candidate for wear resistant for its exceptional hardness.

- Fabricating 3-D LENS parts with WC-Co composites using LENS;
- Understand thermal stability of WC particles during LENS printing;
- Preventing WC decomposition from rapid solidification rate and low oxygen environment during processing.



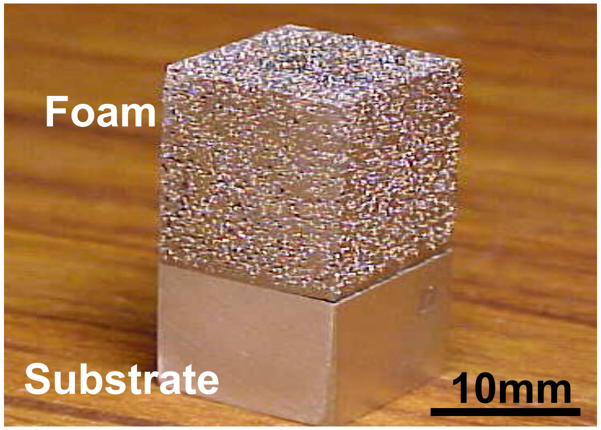


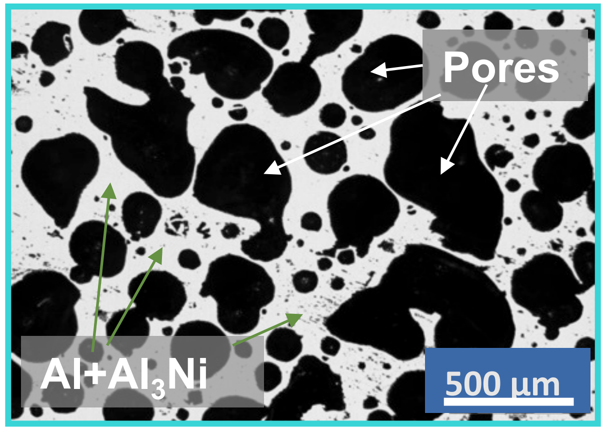
Possible reactions of W-CO-C system.

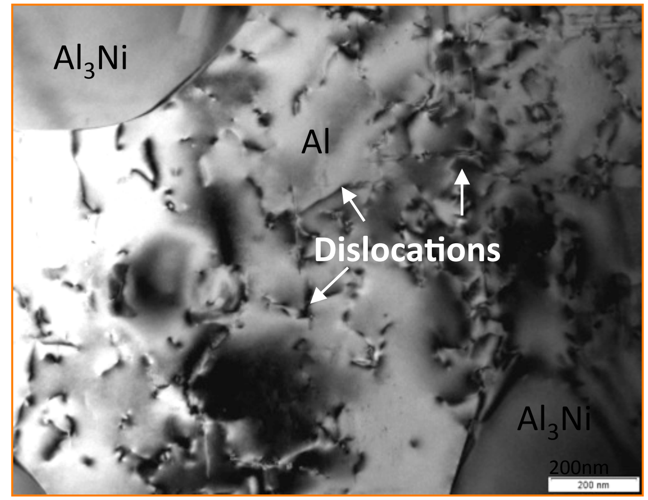


[Xiong, Schoenung, et al., Mater. Sci. and Eng. A, 2008]

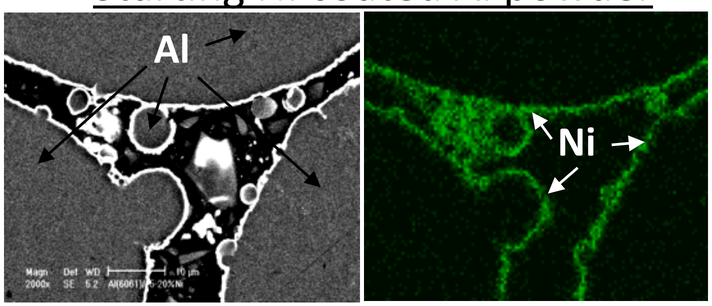
LENS Printing for Hybrid Al/Al_3Ni Foams

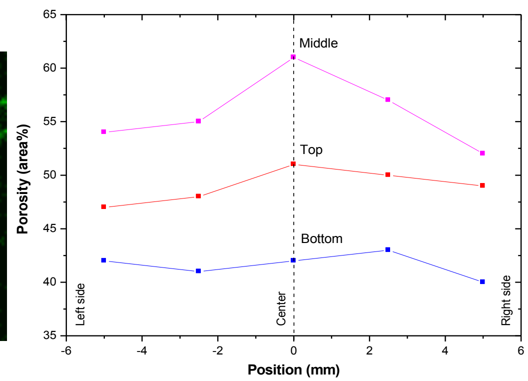


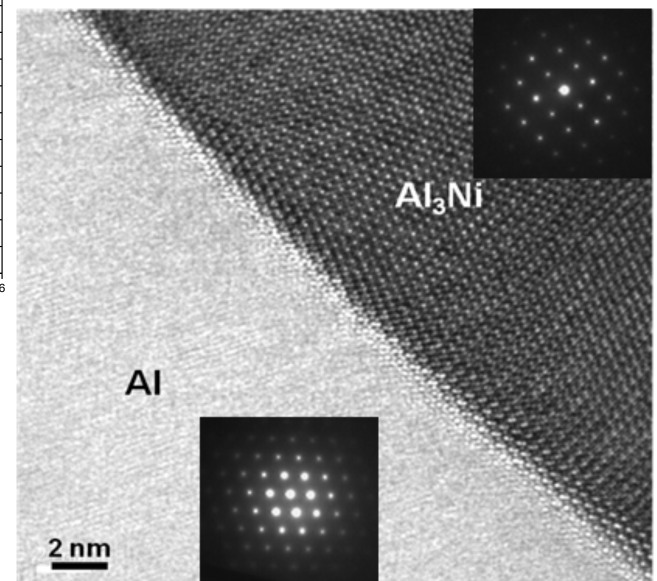




Starting Ni coated Al powder







- The Al/Ni coating reaction yields high porosity, > 60 vol. % and low density, 2.0 g/cm^3.
- The deposited hybrid $Al+Al_3Ni$ foams possess higher strength, attributed to uniformly dispersed Al_3Ni intermetallic in Al matrix,

[Zheng, Lavernia, et al., Philosophical Magazine, 2011]

S&T Maturation for 316L 3-D LENS Prototyping

Manufacture processing
(Development & control)

Materials
(Structure & properties)

Numerical simulation
(prediction and validation)

To establish

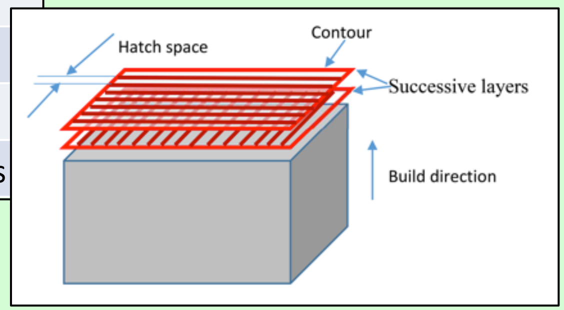
Focus

- Process-structure-property relationship
- Dimension/shape limitation and precision
- Material property control and tailoring

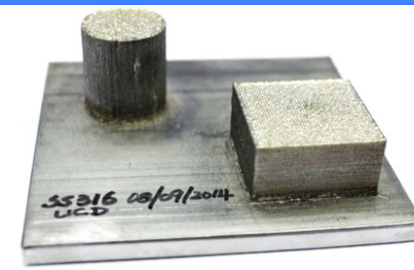
Initial Production of 316L Prints for On-going S&T Maturation Efforts

Weld/traverse velocity (mm/s)	16.92
Input power (W)	360
Input Beam Spot Size (mm)	0.6
Base temperature (°C)	25
Plate thickness (mm)	6.35
Material	316 Stainless

Initial printing parameters & printing hatch selected



(I) Inch-size bulk materials



1” Dia/ (square) X 2” height

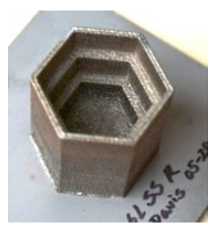
(II) Sub-inch thin part designs

Thin film coating

½” dia. X 0.16” thick

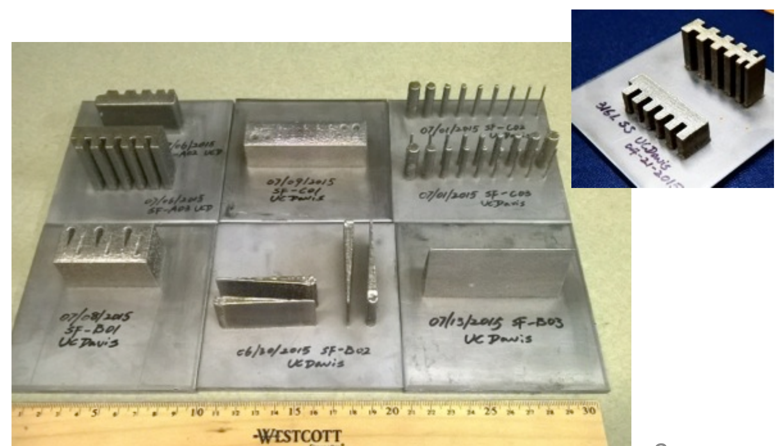
Thin wall funnel & multi-tier hexagon

0.04” wide X 2” height



1” wide X 2” height

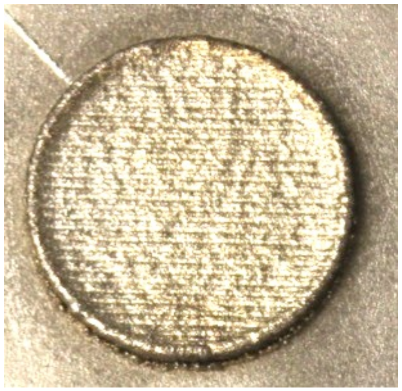
(III) Prints with shape and dimension gradient

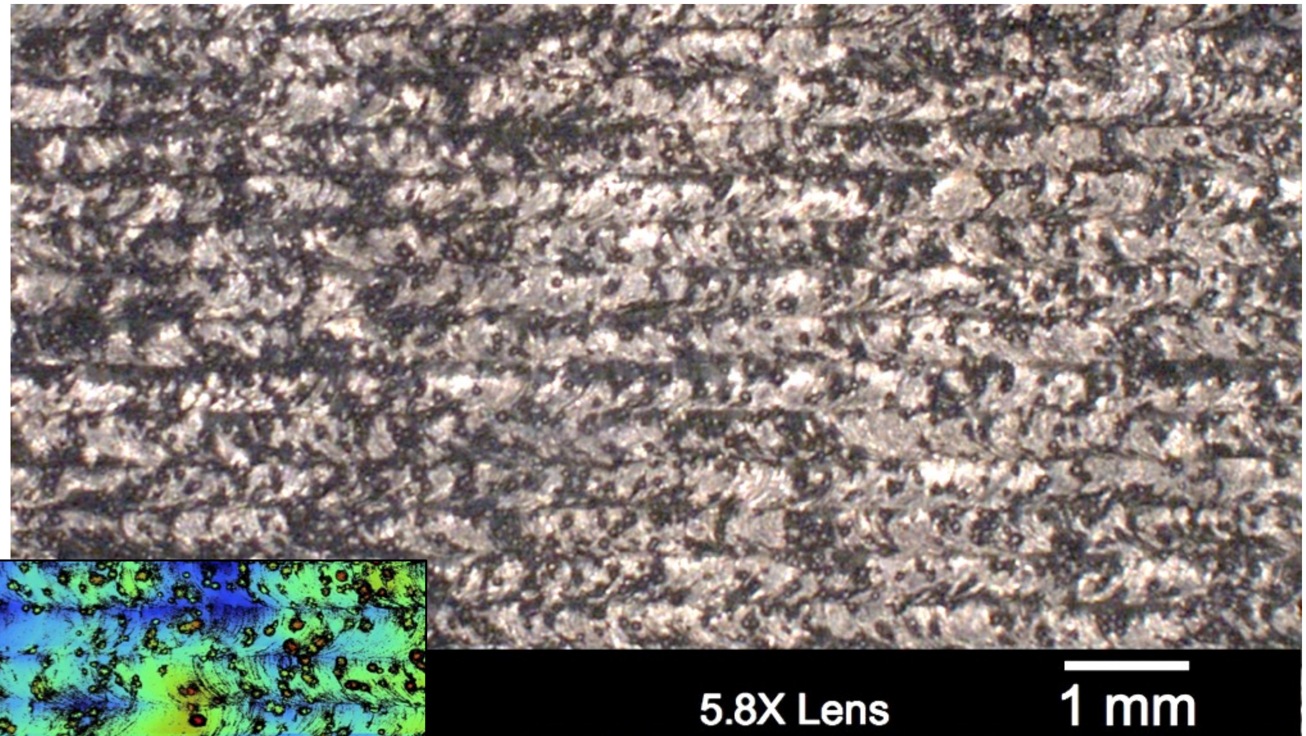


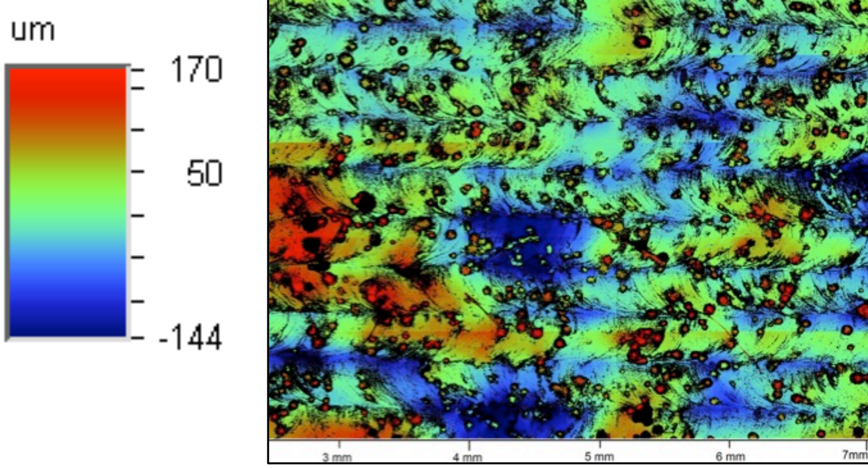
3-D LENS-induced Physical Metallurgy

- Surface topography
- Microstructure
- Process-induced structure defects
- Mechanical properties

Modulated Surface Contour Induced by the 3-D Multi-pass LENS Printing

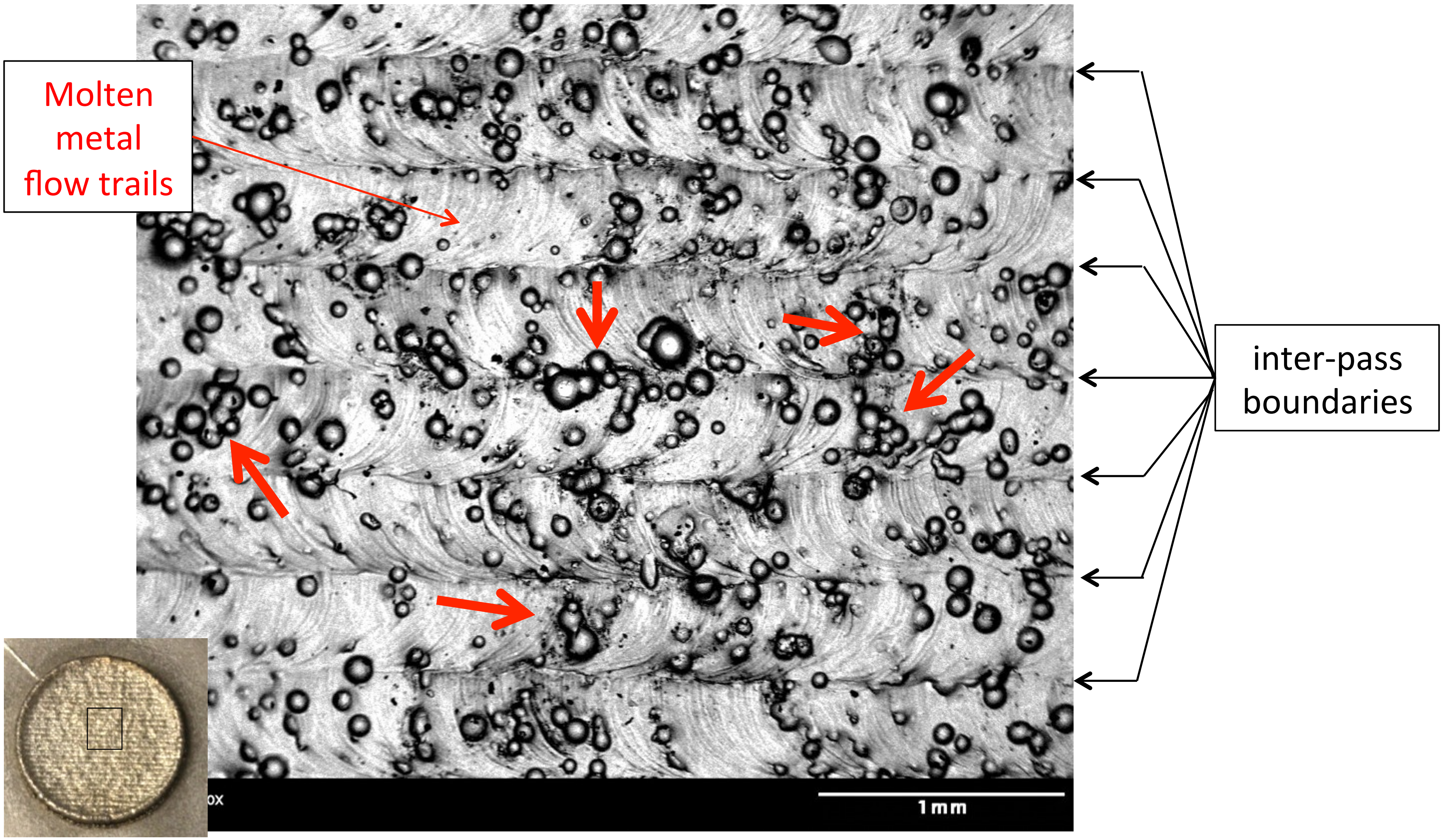






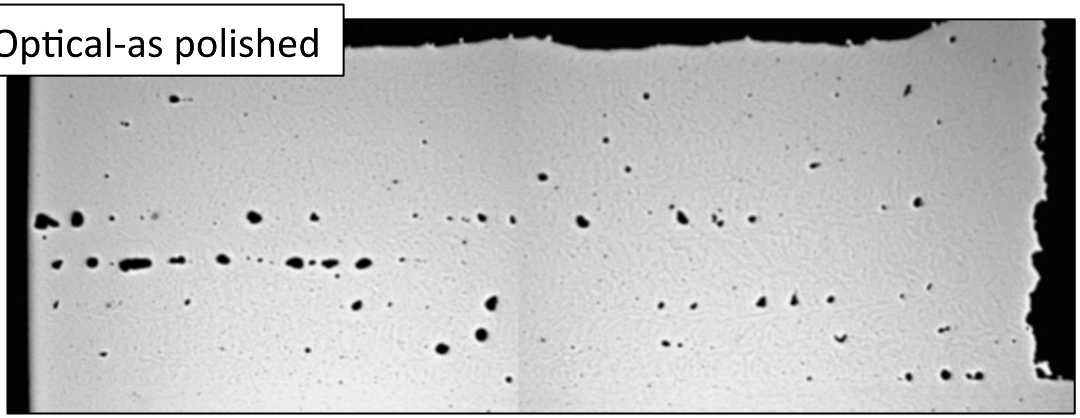
Average peak to valley is ~300µm which is rougher than mechanical machined finishing, ≤100µm.

Unmelted Powders Fused on Print Surface, Along Metal Flow Trails and/or Inter-pass Boundaries

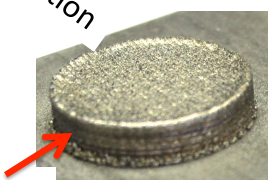


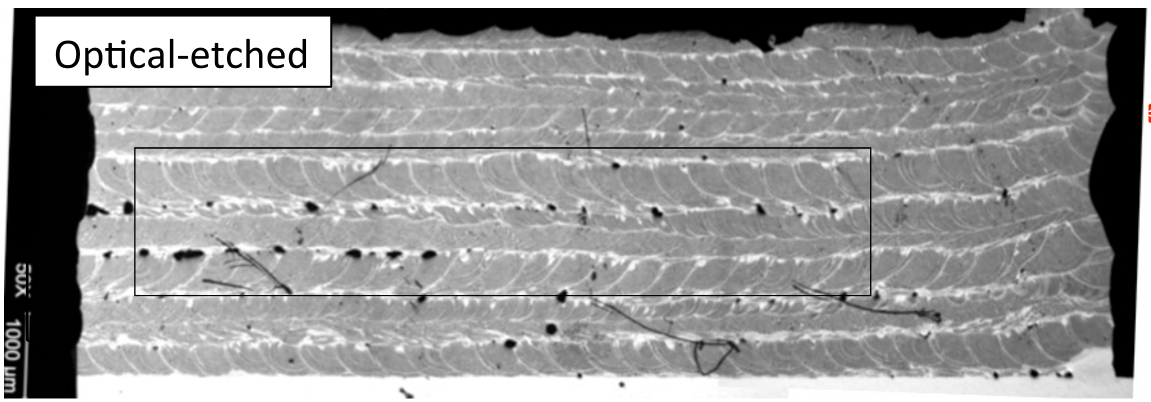
The fused unmelted powder stringers are indicated by the thick arrows

Complementary Optical/SEM Images Show Three Major 3-D LENS Induced Microstructure Features



Large pore stringers along the printing direction (PD).

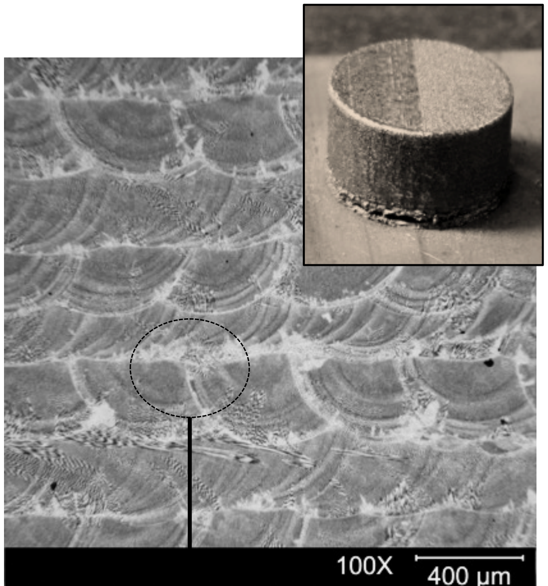




Light contrasted interpass boundaries and curved metal flow trails.

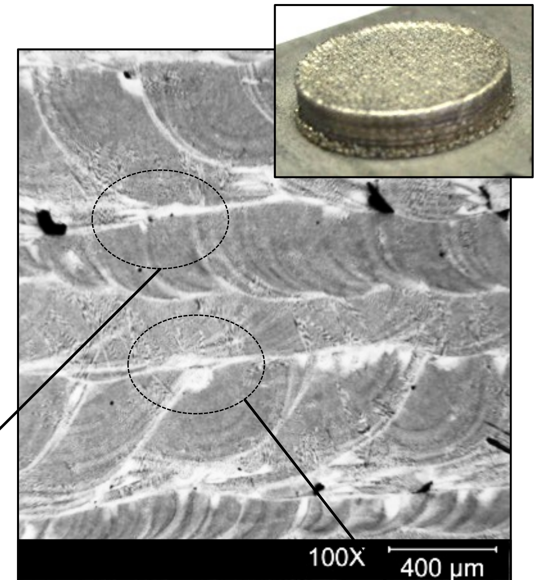
Alternating layer of high aspect ratio curved solidification dendrite cells

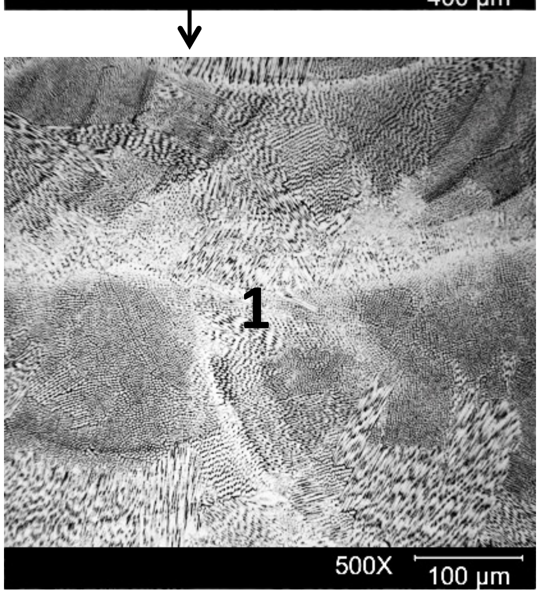
The Light Contrasted Boundaries are the Well-Fused Heat-Affect-Zone (HAZ), Derived from Metal Reheating During Successive Printing Layers

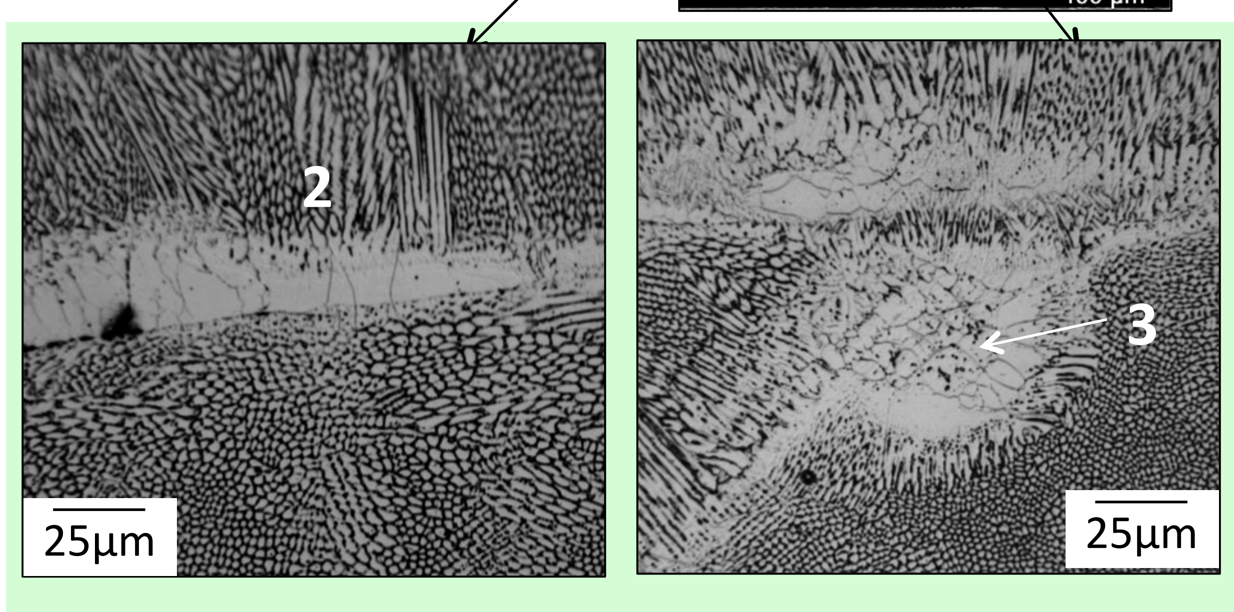


HAZ contains:

1) Mushy zone at the metal flow trails and/or interpass (Lower-Left)
2) Recrystallized coarse grains at interpass boundary(lower-middle)
3) Partially melted flying powder inclusion, which is susceptible to pores formation (Lower-right)

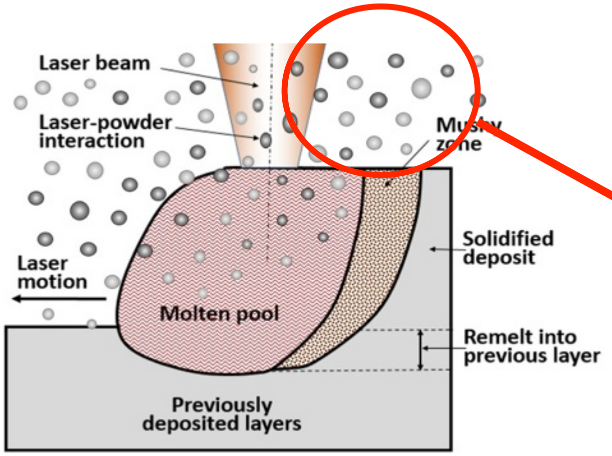


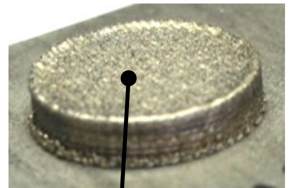


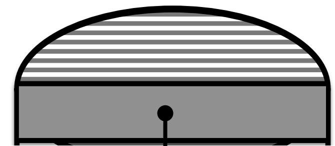


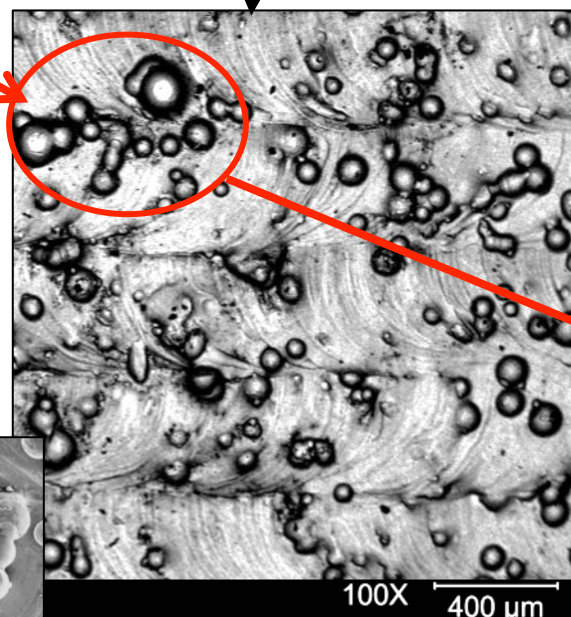
The Observed Interpass Defects are Associated with the Presence of Fused-in Unmelted Powder Inclusion on the Surface During Printing

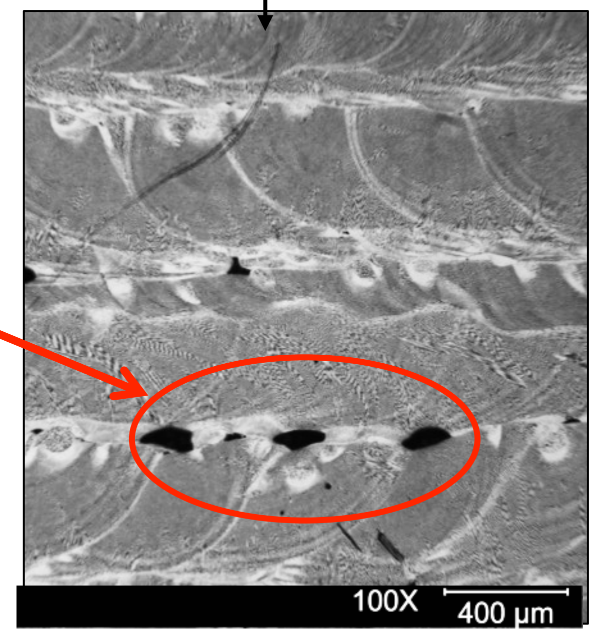
LENS Printing steps



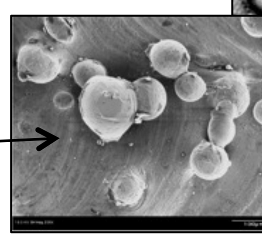






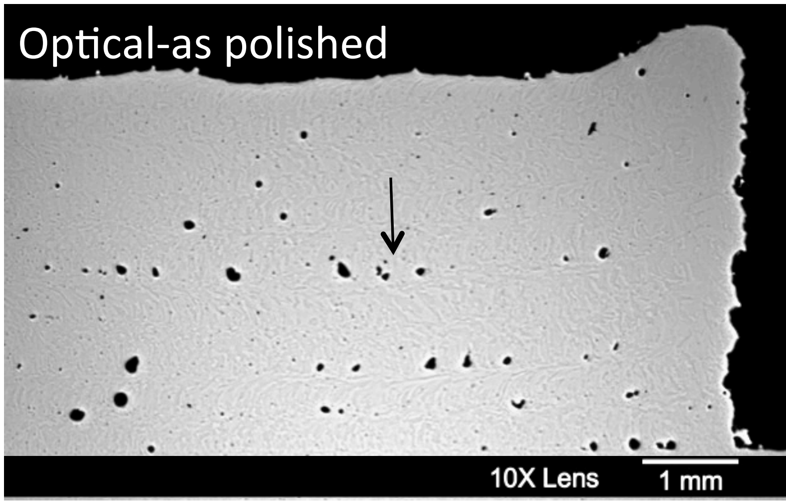


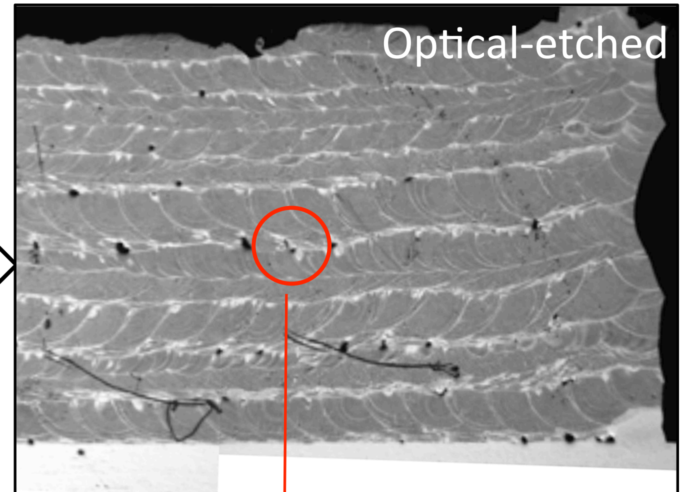
SEM image shows the fused powder stringers on the print surface

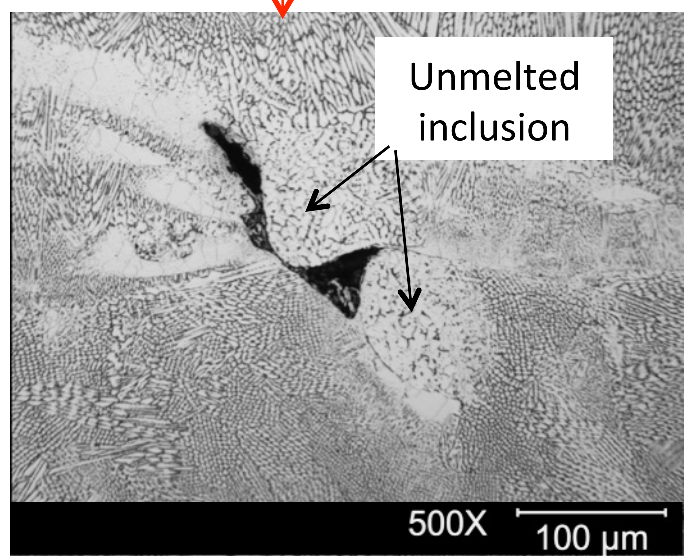


- The flying feedstock powder stringers fused onto print surface (Lower-left).
- The powder stringers remain unmelted and become foreign inclusions, which coexist with the gross pores (Lower-right).

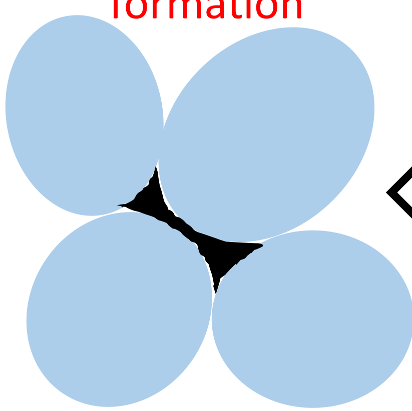
Schematic Illustrates the Correlation Between Entrapped Unmelted Powder Stringers and Gross Interpass Pores



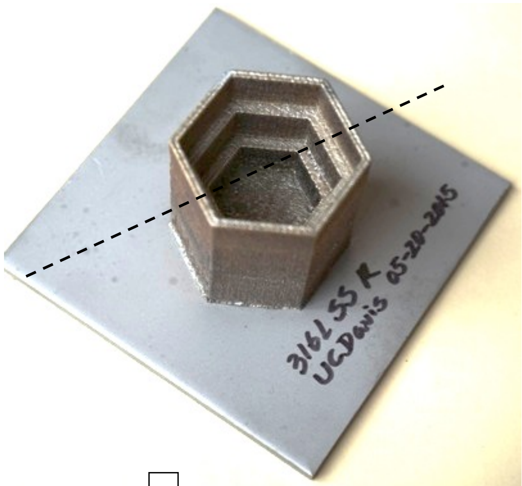




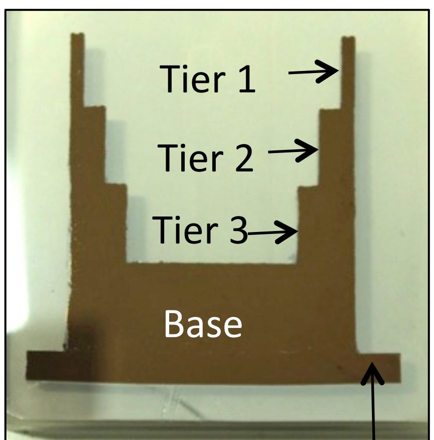
Schematic of dog bone pore formation



Systematic Decreases in Vickers Hardness with the Width of Thin Wall and it's Distance from the Deposit-substrate Interface

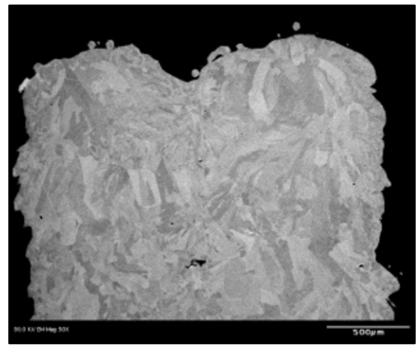


Cross section

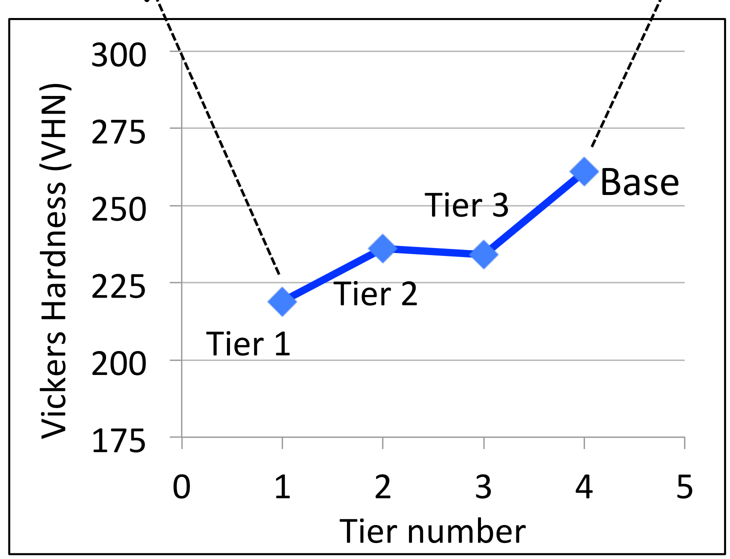


316L substrate

Coarse dendrite cell

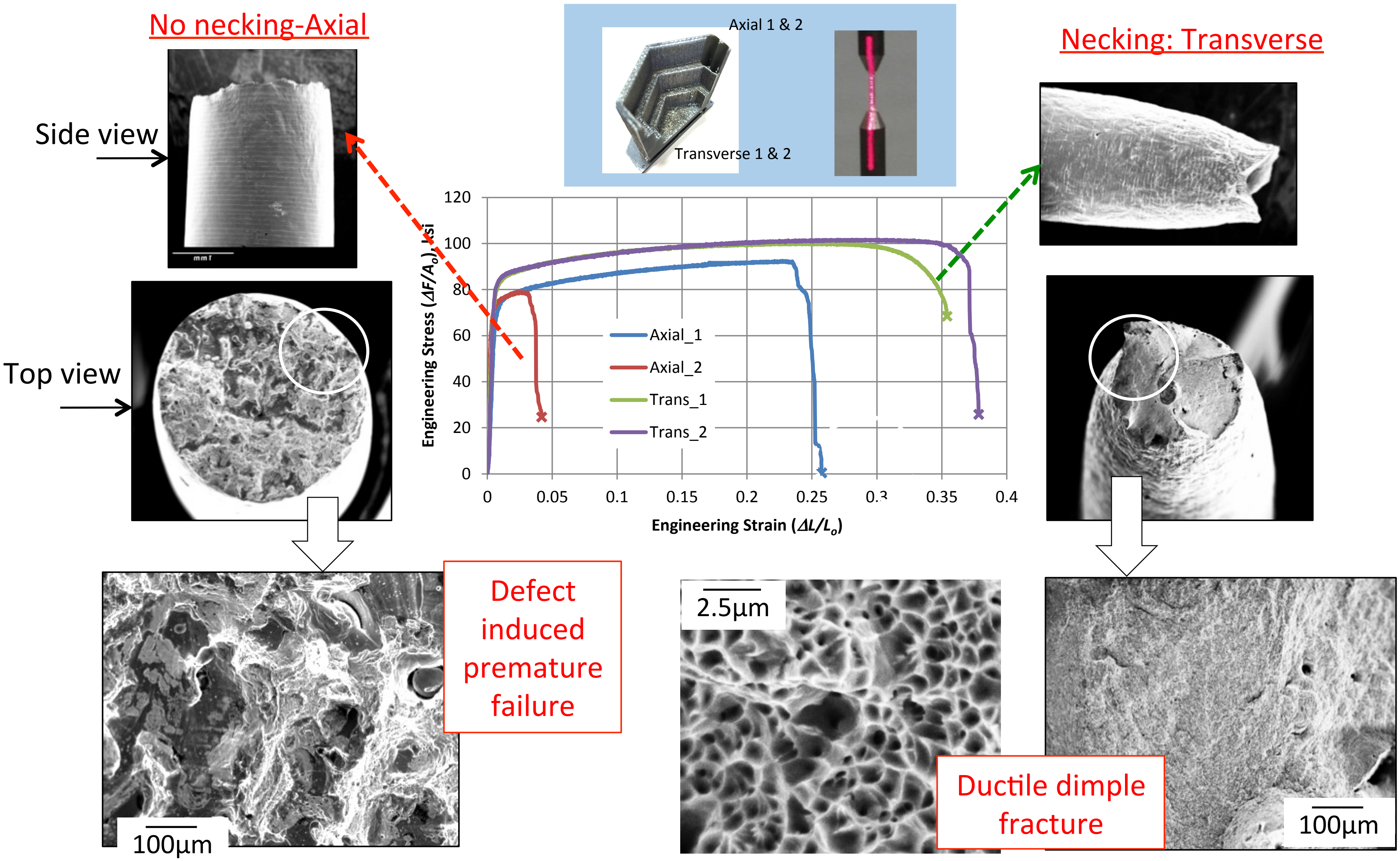


Fine dendrite cell



Vickers hardness is print dimension & location dependent, attributed to dendrite size variation

Presence of Unmelted Flying Powders at Interpass Boundaries Compromise UTS and Ductility of the Multi-tier Hexagon



The Mechanical Strength for the Defect-free Part Generally is 15-50% Higher than Those of Wrought 316L Stainless

Properties	YTS (ksi)		UTS (ksi)		Elongation (%)		Vickers hardness*** (VHN)	
Processing	LENS	WRT	LENS	WRT	LENS	WRT	LENS (Hexagon)	WRT
Nominal ASM 316L*		25		65		40		222
316L hexagon axial 1**	66		92		25		260** (base) 220**(Tier 1)	
316L hexagon axial 2**	65		79		4			
316L hexagon trans 1**	78		100		35			
316L hexagon trans. 2**	80		102		38			

* Nominal property for wrought 316L (WRT) stainless steel

** Measurement performed at SNL,CA

Summary

- The tensile strength of the current 316L LENS prints in general is ~15-20% higher than those of wrought 316L stainless . However, the ultimate tensile strength (UTS) and ductility appear to be anisotropic, attributed to the anisotropic microstructure.

- The overall microstructure of 3-D LENS print is dictated by molten metal flow trails, multi-pass boundaries and solidification dendrite cells. In general, the metal flow trails and interpass boundaries are well fused with epitaxial interfaces.

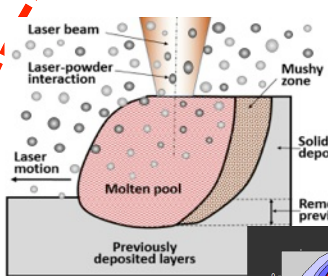
- The multi-pass boundaries are susceptible to gross defects, attributed to the presence of process-related unmelted flying powder inclusions, which could compromise ultimate tensile strength and ductility.

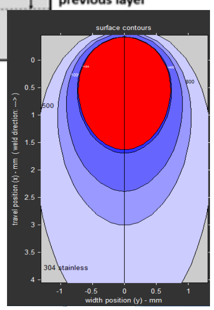
- Mechanical property, such as hardness, within a complex component is print dimension and location dependent, due to the variation in dendrite cell size resulted from the localized heat transport and distribution.

- The process optimization for controlling the material properties and mitigating structural defects is underway.

Scientific Progress and Future S&T Path Forward

Identify key parameter(s) → Determine → Metallurgical evolution → Enable → Control property & performance





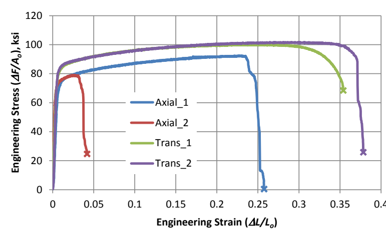
Experiment plus numerical simulation

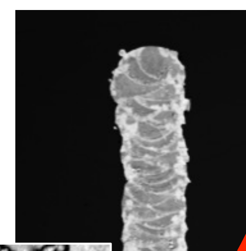
Predict & validate

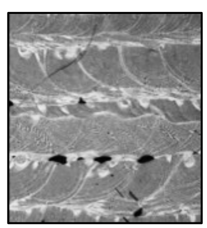
- Molten metal heat distribution
- Thermal transport at liquid-solid interface

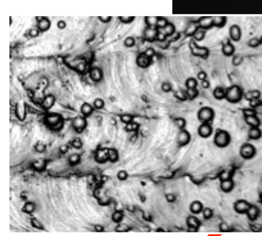
Impact on ?

- Surface contour
- Solidification structure and defect formation
- Final dimension/shape
- Mechanical property & mechanics







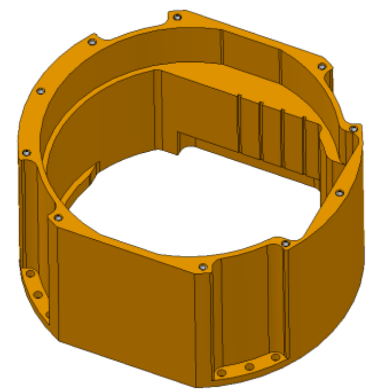


On-going S&T progress

Achieve

- Dimension/shape precision
- Mechanical properties
- Defect mitigation

Prototype housing



Future goal

Acknowledgement

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