SAND2017-7500C

Thermal stability of the 3-D AM 316LSS prototypes

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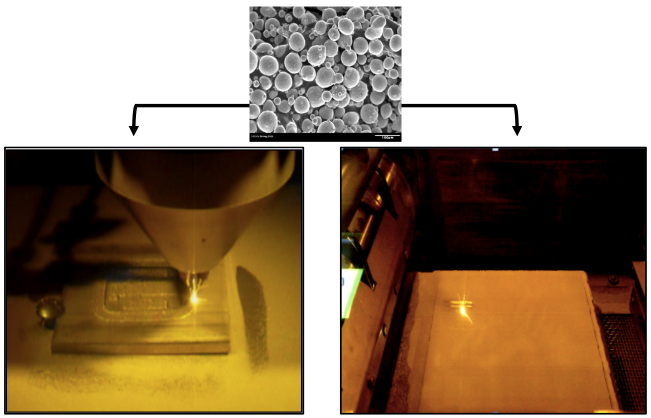

<u>Technical team members</u>

- 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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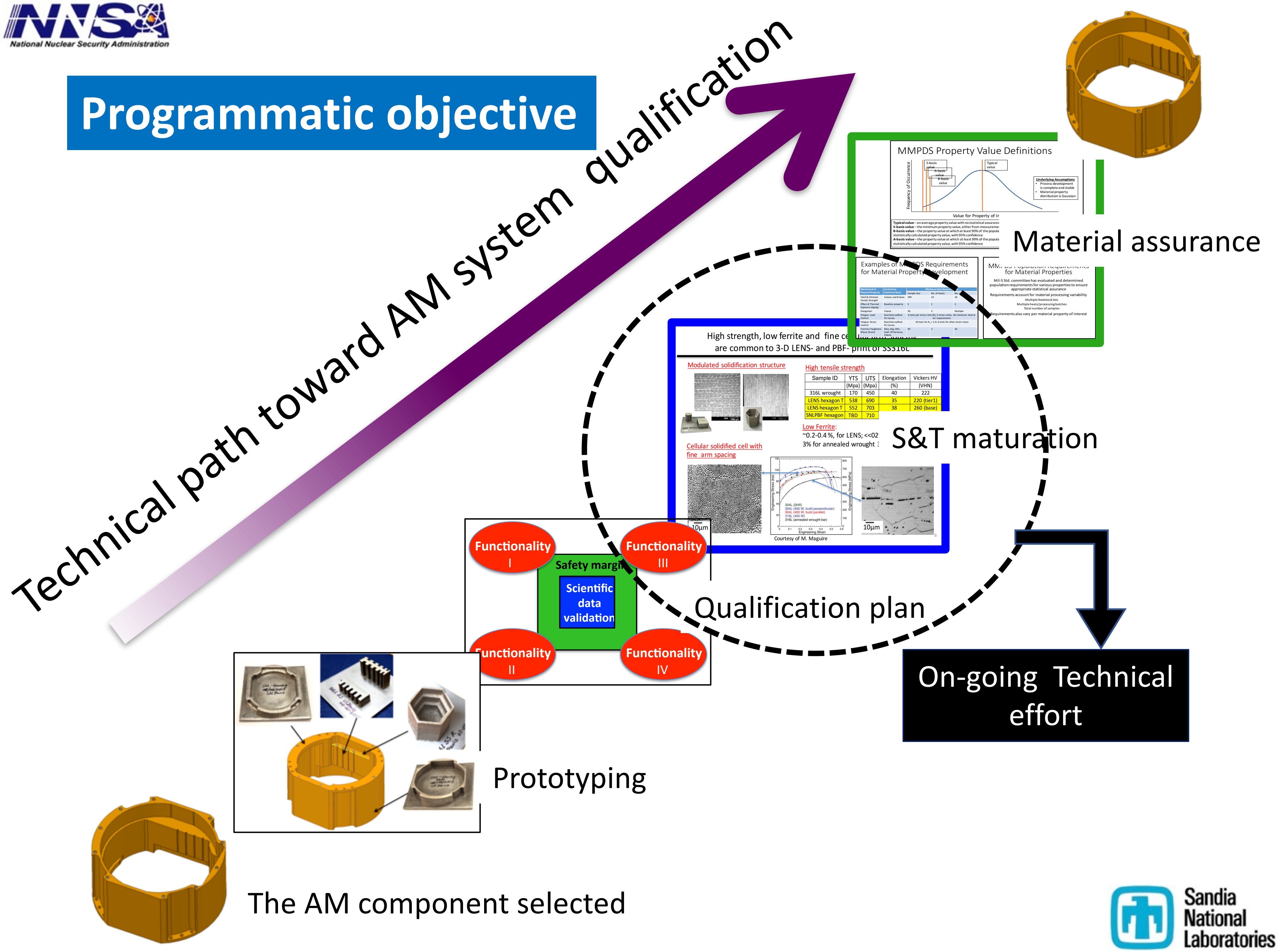
Outline

- Programmatic objective
- Science and technology (S&T) maturation activities
- As-printed metallurgical characteristics of AM 316L SS
- Thermal aging and stability of AM 316L SS prototype
- Summary and discussion


National Nuclear Security Administration
Programmatic objective
Technical path toward AM system qualification
MMPDS Property Value Definitions
Material assurance
High strength, low ferrite and fine ce
are common to 3-D LENS- and PBF- print of SS316L
Modulated solidification structure
High tensile strength
Low Ferrite:
Cellular solidified cell with fine arm spacing
Courtesy of M. Maguire
S&T maturation
Functionality I
Functionality II
Functionality III
Functionality IV
Safety margi
Scientific data validation
Qualification plan
On-going Technical effort
Prototyping
The AM component selected
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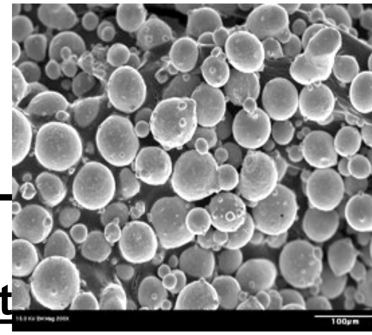
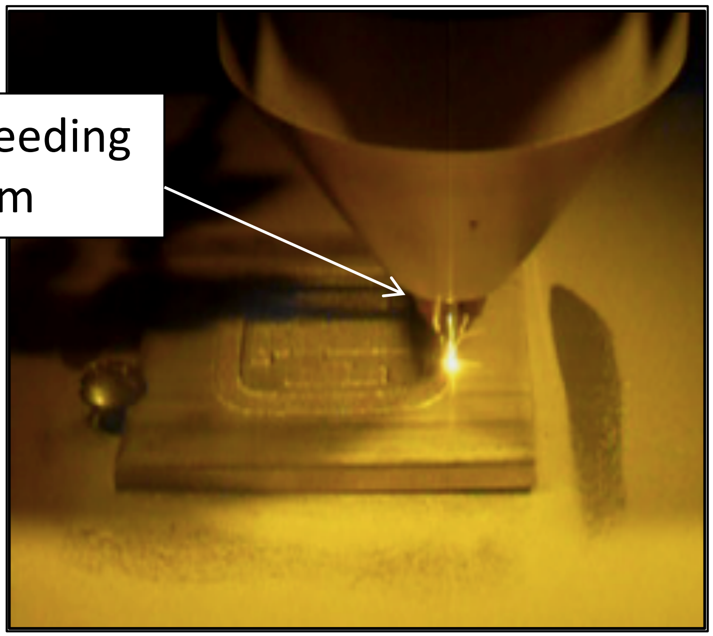
3-D LENS and PBF metal printing demonstration

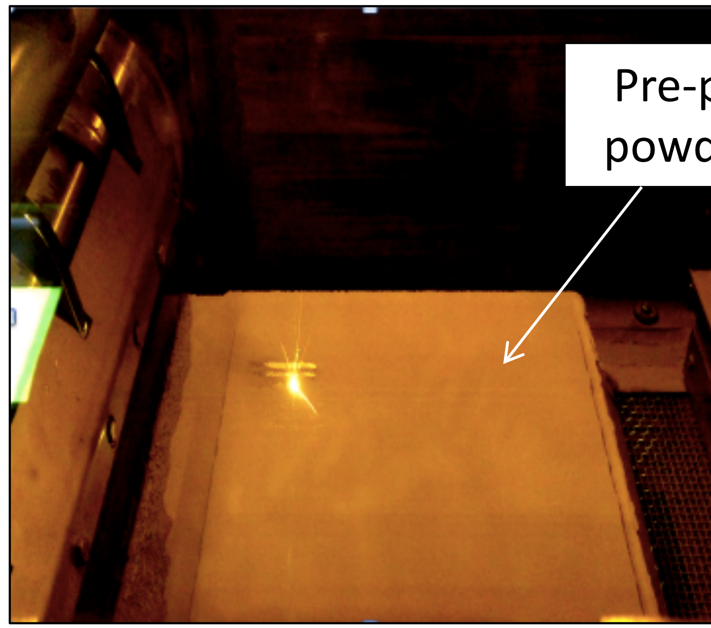
Starting 316L atomized feedstock powders



3-D LENS deposit

3-D PBF printing

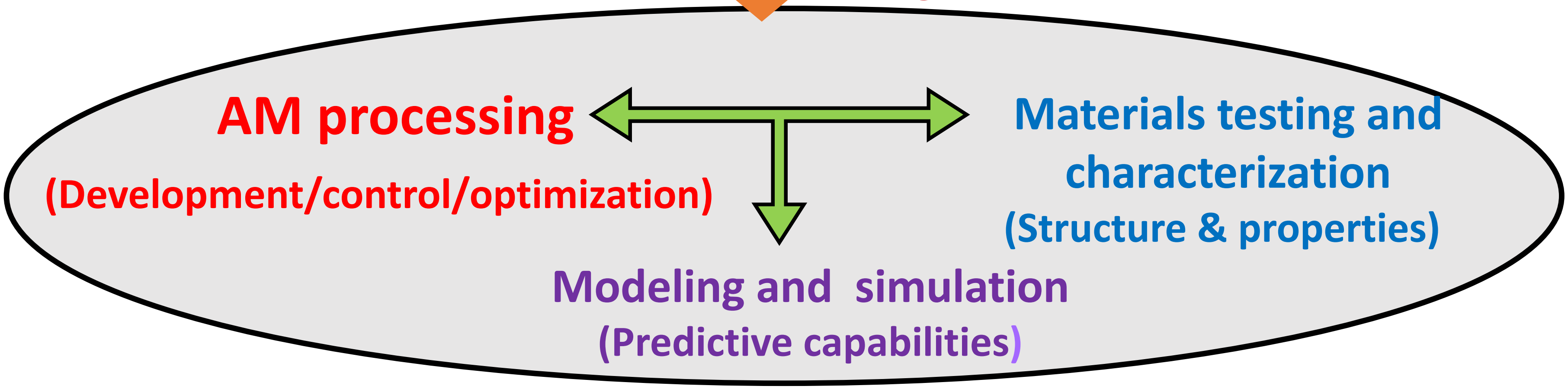




Programmatic objective: Integrating a robust scientific approach

AM Science and Technology (S&T) Maturation

Integrate



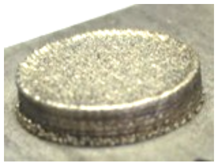
Discover

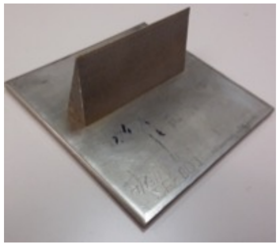
- **Process-structure-property-performance relationships**
- **Geometry/precision & limitation/manufacturing constraints**
- **Materials properties control and defect mitigation**

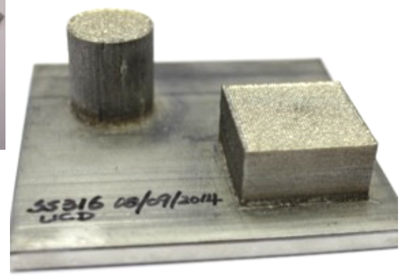
Enable

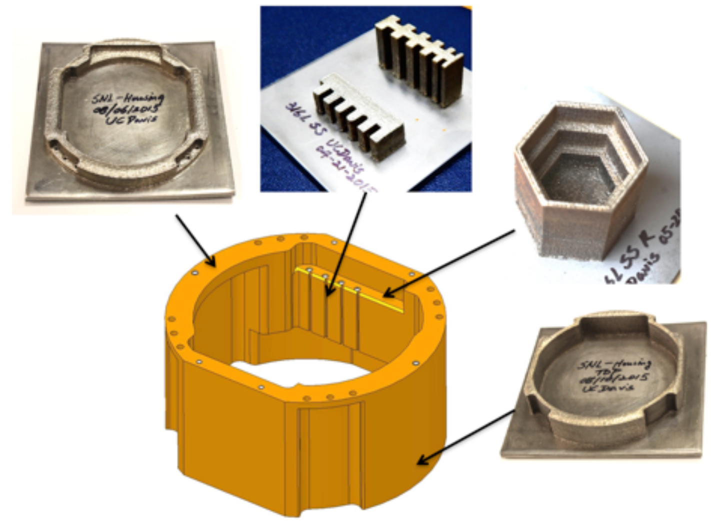
Science-base AM system engineering

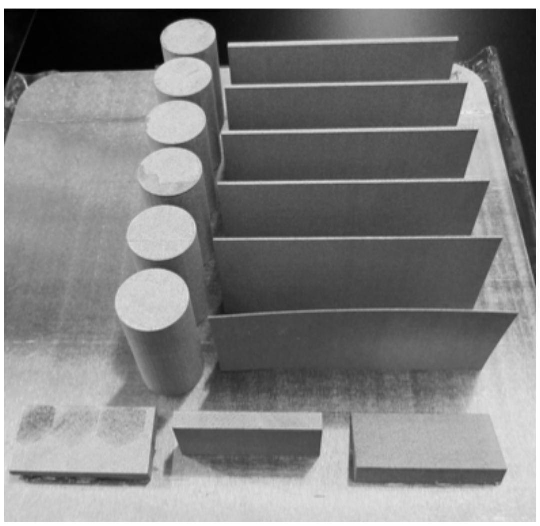
3-D LENS- & PBF- 316L SS prototyping

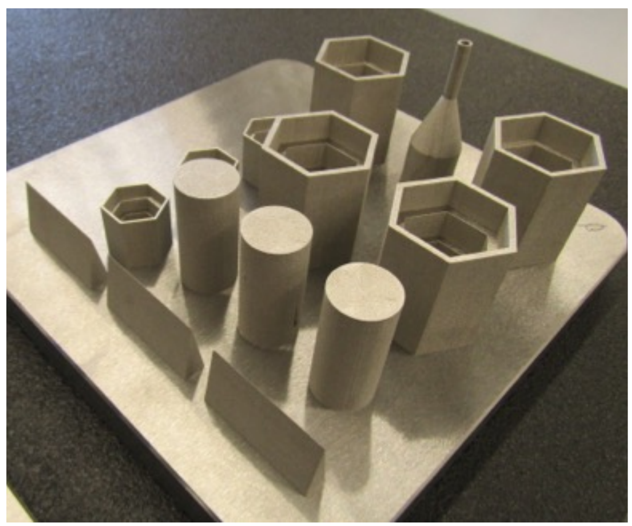








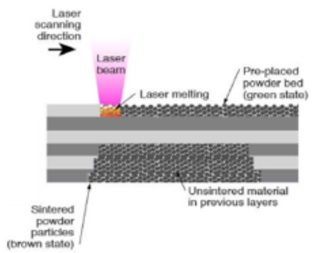




On-going science & technology maturation activities

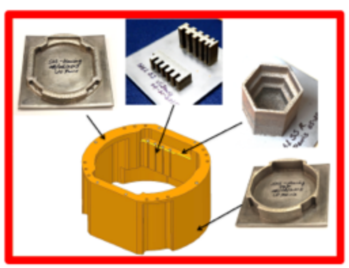
Process & prototyping

Laser-material interaction



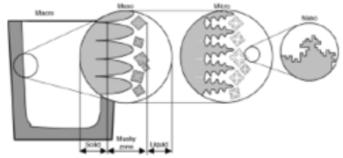
Process optimization

Prototyping feasibility

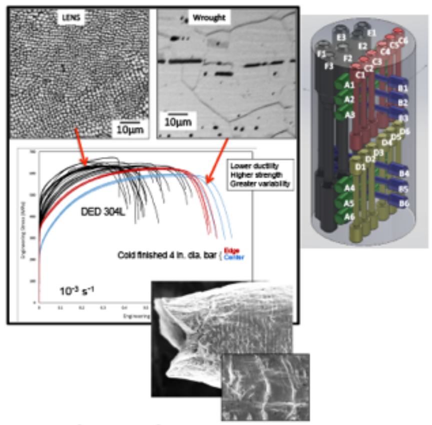


Material science

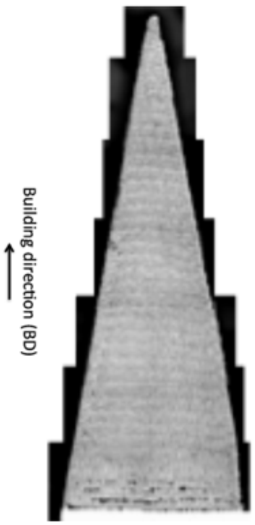
Metal solidification



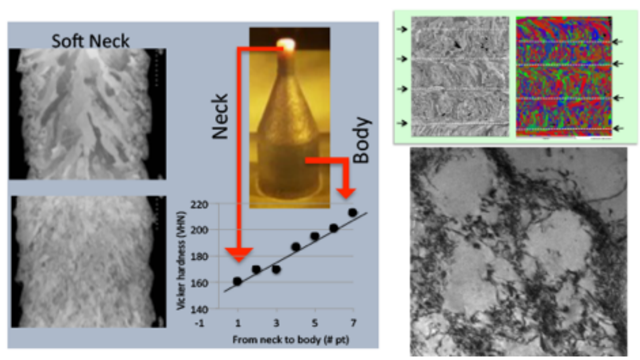
Mechanical behavior



Geometry & structural defect

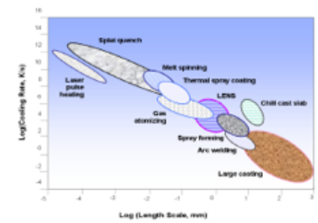


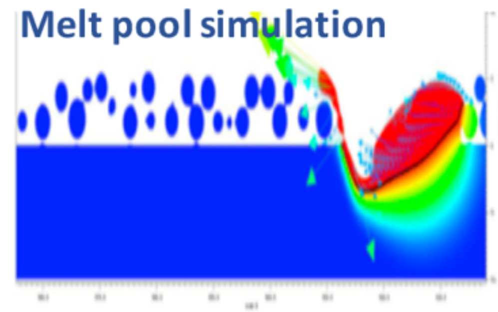
Thermal cooling- Microstructure-Anisotropy



Numerical modeling

Thermal transport & Solidification cooling validation &prediction



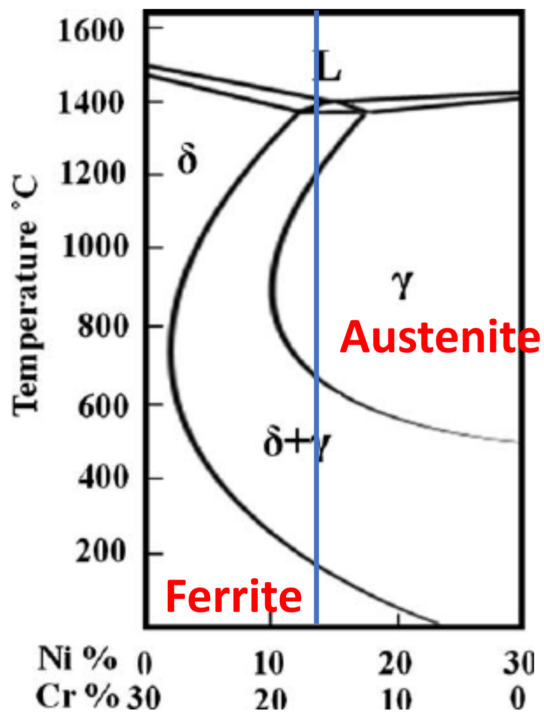


External collaborations

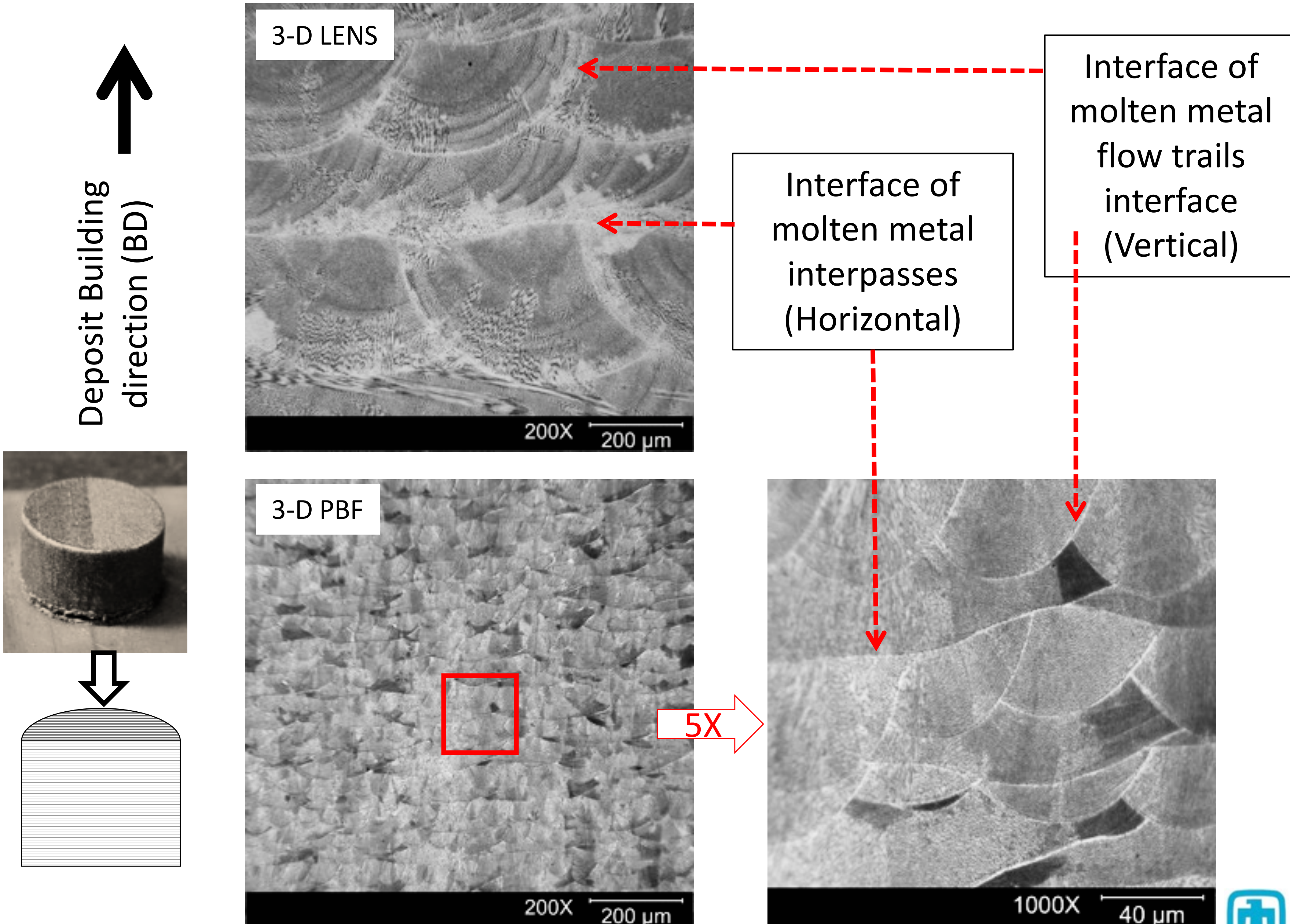
- UC Davis/Irvine
- UC Berkeley:
- Stanford
- PolarOnyx INC

Solidification of 300 series stainless steel

Type	Composition (wt%)							
	C	Mn	Si	Cr	Ni	P	S	Other
304	0.08	2.00	1.00	18.0-20.0	8.0-10.5	0.045	0.03	
304L	0.03	2.00	1.00	18.0-20.0	8.0-12.0	0.045	0.03	
316	0.08	2.00	1.00	16.0-18.0	10.0-14.0	0.045	0.03	2.0-3.0 Mn
316L	0.03	2.00	1.00	16.0-18.0	10.0-14.0	0.045	0.03	2.0-3.0 Mn



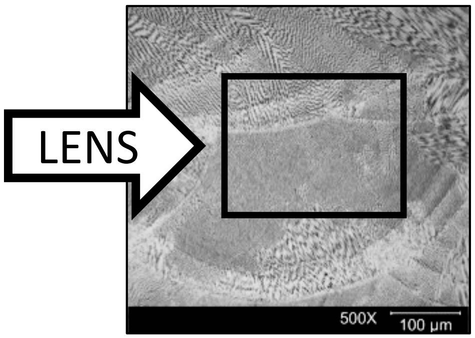
3-D-LENS- & PBF- printed 316LSS exhibit composite structure of solidified cells

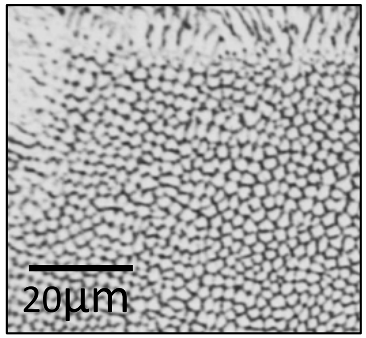


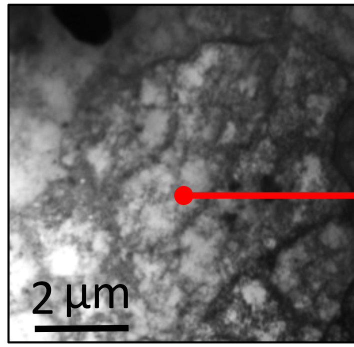
Solidification cell is much coarser and dislocations network is more spread out in the LENS- than in PBF- cylinder

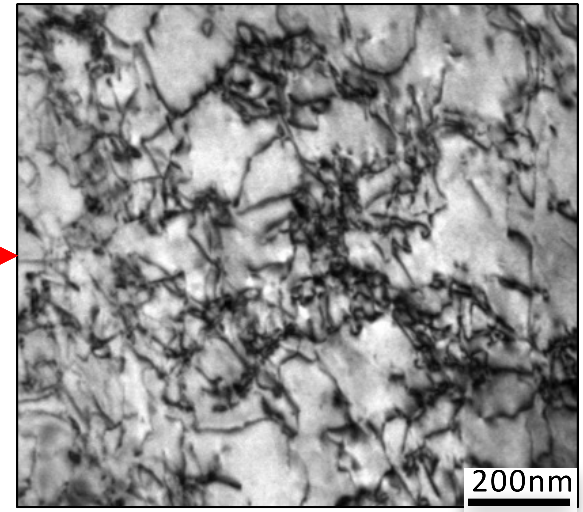
Optical images of cross section (UCD

TEM/BF





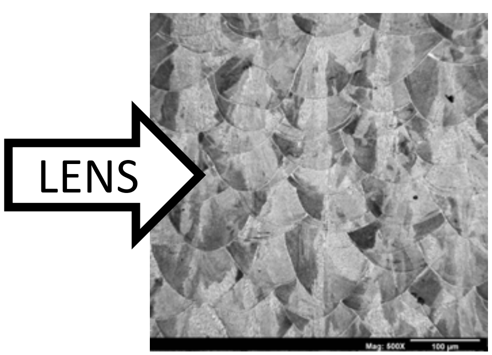


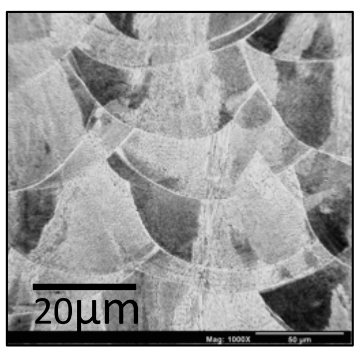


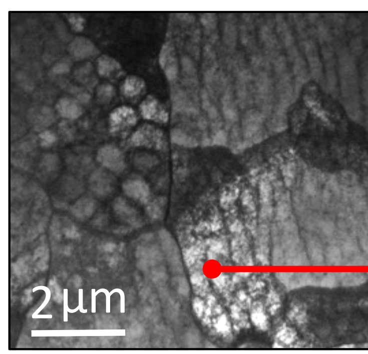
Increasing magnification

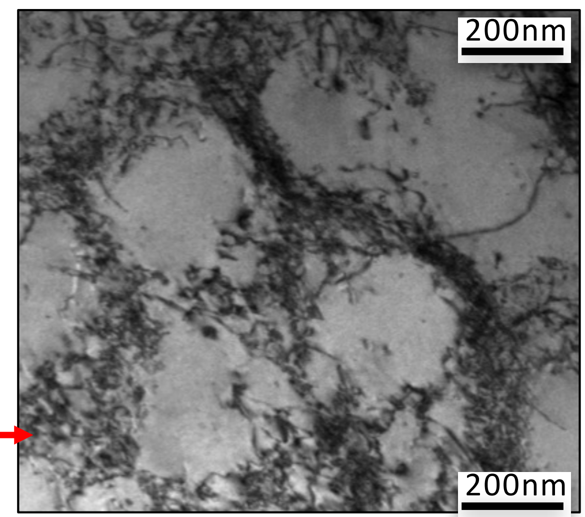
Optical images of cross section (GPI)

TEM/BF





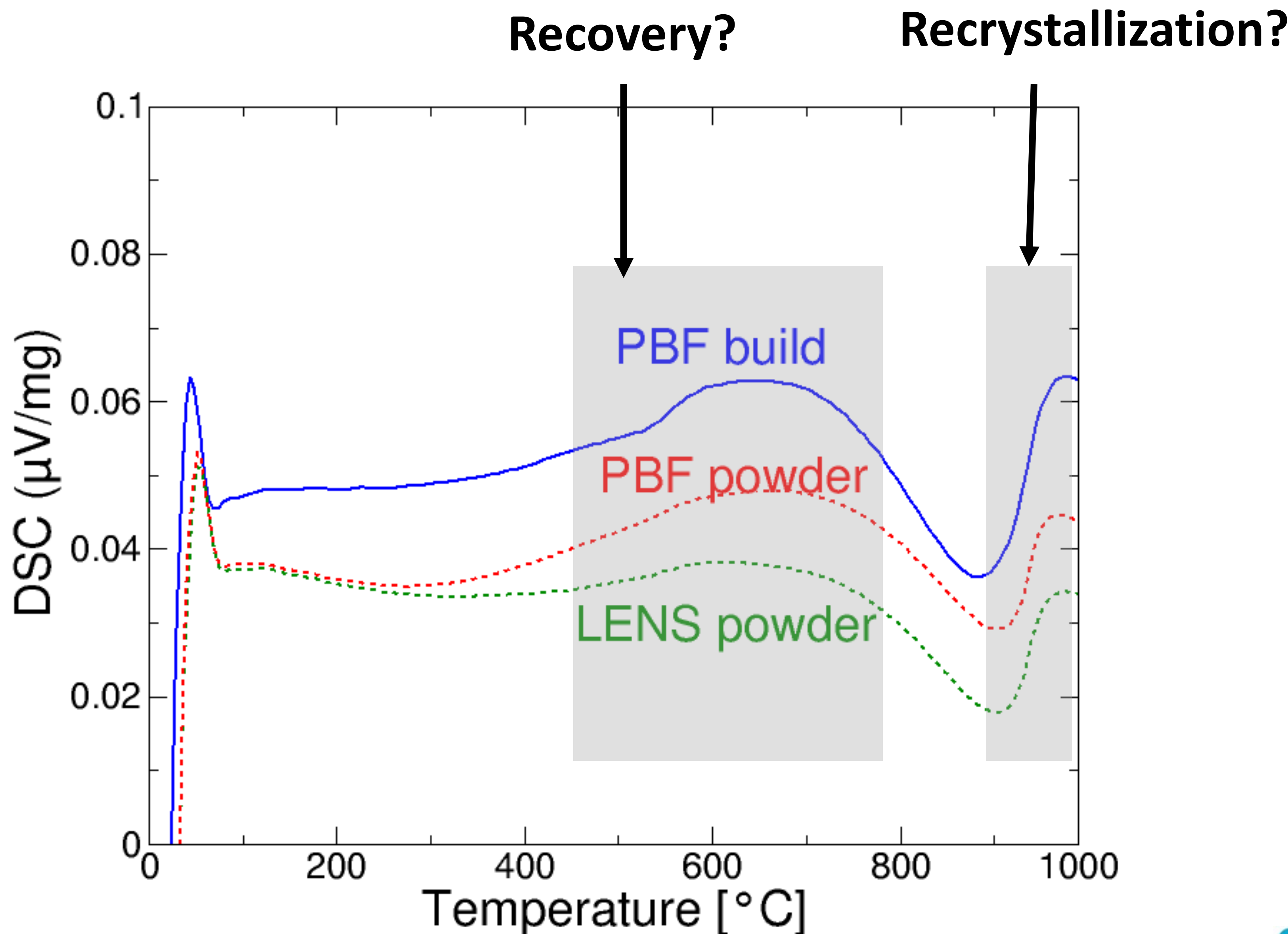




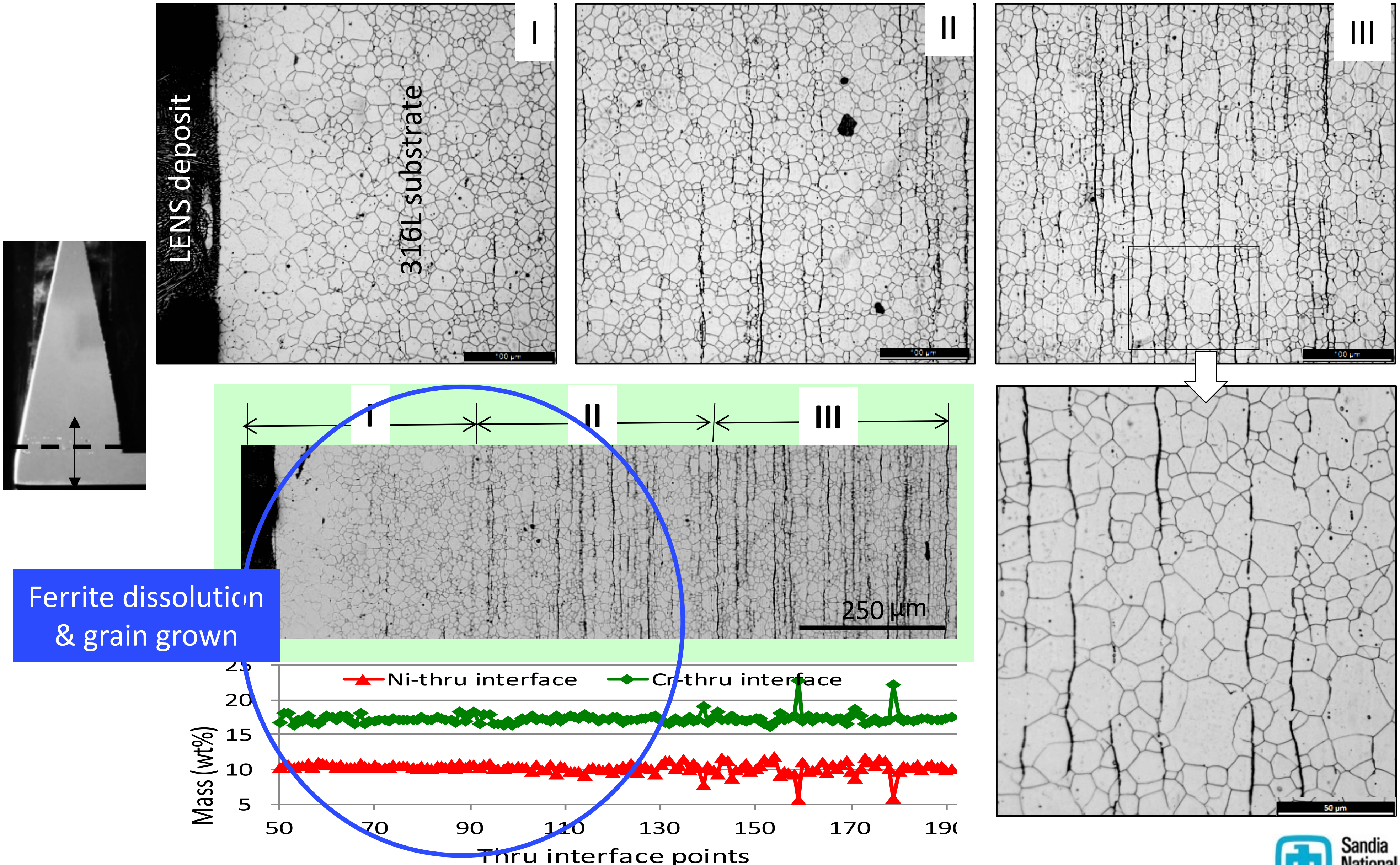
Thermal aging studies of 3-D LENS and PBF printed 316L SS

- Differential Scanning Calorimetry (DSC)
- Physical metallurgy evolution
  - ✓ 3-D AM process induced
  - ✓ System performance induced

DSC: 316L AM build shows same transitions as powder, reasonably stable to ~450C



LENS-induced heat dissipation led to grain growth & ferrite dissolution of the 316L substrate near the interface



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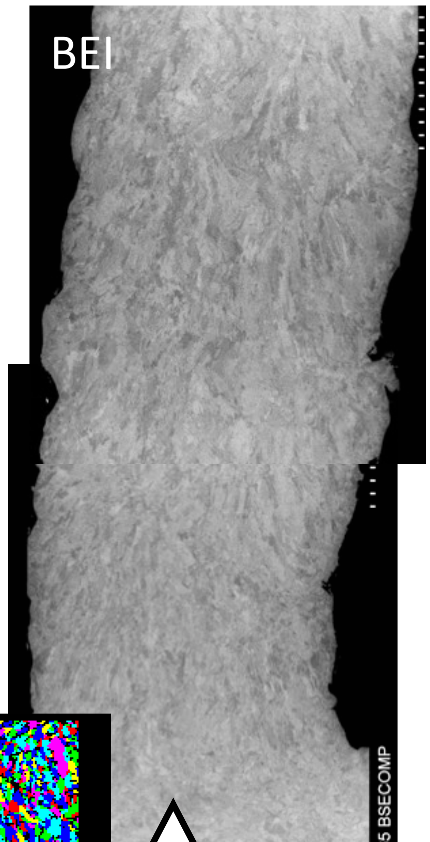
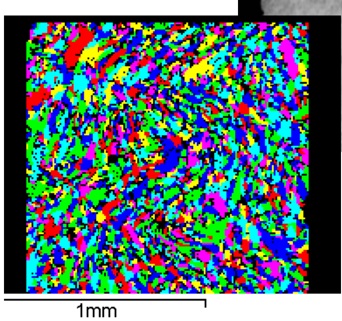
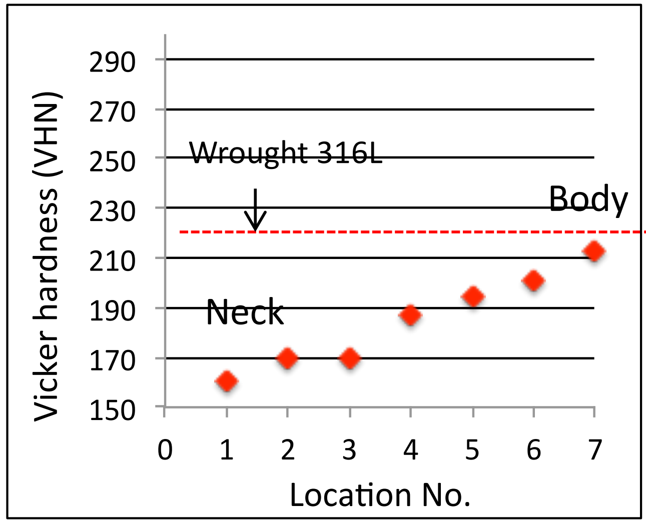
Solidified cell coarsening softens the upper neck of LENS funnel due to the longer exposure of intense heating

Fine-celled body



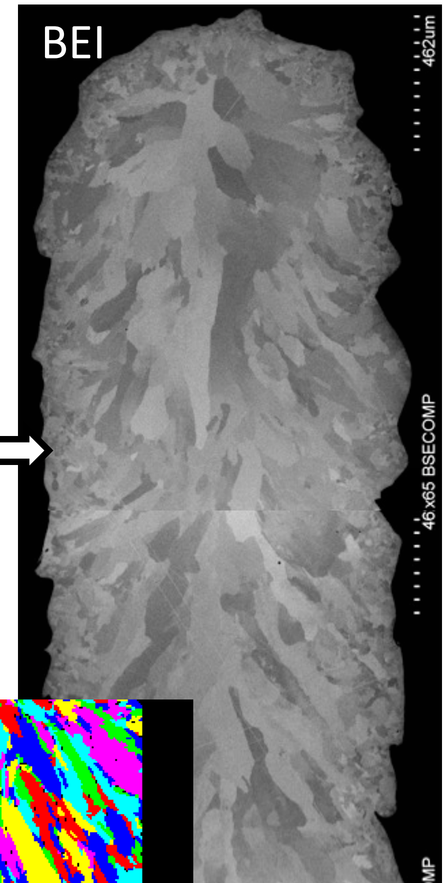
EBSP



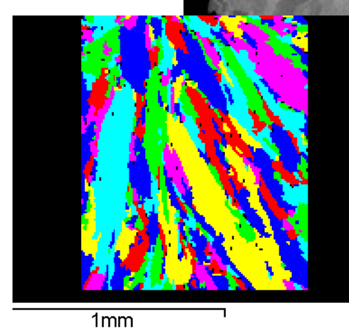


UCI LENS funnel

Coarse-celled neck



EBSP



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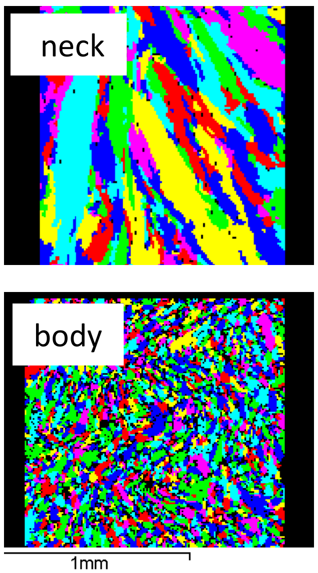
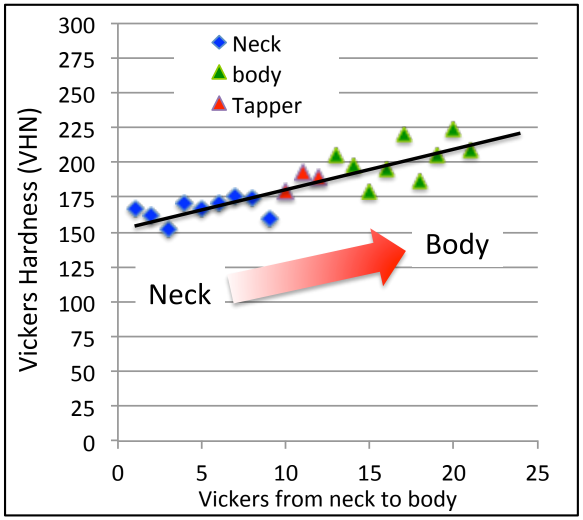
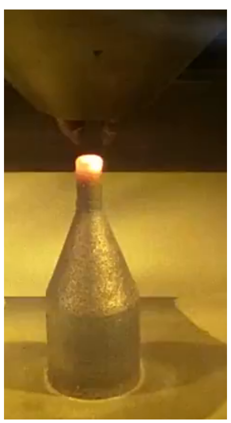
Process-induced thermal aging in 316L PBF prototypes is less obvious, faster/more even cooling thru powder bed?

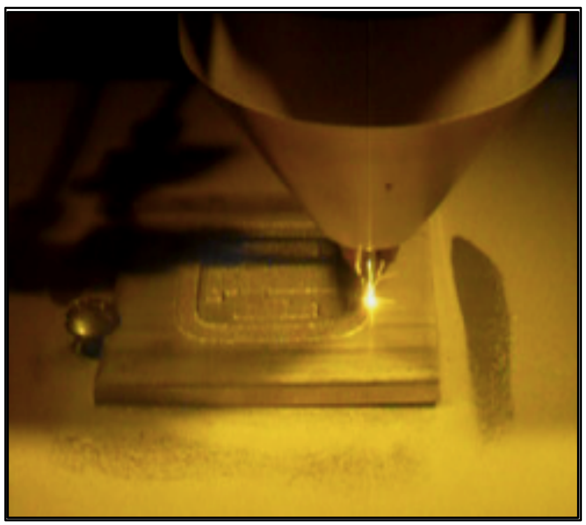
3-D LENS printing

Solidified structure by EBSD



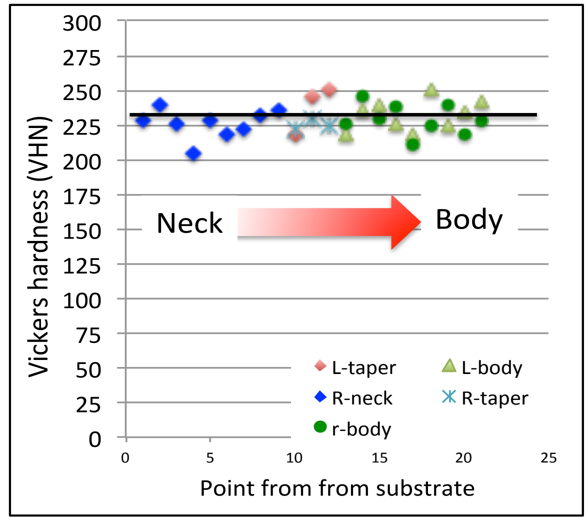


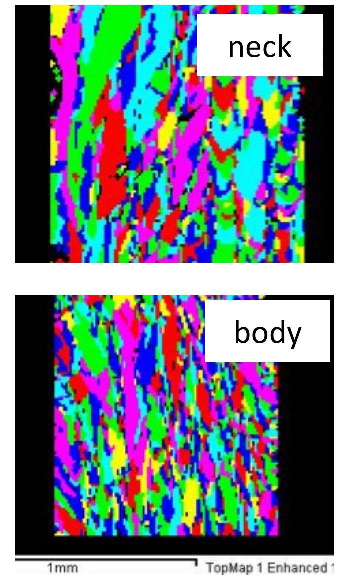


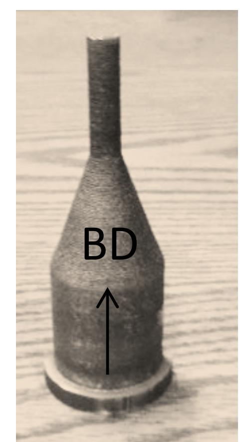


3-D PBF printing

Solidified structure by EBSD

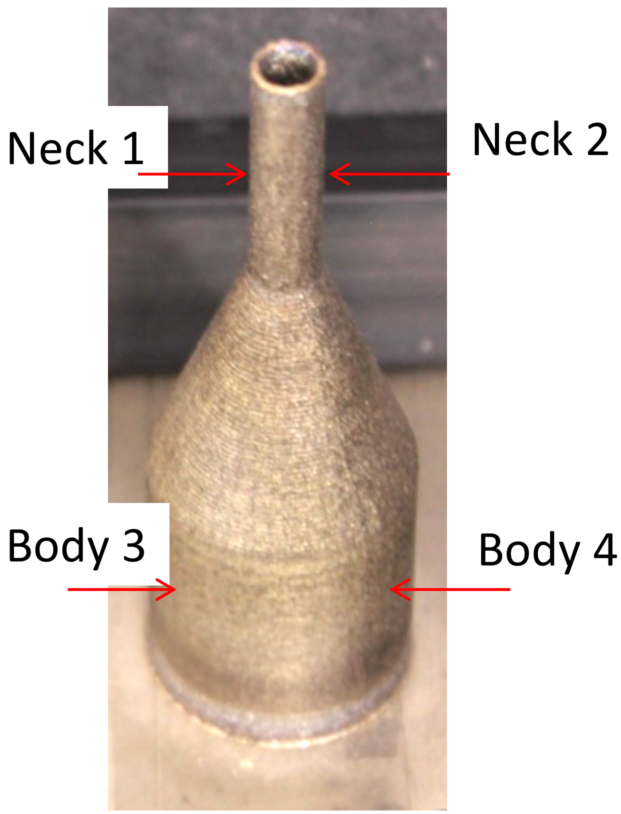






Laboratories

Ferrite % dissolution at the upper neck of the LENS funnel, due to longer exposure of intense heating



Ferrite % increases from neck to body →

Body surface ↓

Funnel Ferrite %				
	UCD #1	YAG laser		
Neck 1	Neck 2	Body 3	Body 4	Body 5
0.3	0.31	0.71	0.57	1.3
	UCD #2	YAG laser		
Neck 1	Neck 2	Body 3	Body 4	Body 5
0.37	0.4	0.72	0.62	0.96
	UCI #1	F-Optic		
Neck 1	Neck 2	Body 3	Body 4	Body 5
0.46	0.49	1	1.1	1.6

- Ferrite % increases gradually toward the substrate interface. And is highest on the body surface
- PBF prototype in general contain <0.2%, the detection limit.

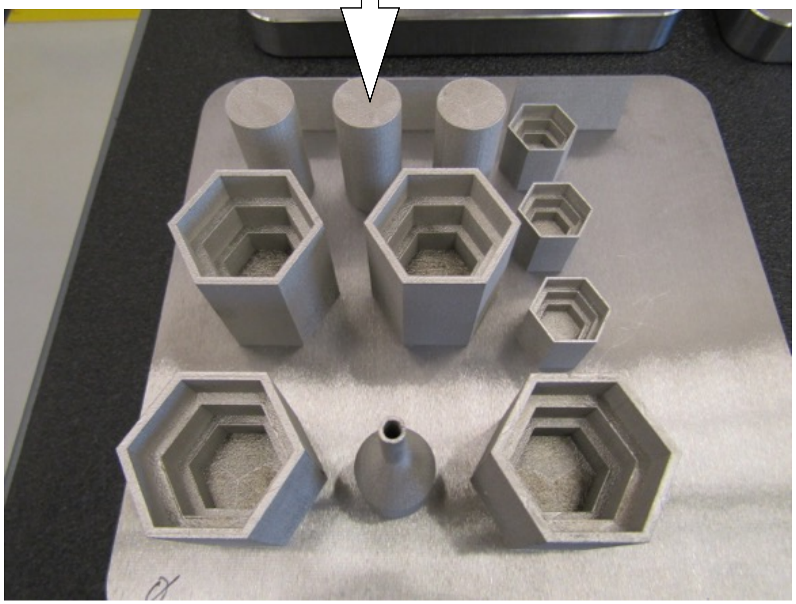
Thermal aging

- Process induced aging in LENS
- Post printing thermal aging and stability

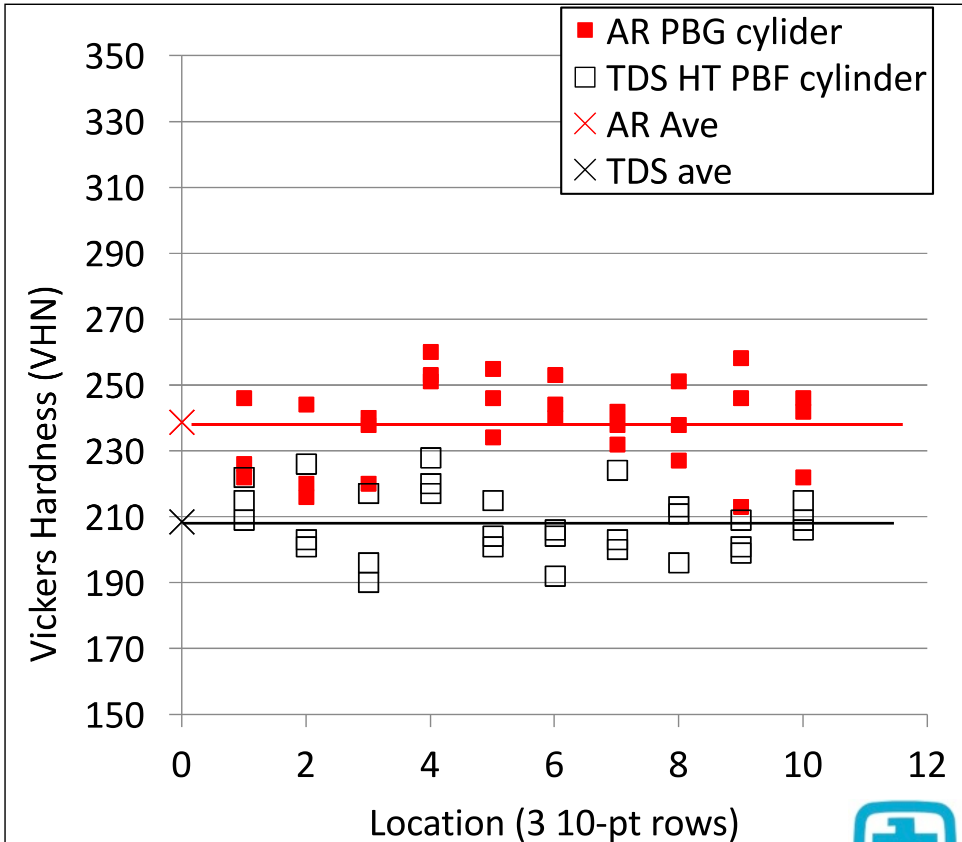
PPBF cylinder softened upon the temperature ramping, from 23 to 1000°C at 6°C/minute

1” PBF cylinder

Sample: EO17-01	Average	STDEV	Remark
SNL PBF coin	240.00	10.12	
SNL PBF small hexagon	242.00	13.07	Consistent
SNL PBF cylinder-AR	238.77	13.00	
PBF cylinder TDS HT	208.00	10.02	
SNL PBF funnel	227.44	15.30	Slightly lower
GPI small PBF hexagon	247.32	7.80	High/consistent

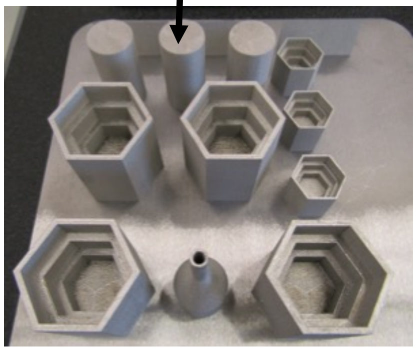


Thermal again was performed in the TDS chamber



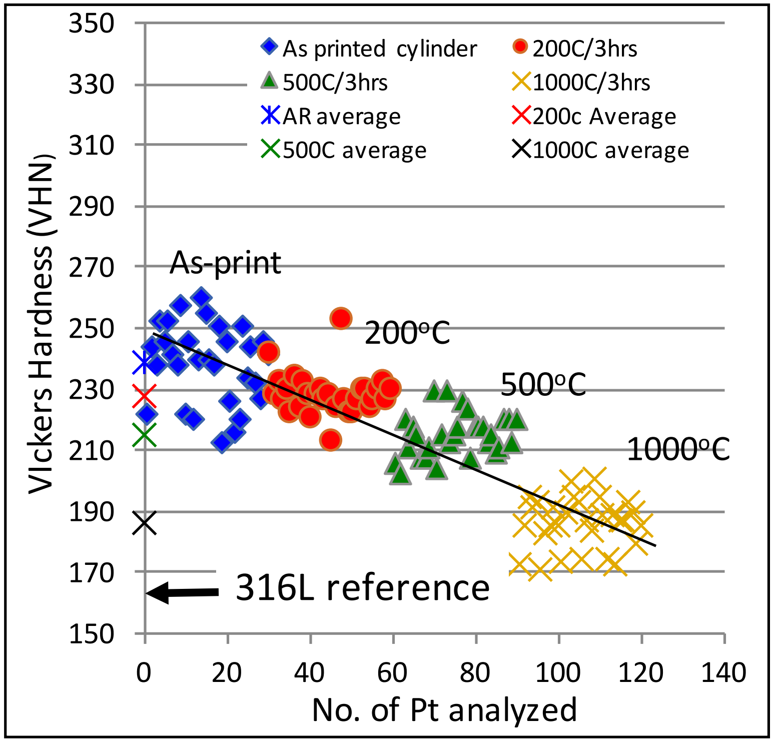
PBF cylinder softening are evident from both isothermo and temperature ramping aging

1" PBF cylinder

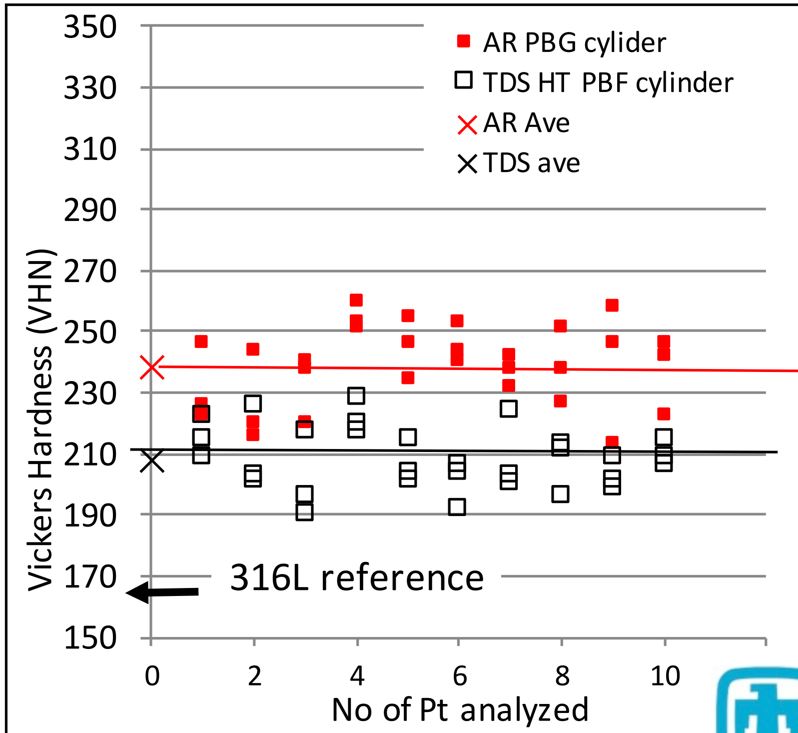


Vickers microhardness is lower in the cylinder which was subject to isothermo-aging for longer times, 3 hours

Isothermo aging for 3 hours



TDS ramping to 1000°C, at 6°C/minute



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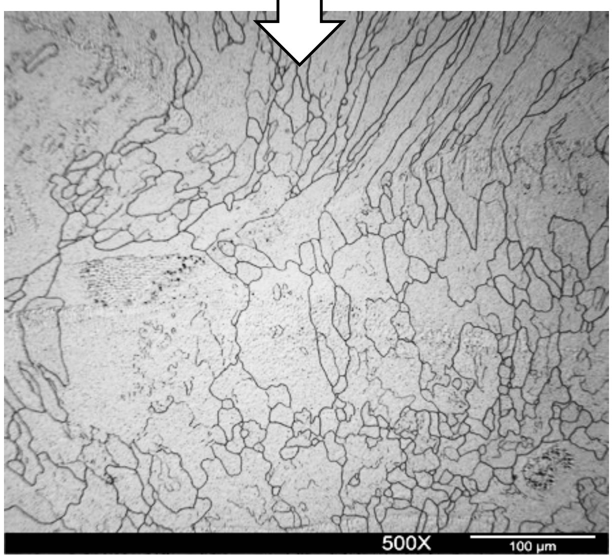
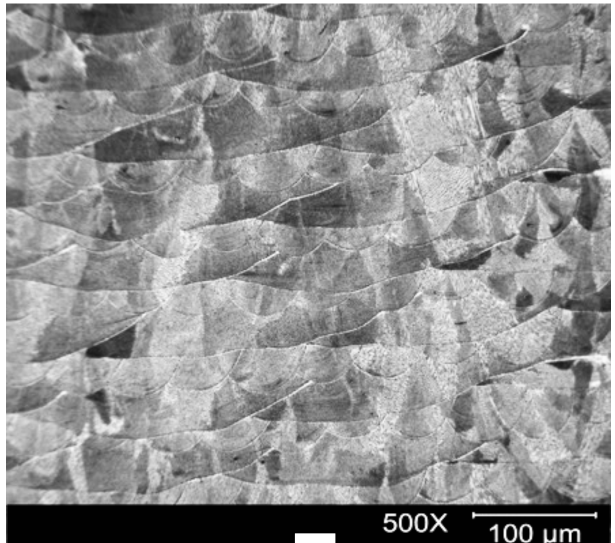
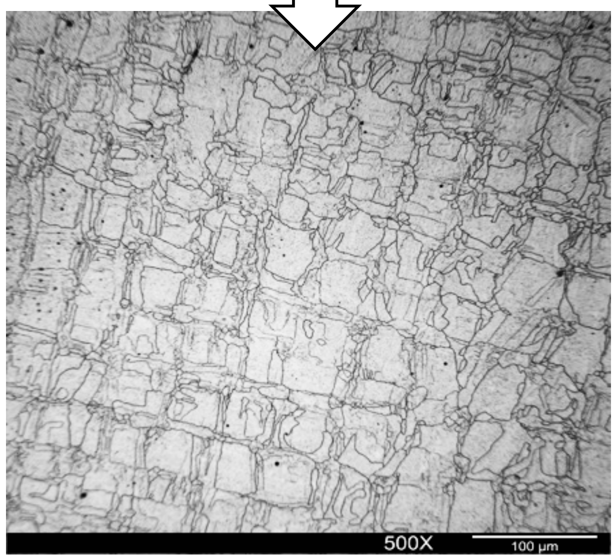
Solidification initial landscape determines the final recrystallized structure

UCD LENS Post #2



GPI PBF hexagon tier 1





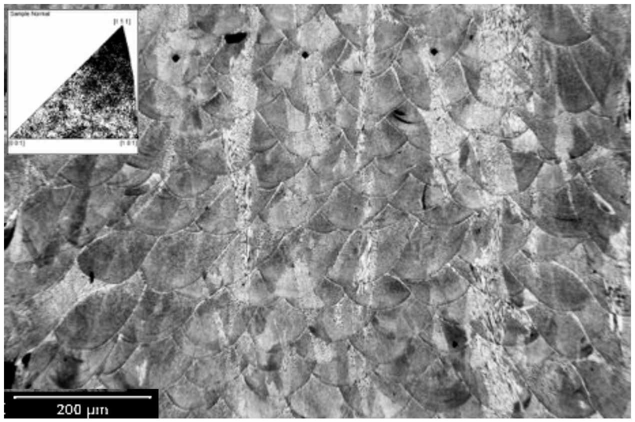
- Significant difference in recrystallized grain structure in AM prototype relative to those in the annealed wrought 316L SS, even-sized equiaxed grains.

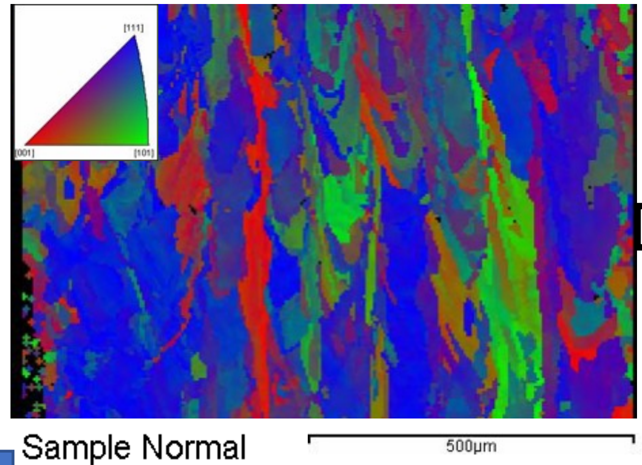
Annealed wrought 316L SS

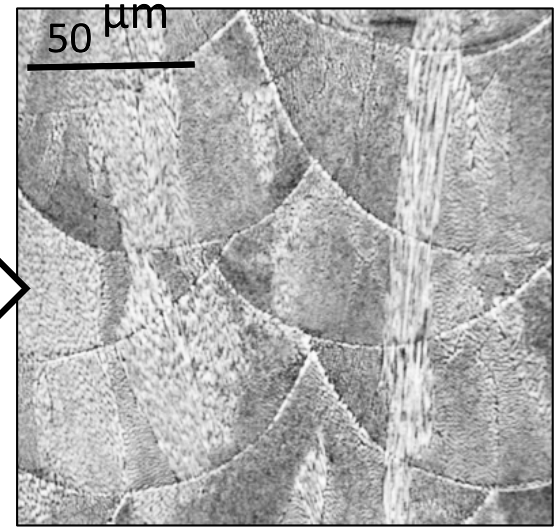
NNSA National Nuclear Security Administration

Interpass-solidified cell spacing-epitaxial crystal growth control length scale & texture of resultant recrystallized structure

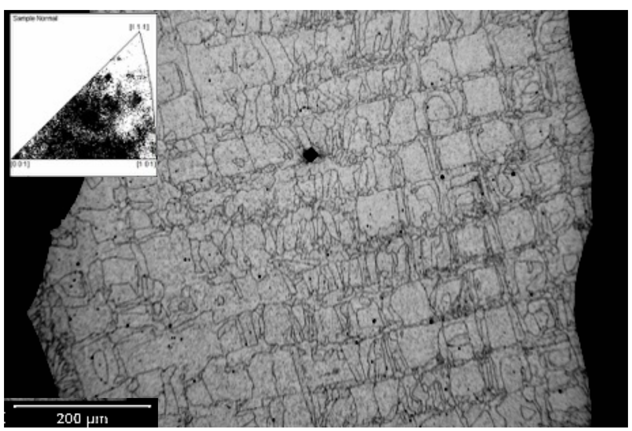
As-printed PBF hexagon

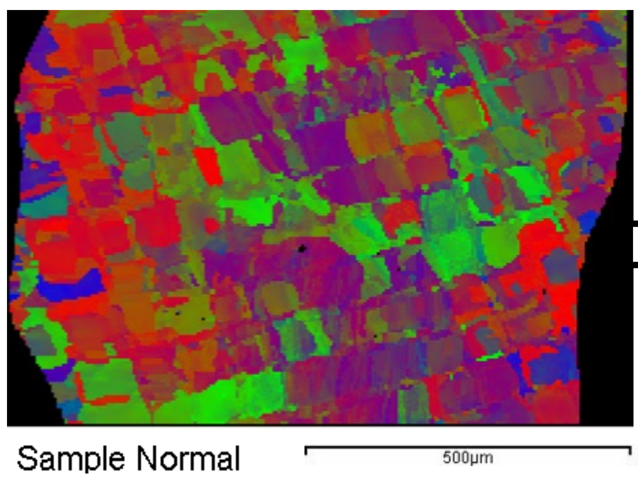


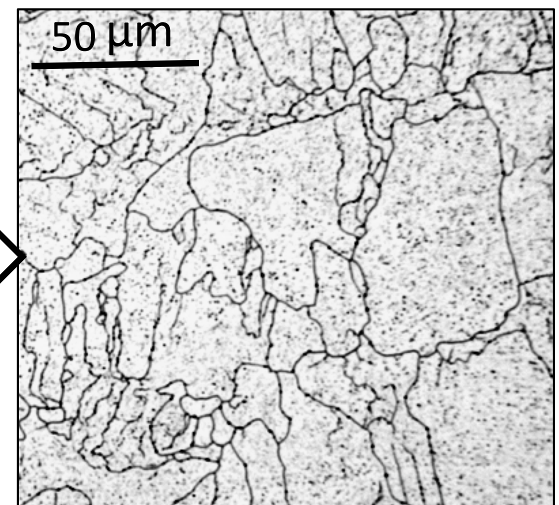




Thermally aged at 1000°C







National Laboratories

Summary

- Thermal aging of 3-DAM 316L SS studied are:
  - ✓ Specific thermal history during printing matters
  - ✓ The relevant post-printing thermal environment

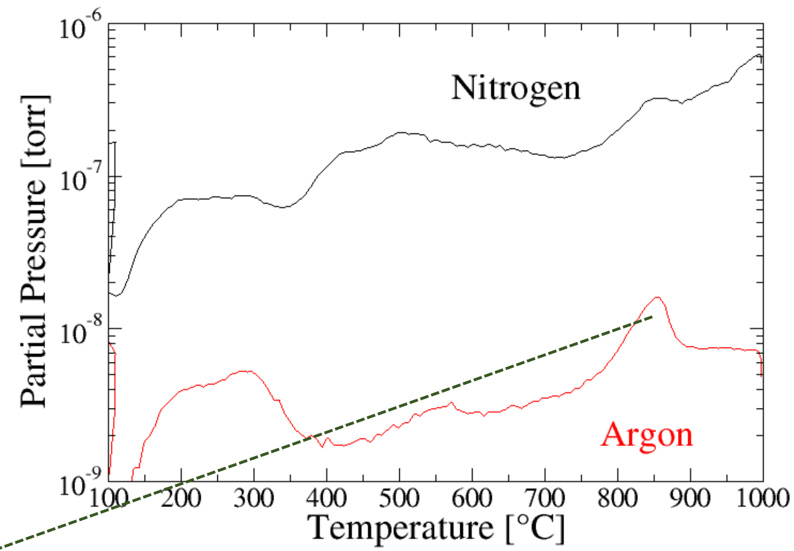
- Recrystallization to austenite observed by 900^{o} C

- For the case of post-printing aging, the initial AM solidification landscape dictates the recrystallization/grain growth, therefor, the resultant microstructure and mechanical behavior.

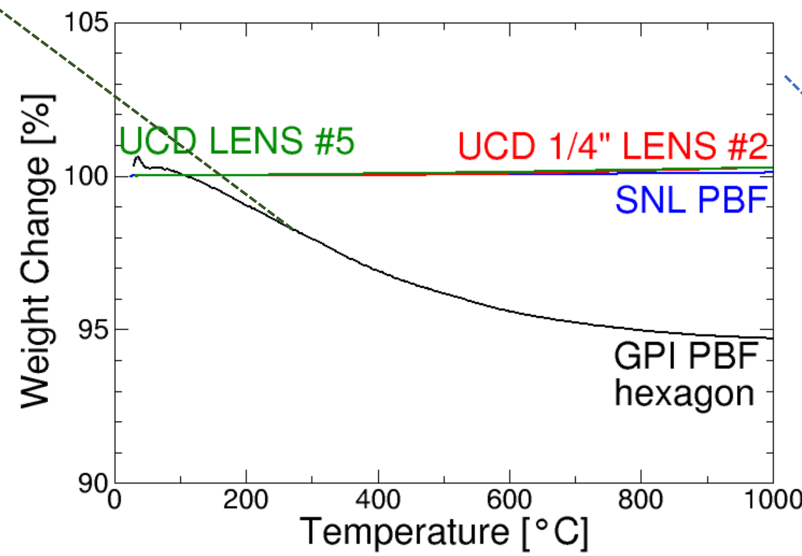
Extra slides

Thermal Desorption Spectroscopy and Thermo-gravometric analysis show Ar loss from pores during heating of GPI hexagon

GPI PBF hexagon

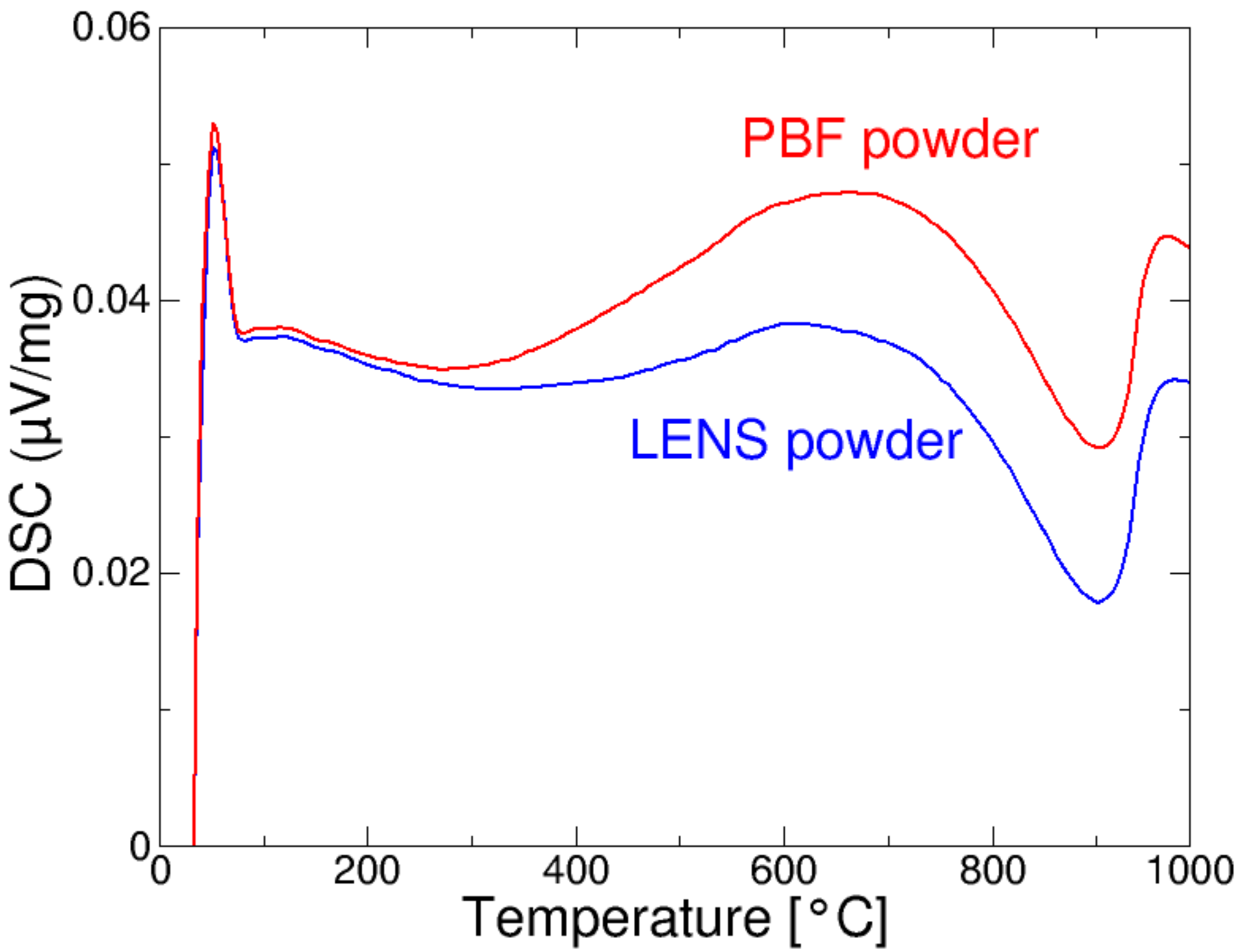


Large weight loss in GPI PBF hexagon attributed to Ar being released from pores



No other build showed weight loss

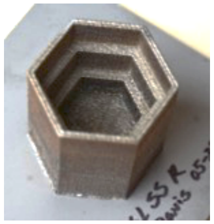
LENS and PBF powders have same transition temperatures



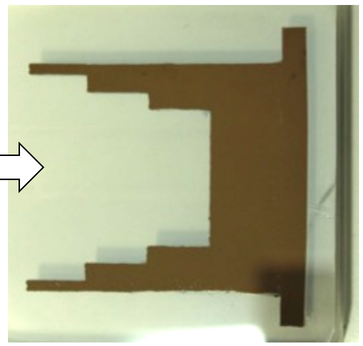
Tm → ~1400 C

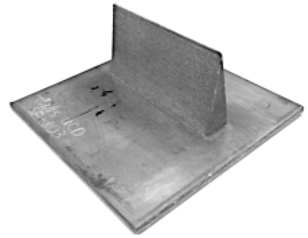
Material strength of the 316L LENS prototypes is geometry dependent, i.e., lower at smaller-sized features

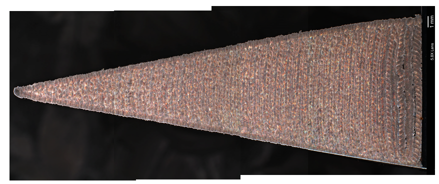
As-printed geometry

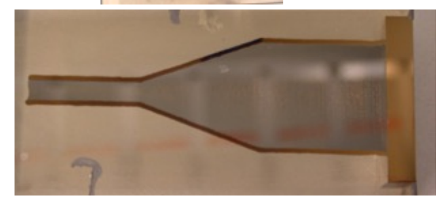


Polished cross sections

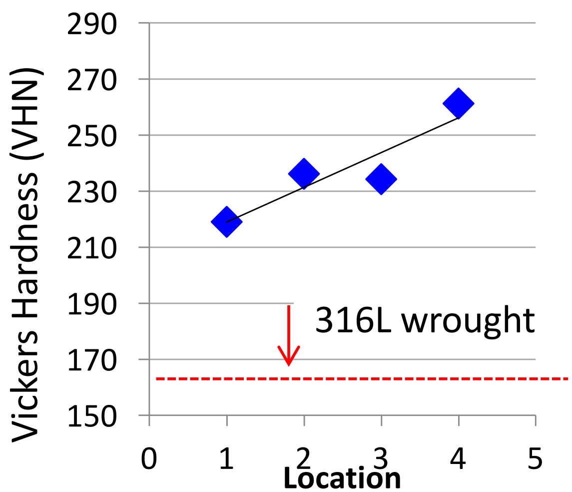




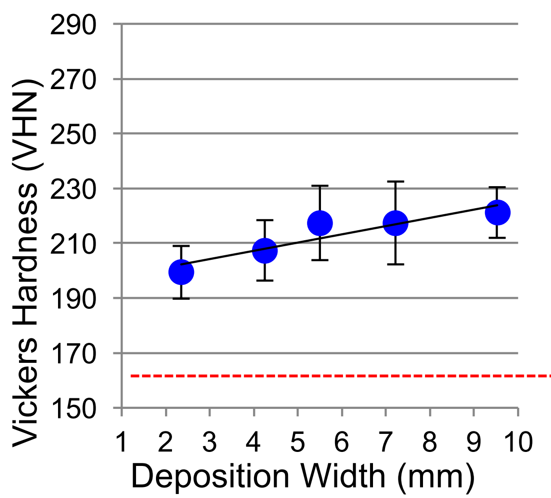


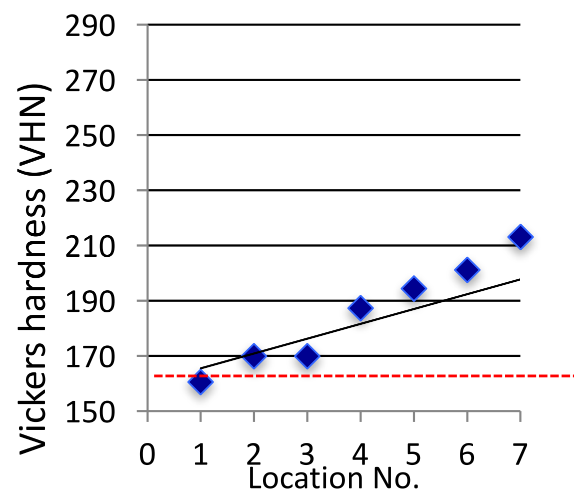


- Harder than wrought 316Lt



- Softer than wrought 316L





The Vickers hardness increases toward the substrate interface in all cases