

Thermal-Mechanical Process Modeling of LENS Additive Manufacturing

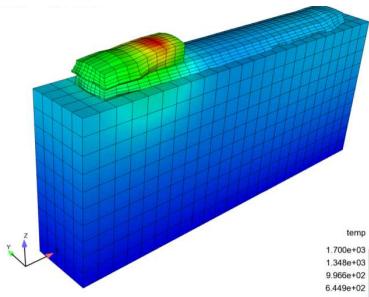
M. E. Stender, L. L. Beghini, M. G. Veilleux, S. R. Subia, J. D. Sugar

April 27th, 2017

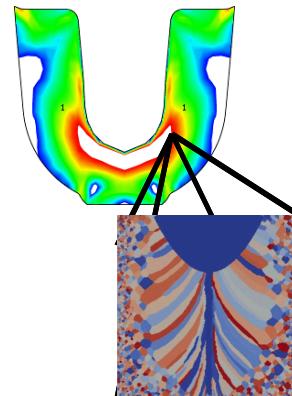
Lifecycle Analysis of Additively Manufactured Components

Process Design and Simulation

Advanced process controls and diagnostics enable simulation tools to “grow” near-net-shape structure

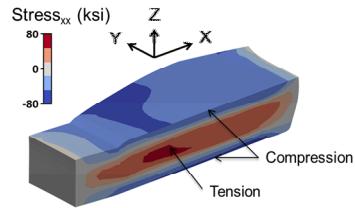


Microstructure and Properties



Internal state variable models account for microstructural evolution and distribution of properties (related to spatial variations of thermal history)

Residual Stresses

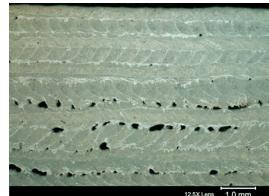


Solidification and thermal history result in strong residual stresses, which can impact performance

Margin/Uncertainty → Design Life

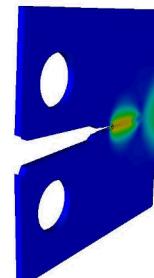
Service requirements may dictate design iteration to assure sufficient margin based on predictive uncertainties.

The lifecycle analysis provides a tool to enable design optimization to meet the requirements.



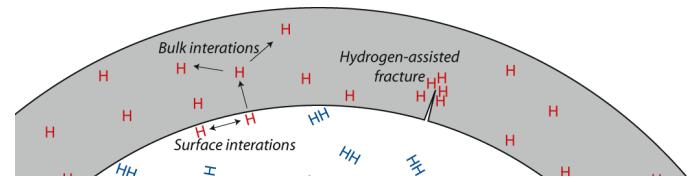
Crack Initiation, Growth and Failure

Transition from crack initiation to failure is not well characterized and depends on microstructure and defects



Assembly and Service

Multiphysics approaches for fully coupled simulation of chemical/thermal transport, mechanical loading, etc. to predict performance



(includes unique service environments, such as hydrogen embrittlement, corrosion, microstructural aging, etc)

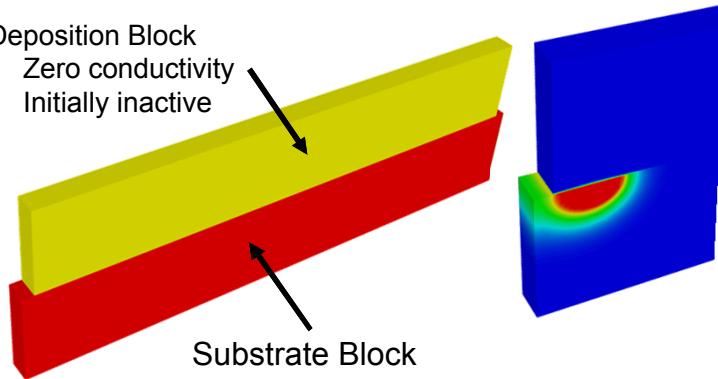
- Predictive uncertainties result in large safety factors, reduced lifetimes, and increased costs.
- Our approach develops tools to reduce uncertainty, increase understanding, and enhance predictive capability.

Process Modeling of LENS Manufacturing

Step 1 Thermal Activation

Initial mesh:

- Deposition Block
- Zero conductivity
- Initially inactive



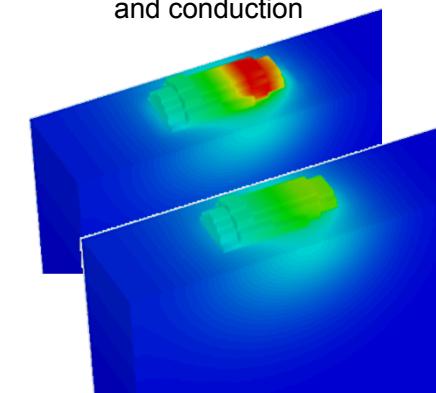
Step 2 Remove Inactive Elements

- Remove elements that are below melt temperature
- Create surfaces for radiation and convection



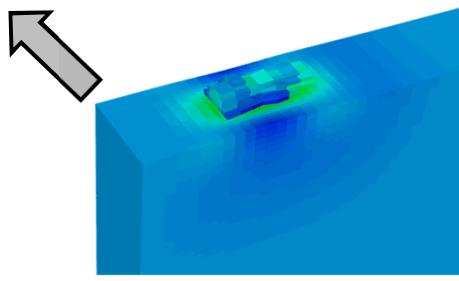
Step 3 Thermal Analysis

- Radiation, convection, and conduction



Step 6 Map Back to Reference Configuration

- Map material state variables, displacements, and temperatures back to original mesh



Step 5 Structural Analysis

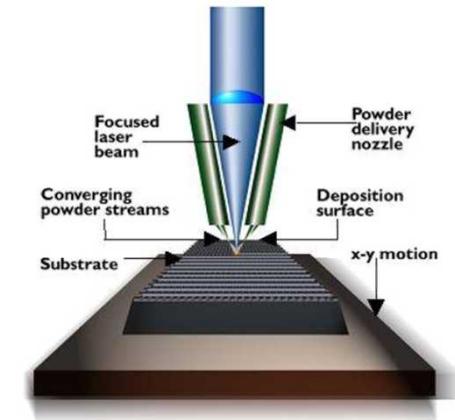
- Calculate residual stresses as a result of thermal gradients
- Solid elements (below melt temperature)
 - Solid material properties
 - Tied contact
- Fluid elements
 - Newtonian fluid material model
 - Sliding frictional contact

Step 4 Map and/or Initialize Mechanical Variables

- Map material state variables and displacements from previous solid mechanics solution
- Newly activated elements are given initial material parameters

Spherical Moving Heat Source

- Material is activated via a spherical, volumetric heat source
 - Inputs: raster path, melt temperature, diameter, efficiency, radius and spatial influence factor
 - Activation user variable – tracks element activation status
 - Zero conductivity in deposition block
 - Laser heat absorbed by specific heat of deposition material within the laser spatial influence
 - Heat not transferred to inactive material



LENS
Process

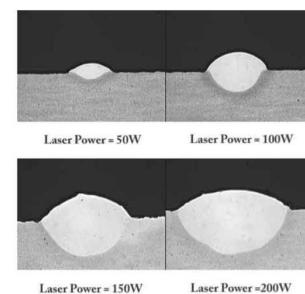
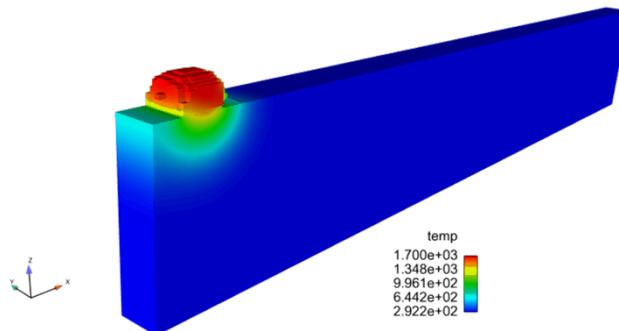
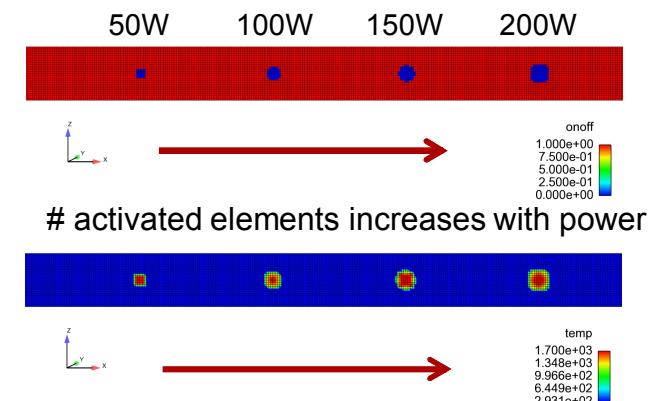


Figure 2: Cross-sectional photographs showing semi-circular type melt pool geometry over a range of laser powers. Travel speed = 5 mm/s, powder mass flow rate = 0.08 g/s.

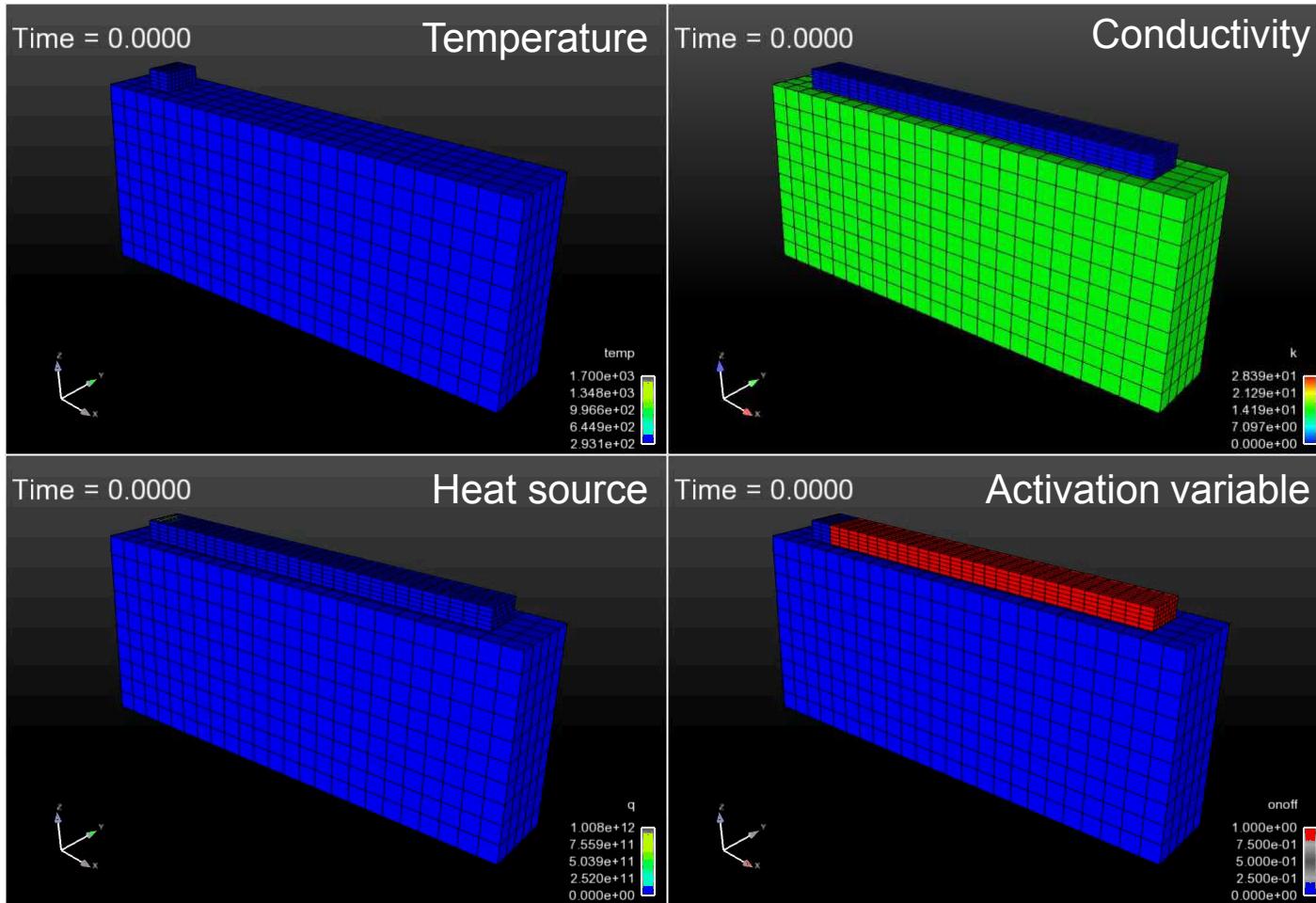
http://www.lehigh.edu/~inemg/Framset/Research_Activities/JLP/LENS/LENS_4.htm



Melt pool size increases with power

Modeling of Material Birthing

- Thermal solution



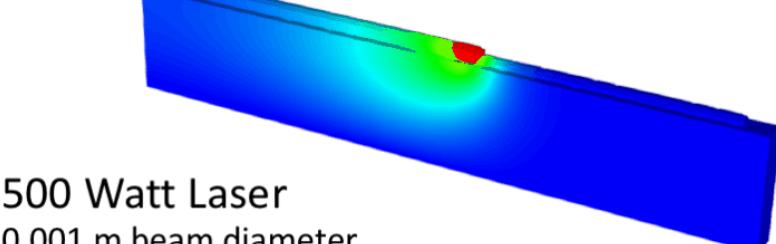
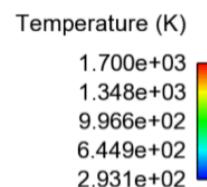
Temperature Profiles Demonstrate the Effect of Laser Power

Thin walled LENS part build

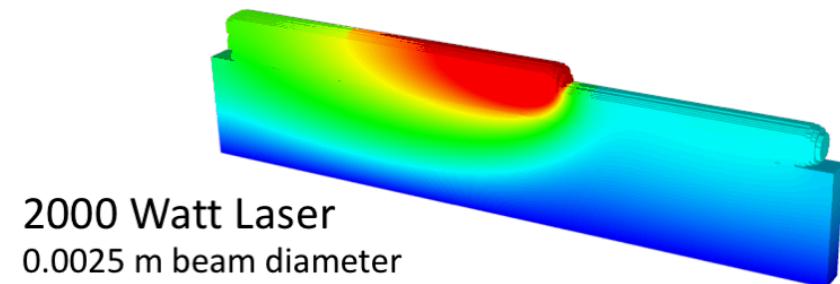
- ~1.8 inches long
- Efficiency = 36%
- Print Speed 20 inches/min
- Material melt temperature = 1700 K



500 W Laser

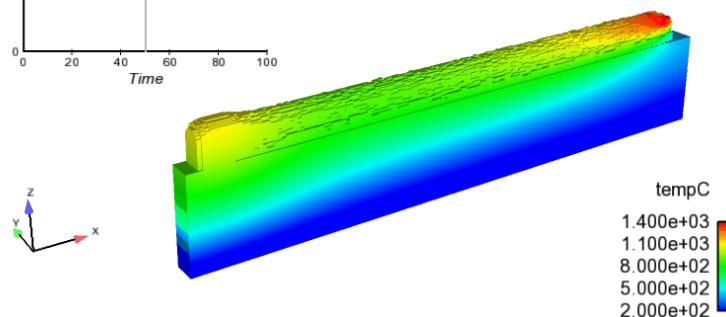
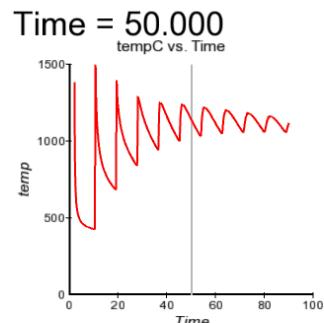


2 kW Laser

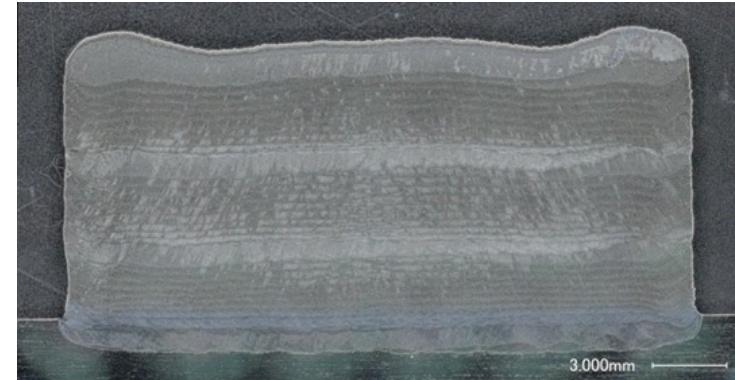


Models Can Predict General Shape

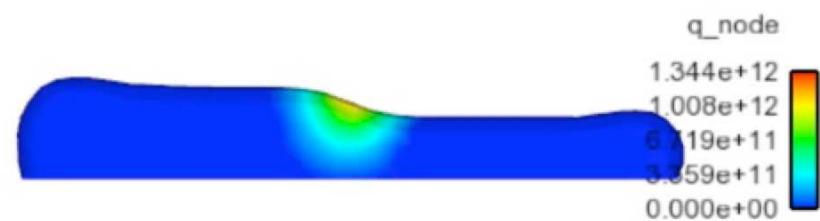
- Validation activities



Modeling the thermal history of
thin wall build

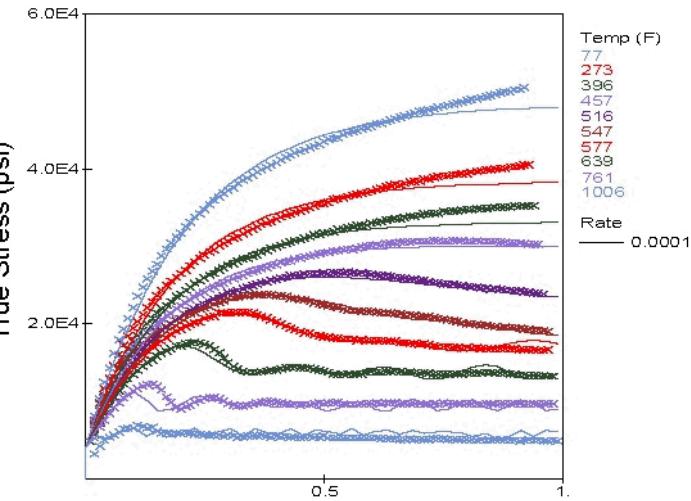
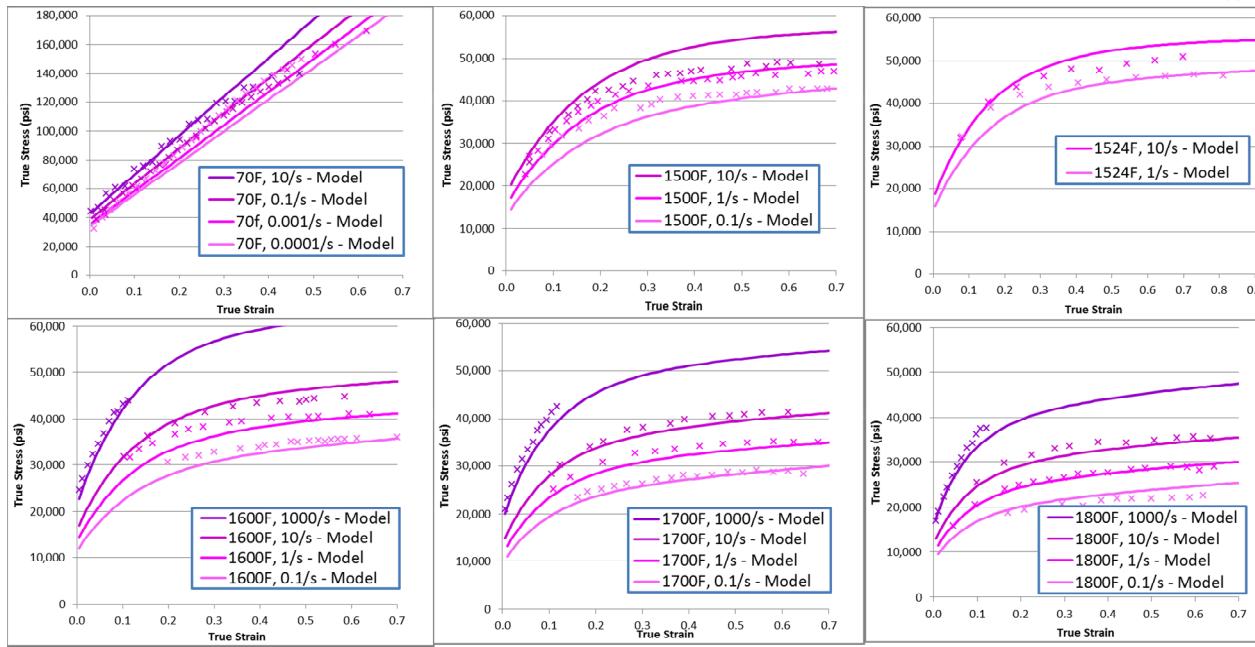


Time = 1.3200



Predictability is Dependent on Material Model

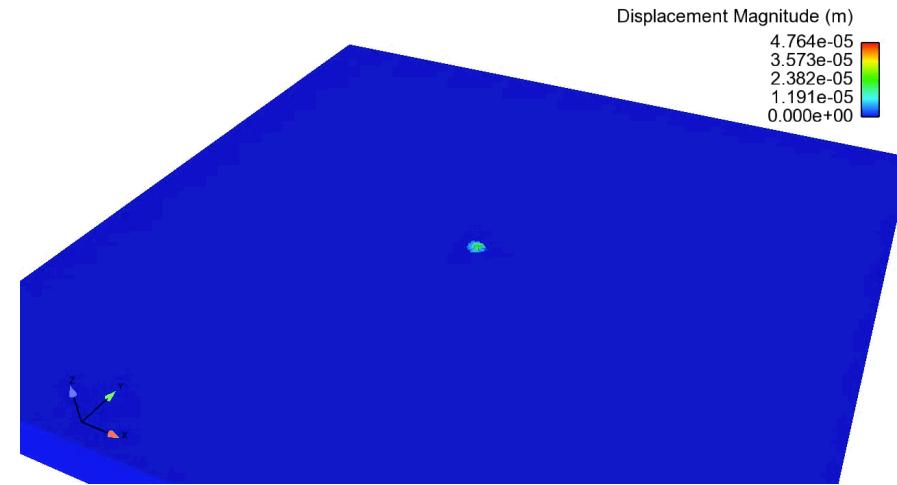
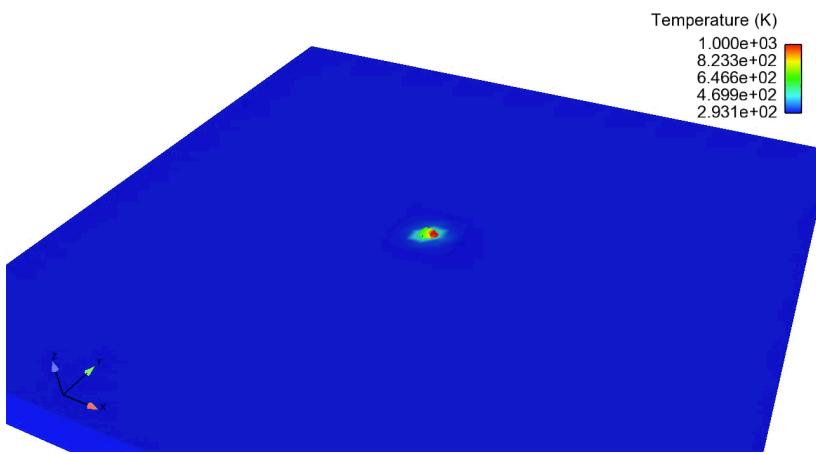
- Thermo-elasto-viscoplastic constitutive model with micromechanical parameters
 - Recrystallization
- For wrought material, model matches experimental response across a wide range of temperatures



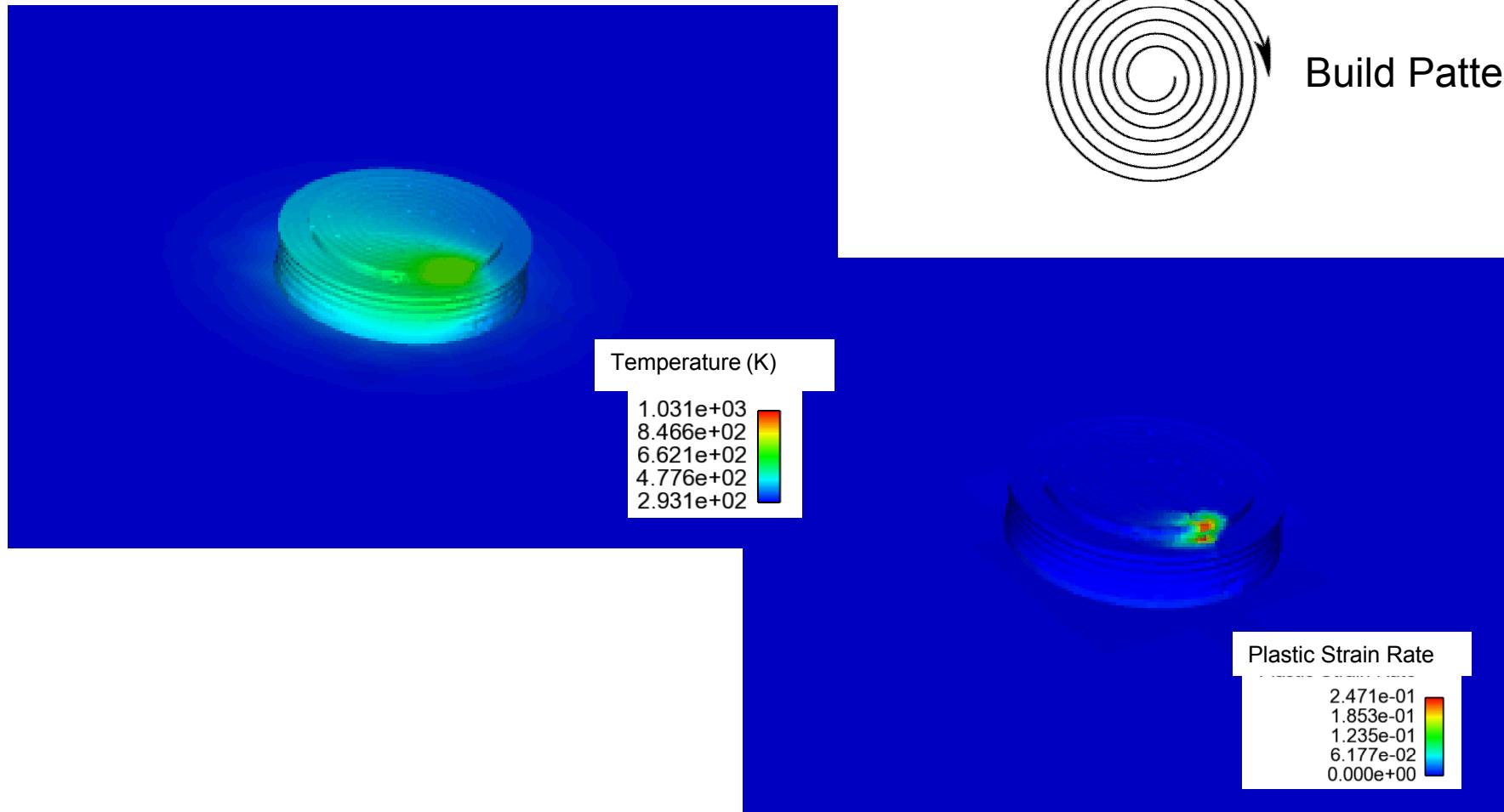
True Strain
Expts: Tanner and McDowell (1999)
Model: Brown and Bammann (2012)
Material: Copper

304L Single-stage compression
(stress-strain data)
Data from B. Antoun

Coupled Thermal Mechanical Modeling

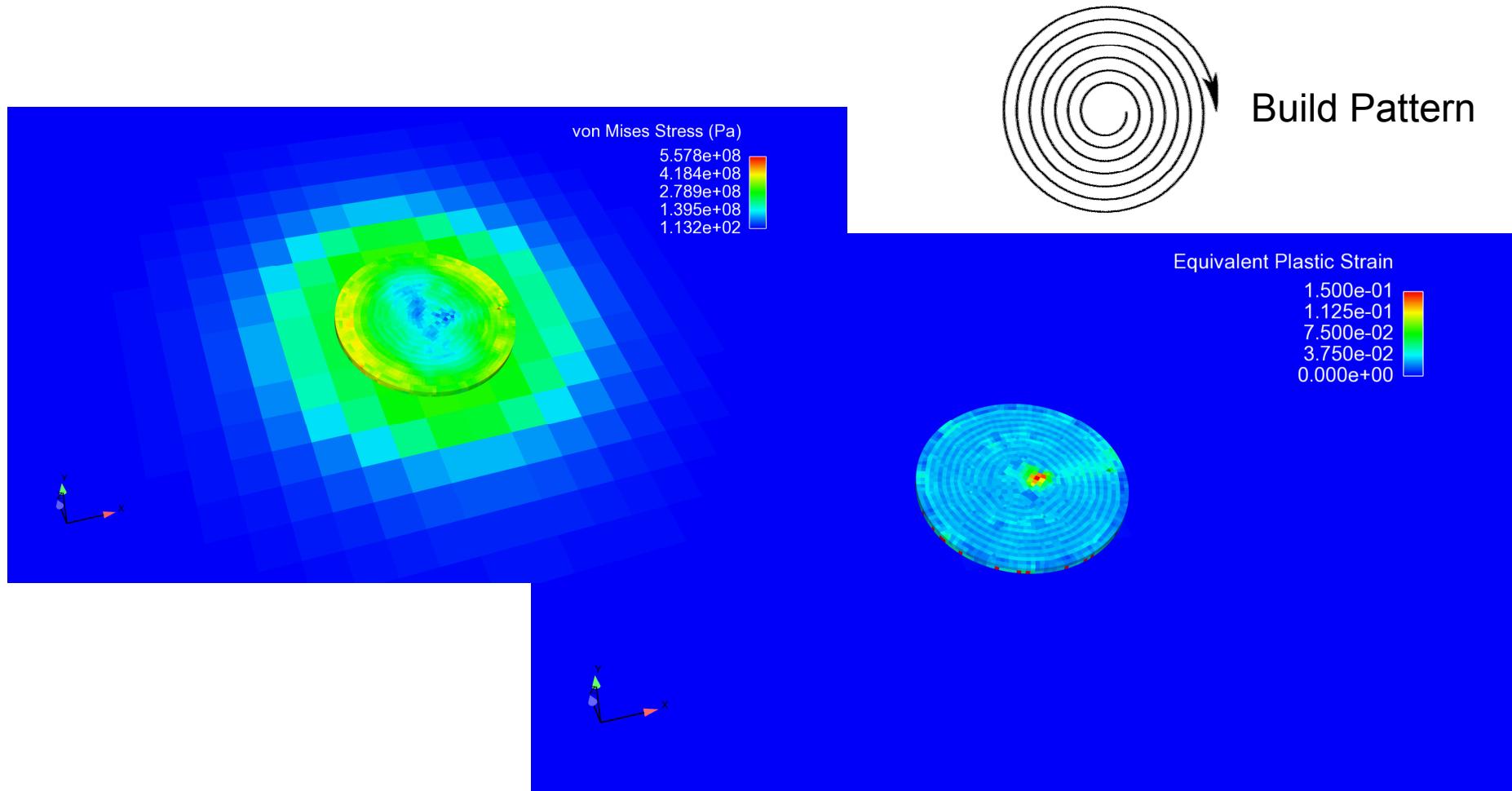


Residual Stresses and Plastic Strains

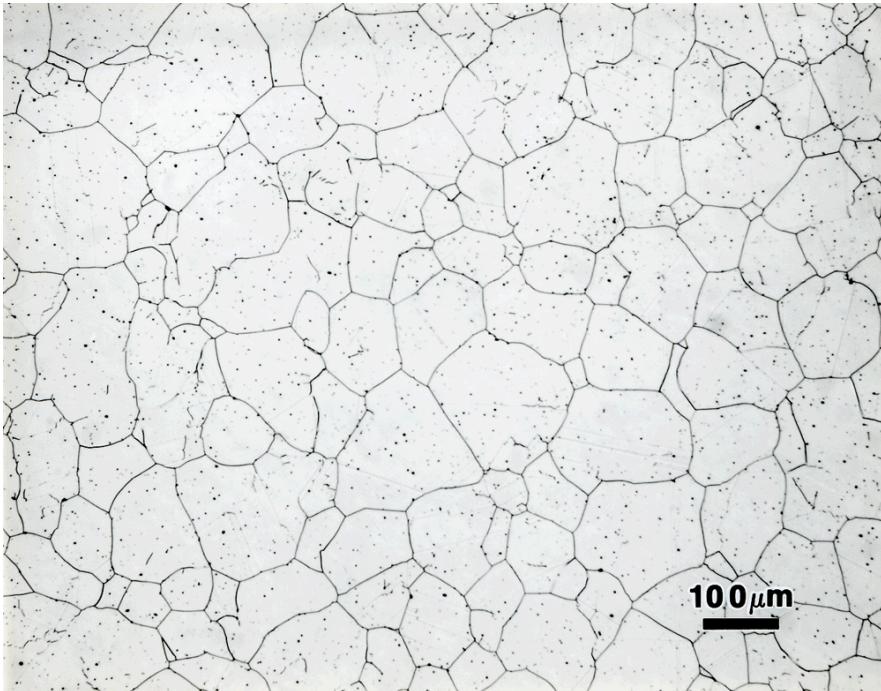


Nonzero plastic strain rate corresponds to high temperature regions

Residual Stresses and Plastic Strains



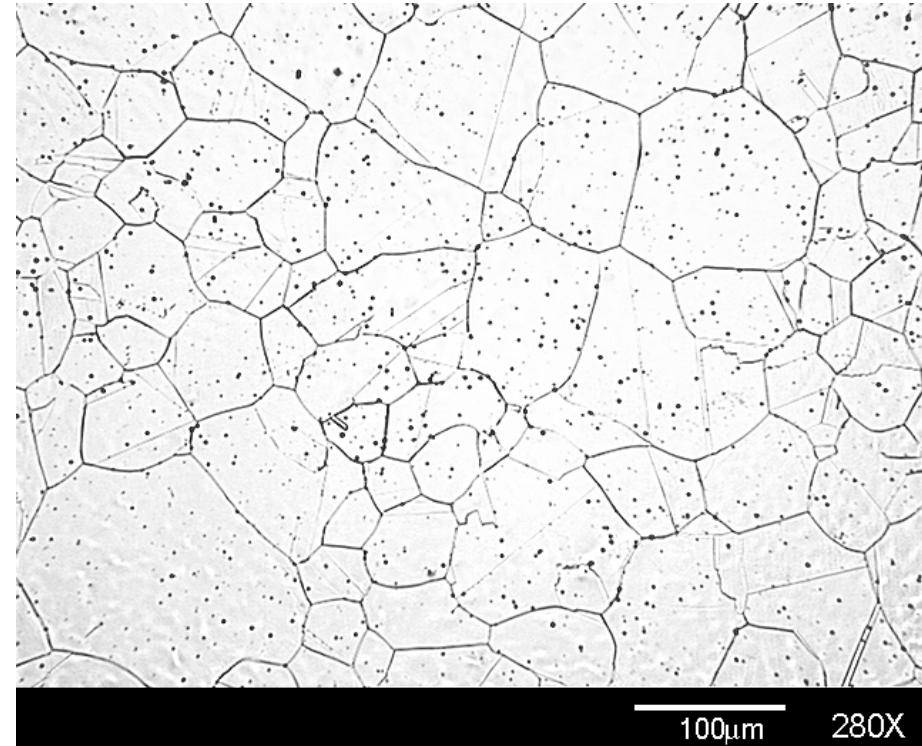
Centuries of Metallurgical Knowledge



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Annealed 316 Stainless Steel
ASM Micrograph Database

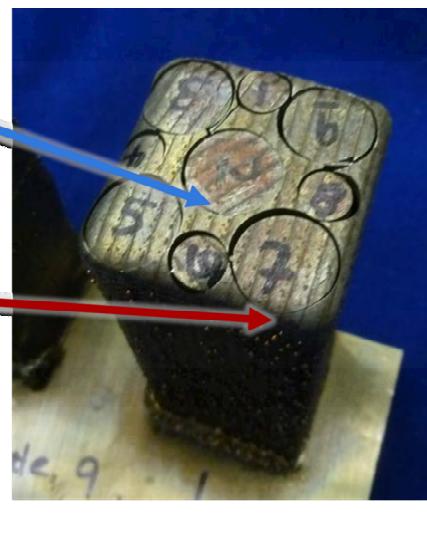
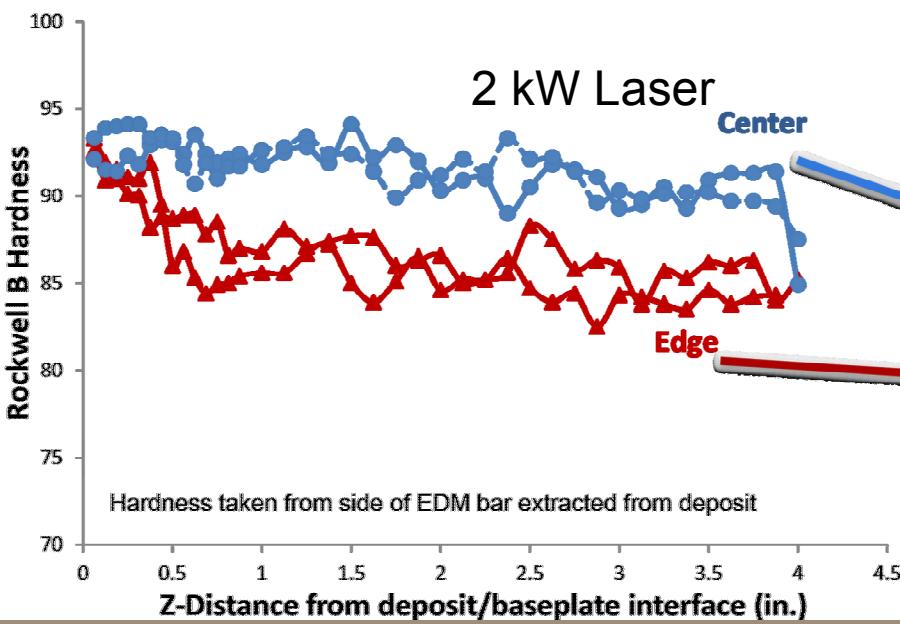
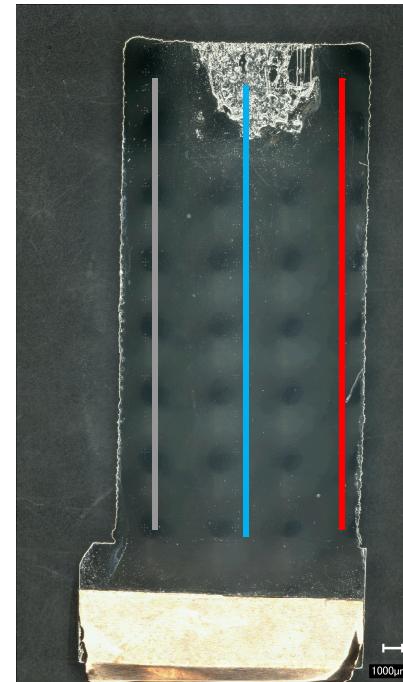
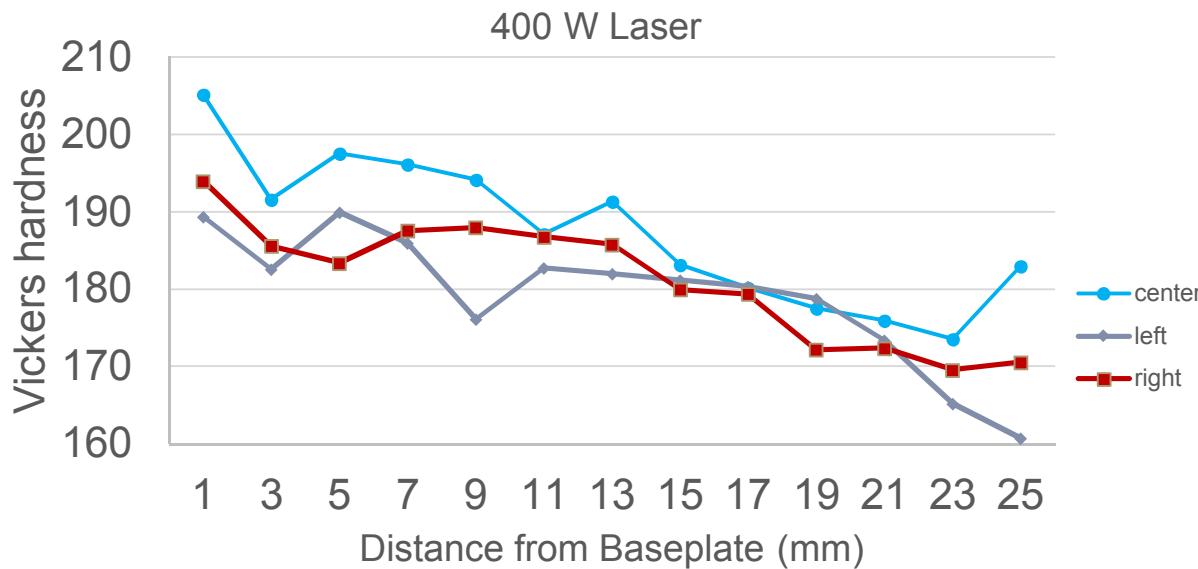
<http://products.asminternational.org/mgd/index.aspx>



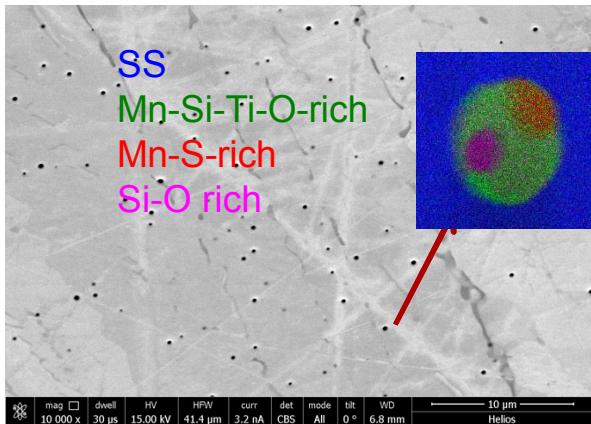
Annealed 316 Stainless Steel
Courtesy of Chris San Marchi

- Annealing conditions that lead to this microstructure are well known, and the properties of this microstructure are well documented

Hardness Values are Higher Near Baseplate

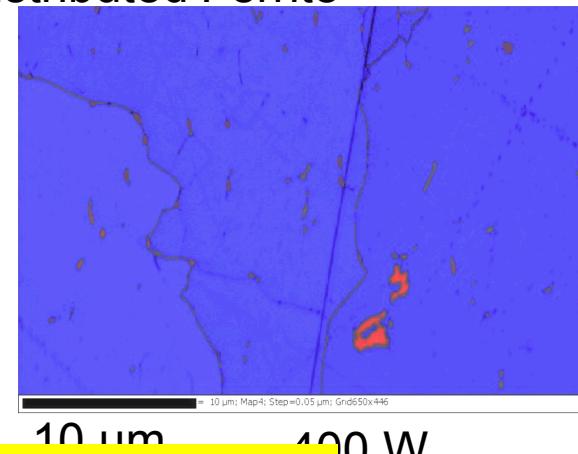
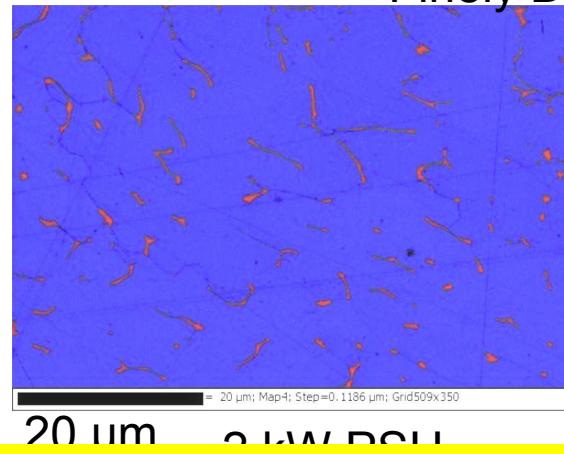


Several Fine-Scale Features to Consider in the Overall Microstructural Picture

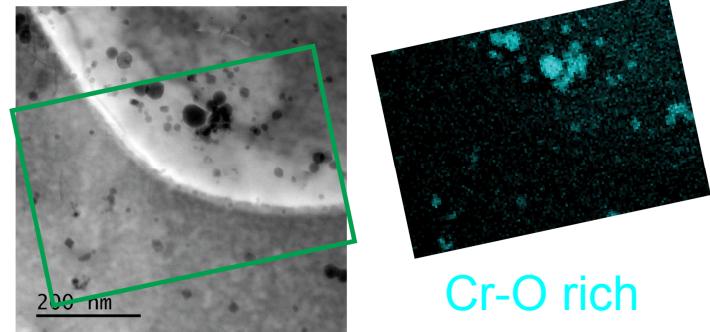


2 kW P
Oxide Par

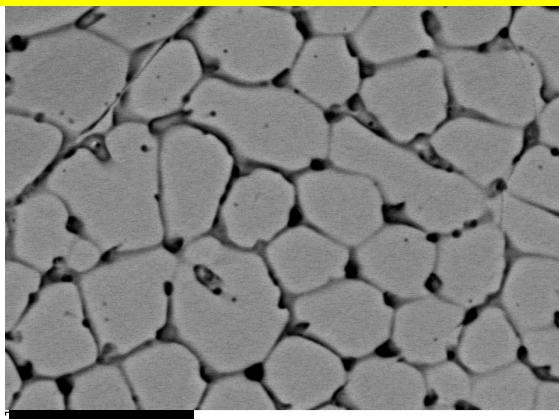
None show an obvious significant variation with distance from baseplate



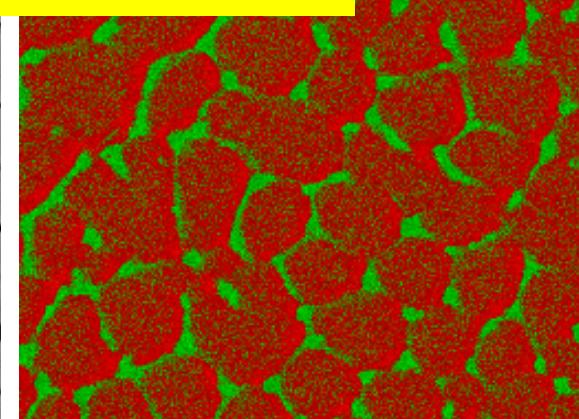
400 W
UCD 316



400 W UCD 316

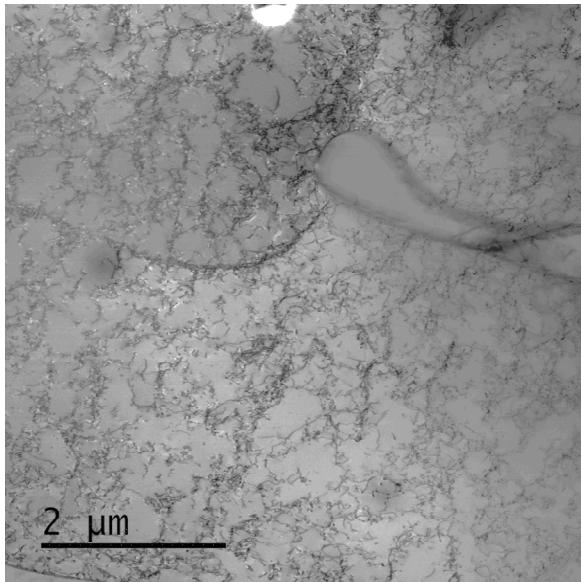


Cellular Solidification Structure

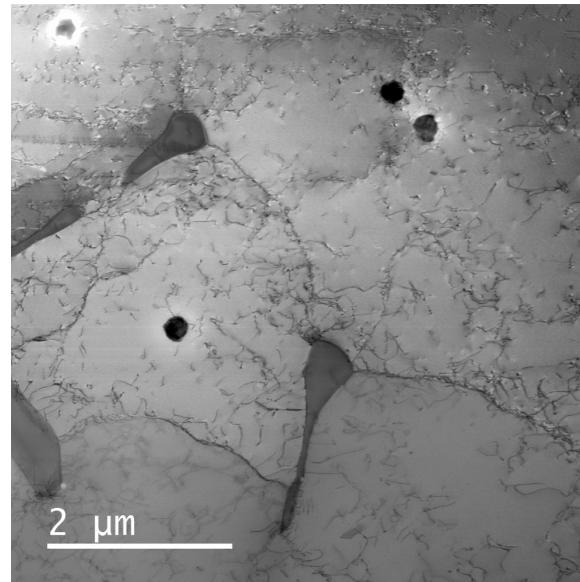


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Dislocation Structure Depends on Location in Build

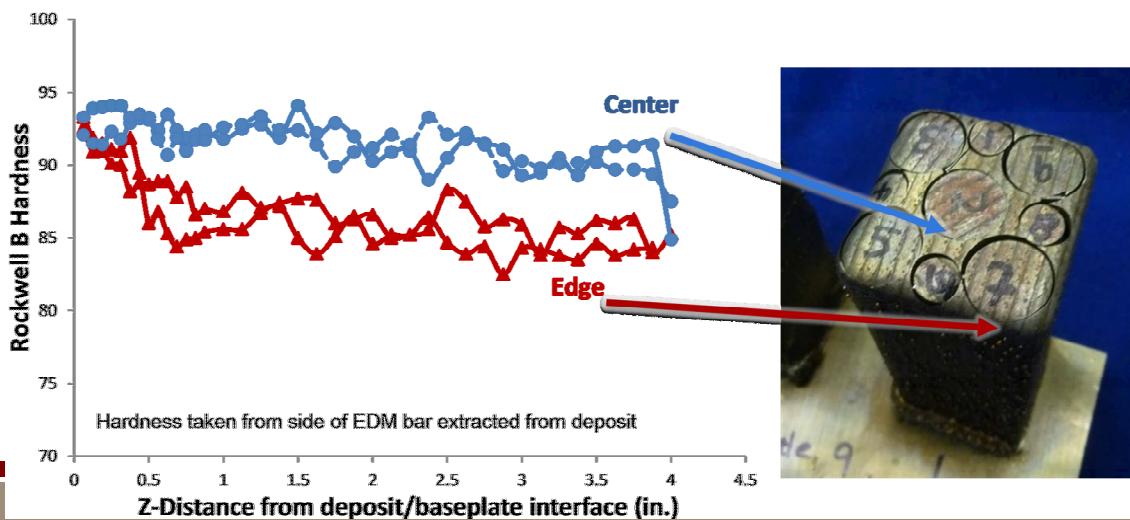


2 mm from Base BF STEM

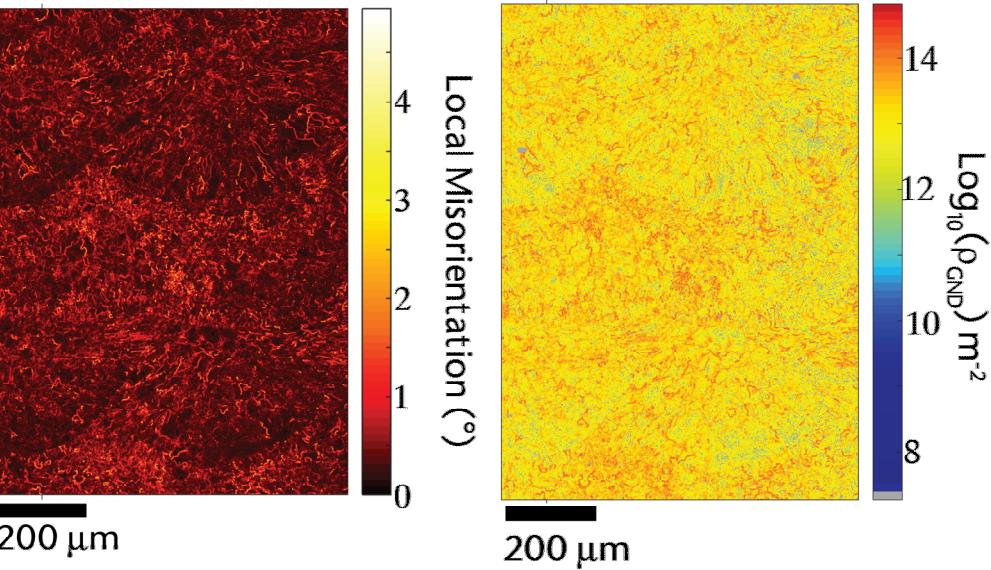
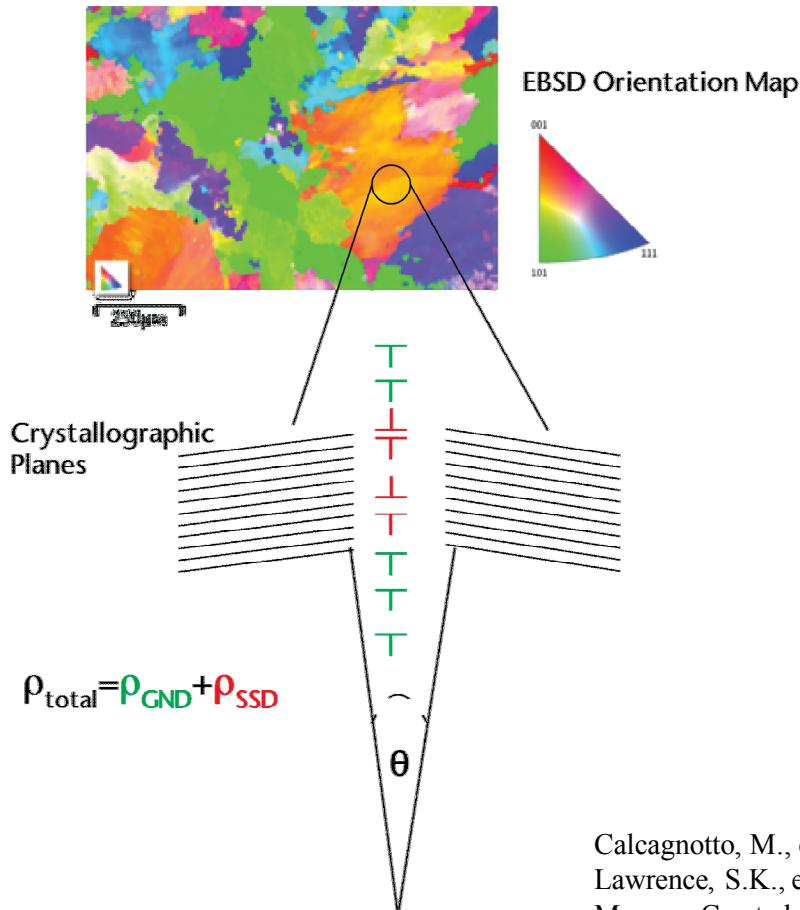


2 mm from Top BF STEM

- Qualitatively, there appear to be less dislocations near the top of the build
- This correlates with lower hardness numbers near the top of the build



Measurement of Geometrically Necessary Dislocations with EBSD

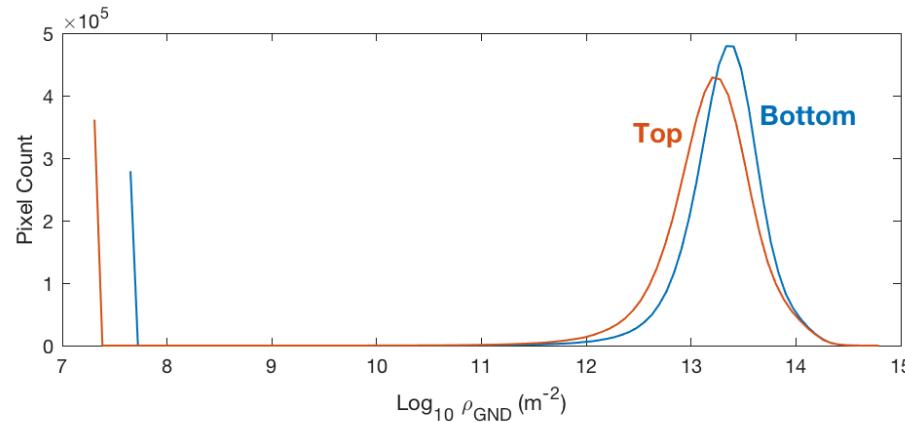
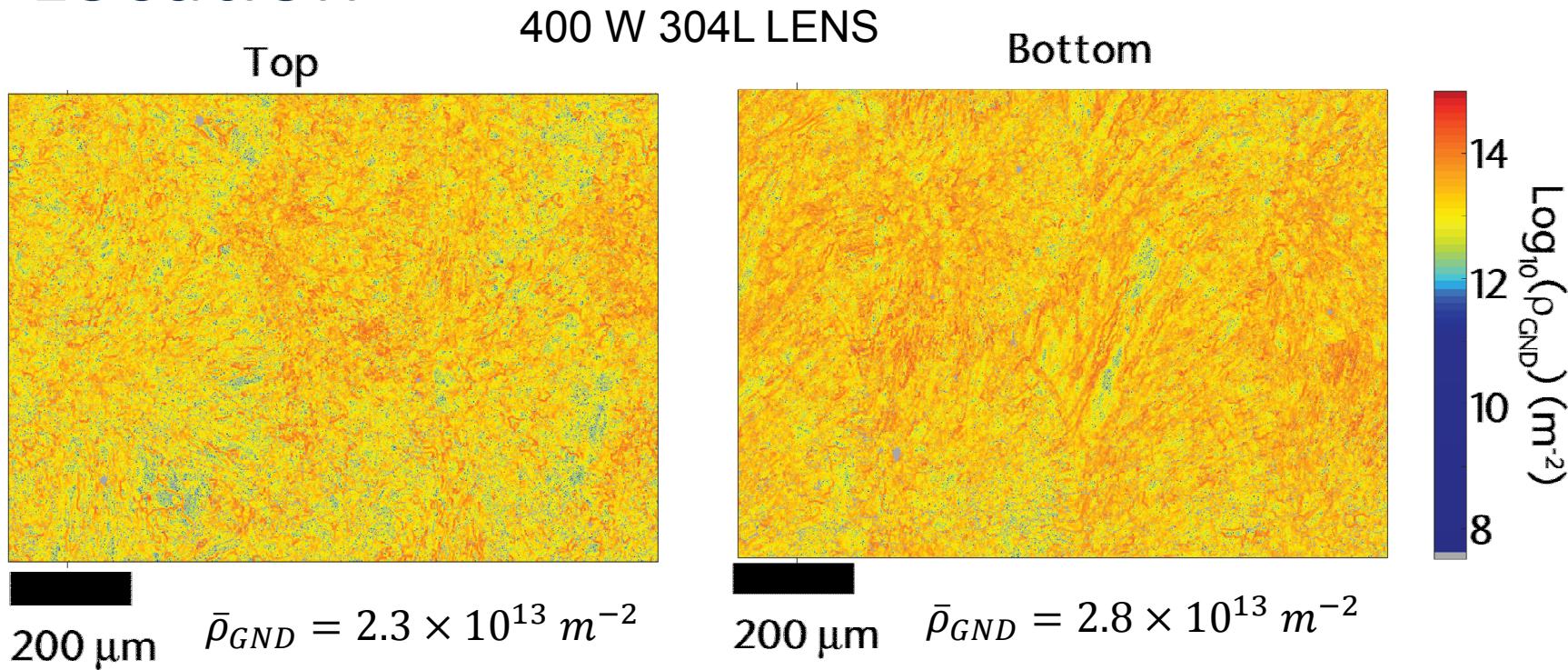


$$\rho_{GND} = \frac{2\theta}{ub} = \frac{2(KAM)}{ub}$$

ρ_{GND} = GND density
 b = burgers vector
 u = unit length

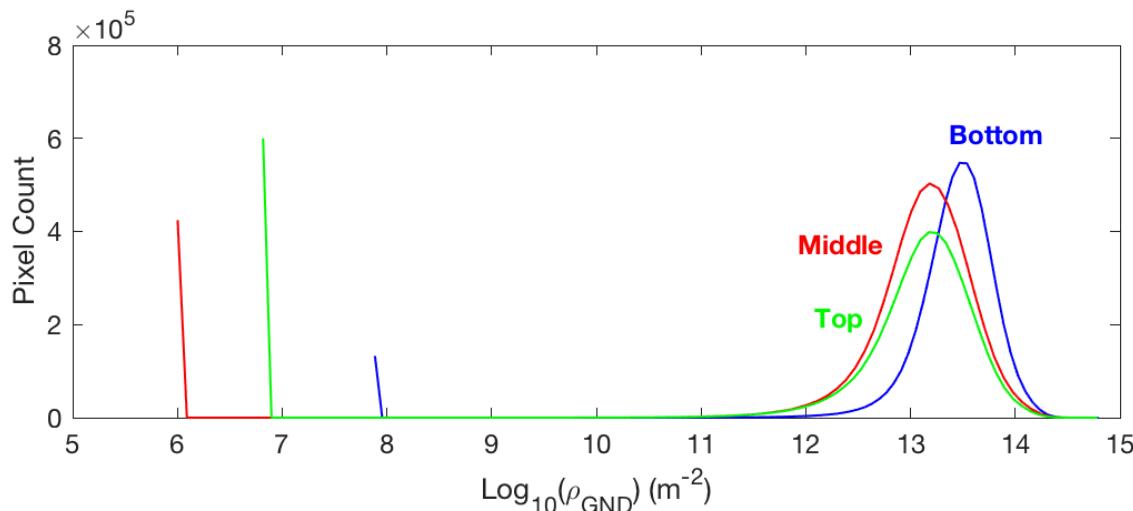
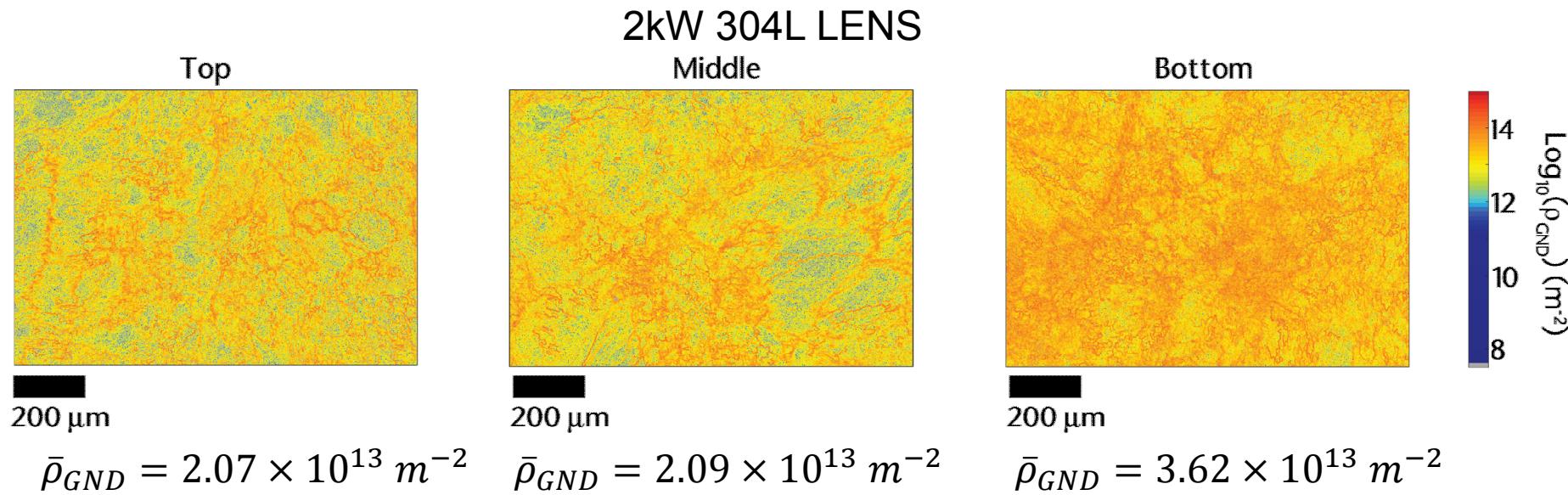
Calcagnotto, M., et al., Materials Science and Engineering: A, 2010. **527**(10–11): p. 2738-2746.
Lawrence, S.K., et al., Metallurgical and Materials Transactions A, 2014. **45**(10): p. 4307-4315.
Moussa, C., et al., IOP Conference Series: Materials Science and Engineering, 2015. **89**(1): p. 012038.
Kubin, L.P. and A. Mortensen, Scripta Materialia, 2003. **48**(2): p. 119-125.
Gao, H., et al., Journal of the Mechanics and Physics of Solids, 1999. **47**(6): p. 1239-1263.
Kamaya, M., Ultramicroscopy, 2011. **111**(8): p. 1189-1199.

GND Distribution Varies with Build Location



Average GND density and GND distribution show higher densities closer to baseplate

GND Distribution Varies with Build Location



Higher energy builds shows same trend of higher dislocation density closer to the base plate

Thermally Induced Plasticity During Processing is Critical

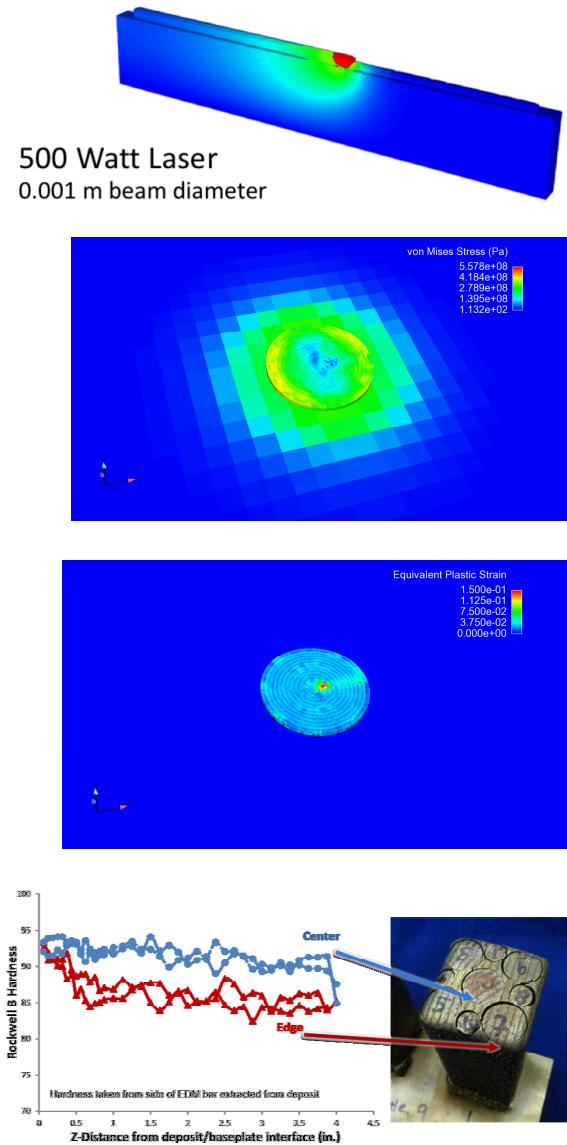


The constraint of the baseplate and thermally induced plasticity during processing make a difference in the dislocation structure and distribution of hardness in LENS 304L stainless steel

This plasticity and the resultant dislocation/hardness/yield distribution are dependent on the geometry of a LENS part

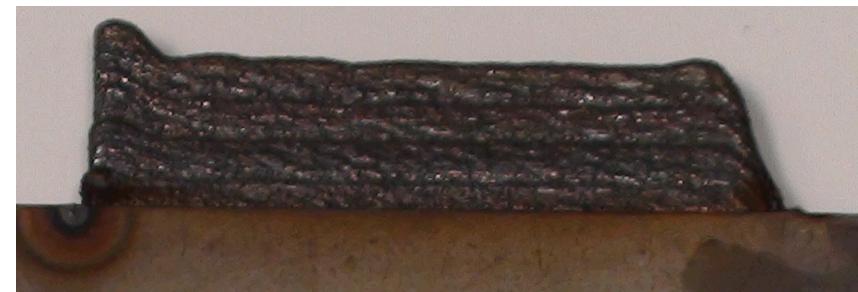
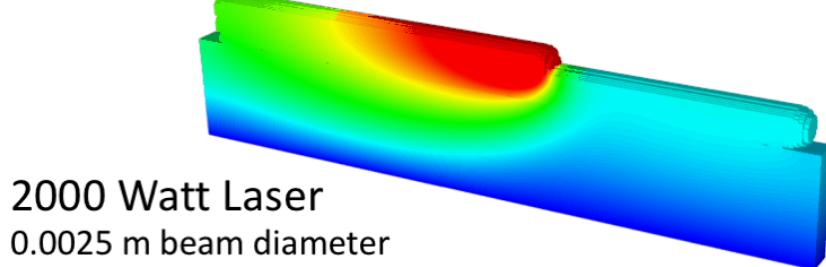
Summary

- A moving heat source has been implemented to enable multiphysics thermal-mechanical modeling of the LENS process for part-scale builds
- Coupled thermal-mechanical simulations predict residual stresses values near the material yield strength of 304L stainless steel
- The prediction of yielding and plastic strain near the baseplate is consistent with microstructural measurements of dislocation density
- Experimental verification of residual stresses and simulations of more complex geometries are currently underway



Conclusions

- The thermally-induced strain and resultant dislocation structure is an important factor in understanding the mechanical property variation in a LENS build
 - The effect of the base plate as a heat sink and a mechanical constraint is significant in the development of microstructure
 - We have measured this in simple builds, but the effect could be more problematic in more complicated builds
- Eventually, these models can be used to optimize build parameters for each specific build geometry
 - Laser pattern can be optimized for residual stress before the build (e.g. spiral out, spiral in or cross hatch)

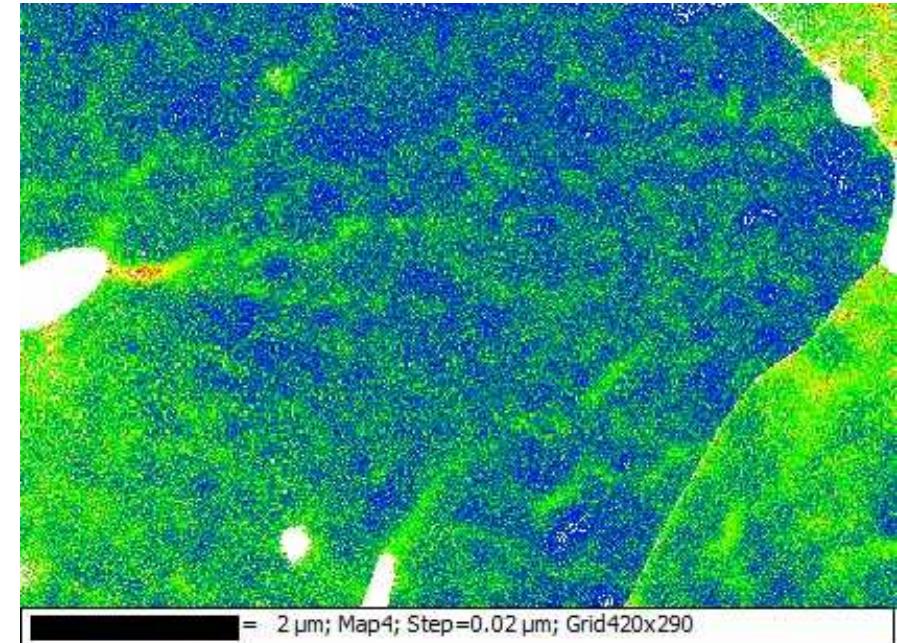
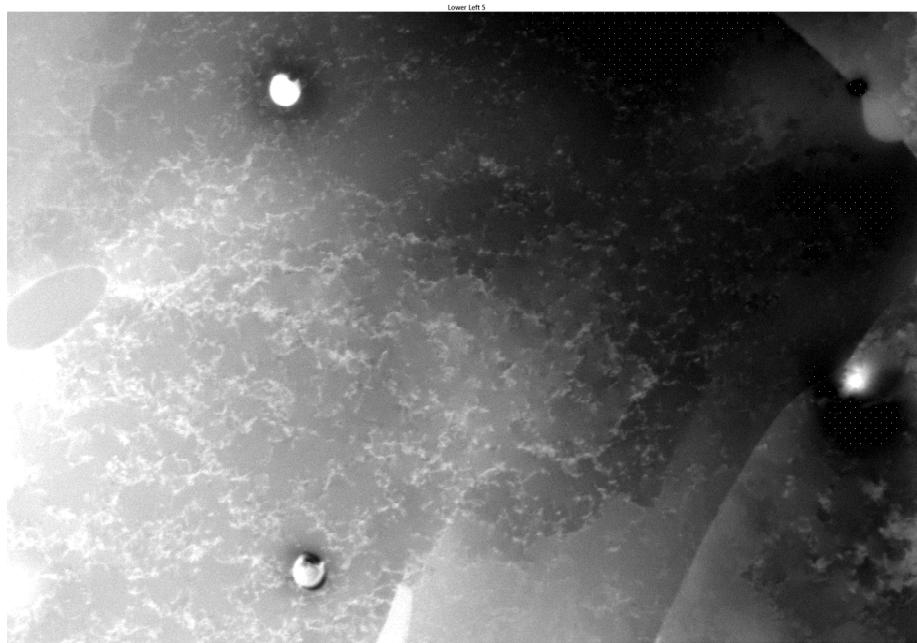


Additional Slides



GND Measurements Correlate With STEM Images of Dislocation Structure

$$\rho_T = \rho_{GND} + \rho_{SSD}$$



Measurements of local averaged misorientation for GNDs are consistent with images of the more general dislocation structure. Higher misorientations occur where the images show higher dislocation densities.



0°

1°

Local Averaged Misorientation