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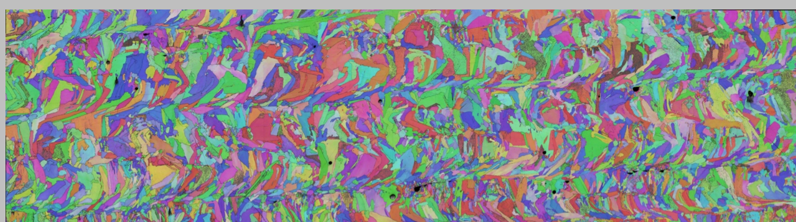
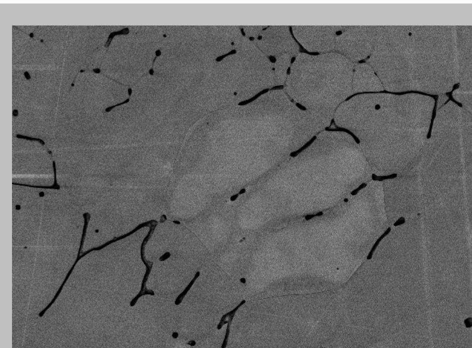
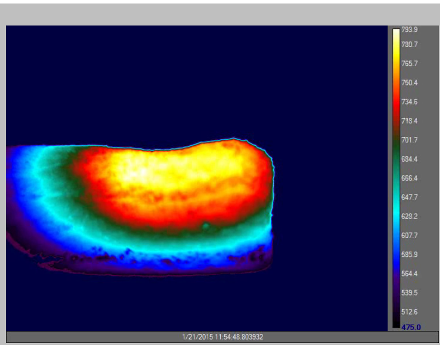
February 26 – March 2, 2017
San Diego, California, USA







Microstructure Variation and Process Model Developments for LENS

J.D. Sugar, L. Beghini, M. Stender, M. Veilleux, D. Keicher, D. Dagel, M. Maguire, and C. San Marchi

Feb. 28, 2017

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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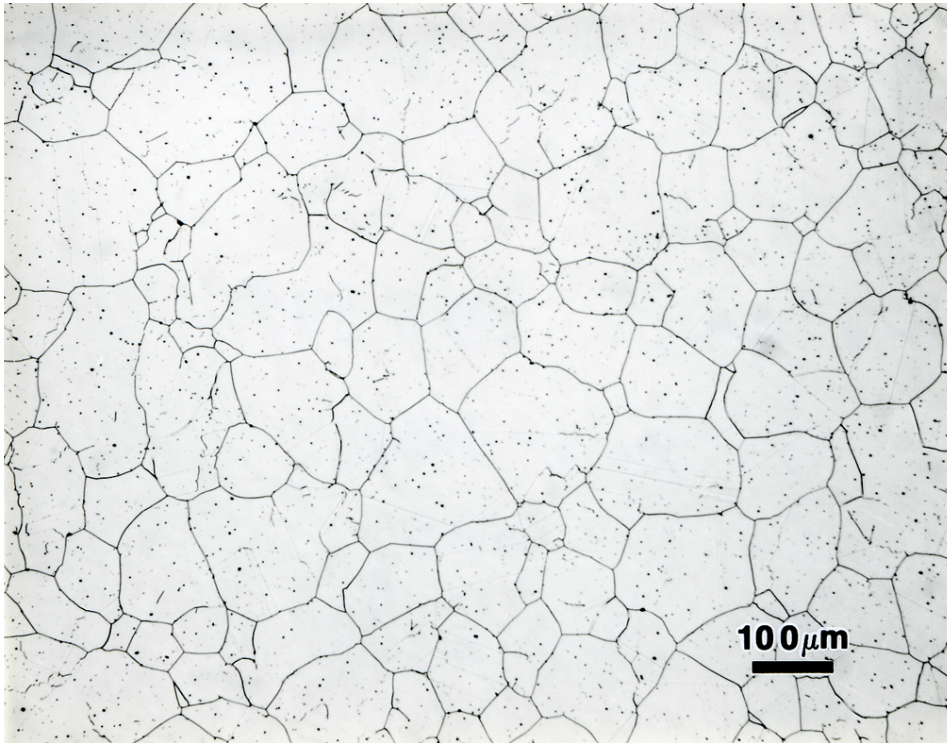
- Thale Smith and Professor Julie Schoenung (UC Davis/Irvine): LENS material and Characterization

- Advertisement
  - Fracture and Fatigue Behavior of Additively Manufactured Austenitic Stainless Steel; presenter: Chris San Marchi; **Wednesday 4:10 Room 7B**
  - Microstructure and Mechanical Behavior of Additively Manufactured Austenitic Stainless Steel; Thale Smith; **Thursday 4:30 Room 7B**

Centuries of Metallurgical Knowledge



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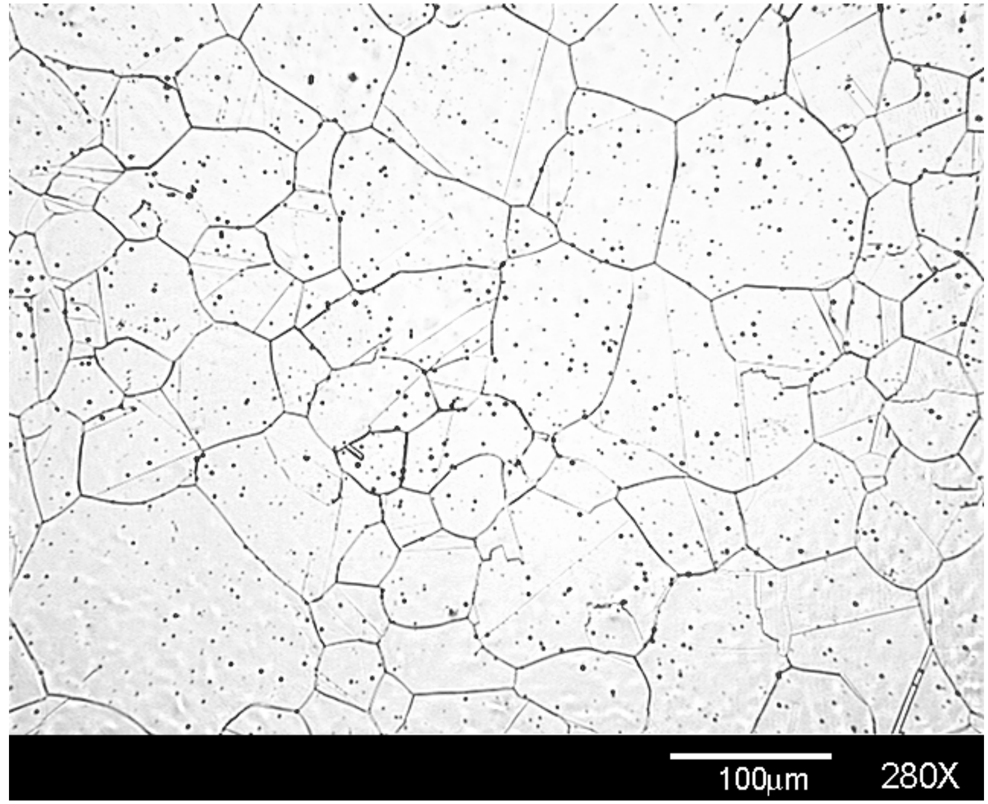

Annealed 316 Stainless Steel
ASM Micrograph Database

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

Need To Fundamentally Understand the Processing-Microstructure-Property Relationships

- An alternative to an empirical database like ASM based on physics
- We must understand the mechanisms that contribute to the microstructural development during AM processes
- Properties and final form/function are coupled in AM through processing parameters (thermal history) and slice/build approach

- Goal is to answer:
- How do thermal and compositional gradients compete to effect the rapidly solidified microstructure during AM, and how does this ultimately affect properties?
- Develop a process model to predict lifetime performance that is validated by in situ thermal measurements

Lifecycle Analysis of Additively Manufactured Components

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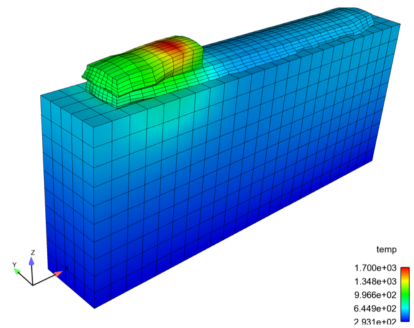
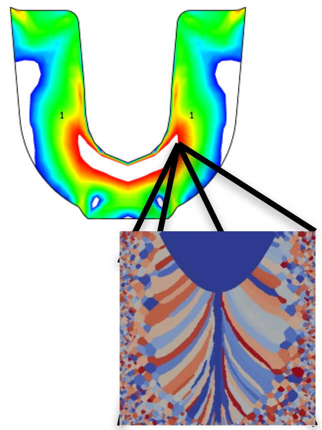
Process Design and Simulation

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

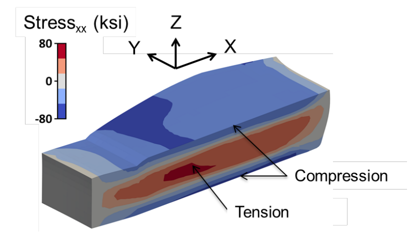


Microstructure and Properties



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

Residual Stresses

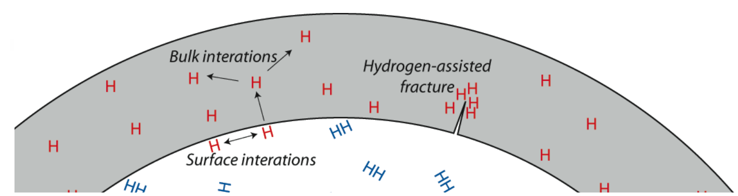


Solidification and thermal history result in strong residual stresses, which can impact performance

- 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.

Assembly and Service

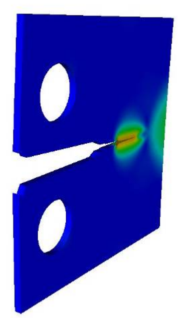
Multiphysics approaches for fully coupled simulation of chemical/thermal transport, mechanical loading, etc. to predict performance



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

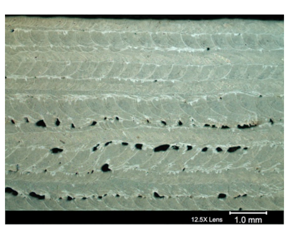
Crack Initiation, Growth and Failure

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



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.



Lifecycle Analysis of Additively Manufactured Components

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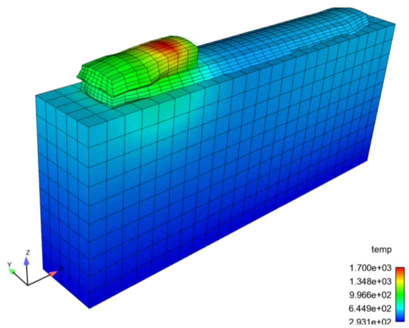
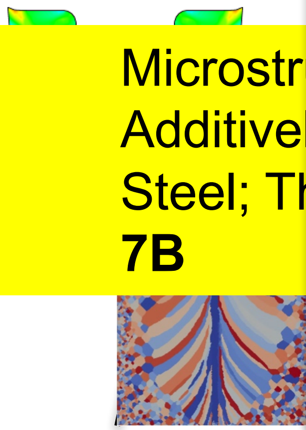
Advanced process controls and diagnostics enable simulation tools to "grow" near-net-shape structure

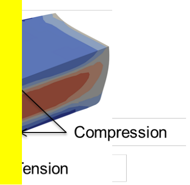


Microstructure and Properties



Microstructure and Mechanical Behavior of Additively Manufactured Austenitic Stainless Steel; Thale Smith; **Thursday 4:30 Room 7B**

Residual Stresses



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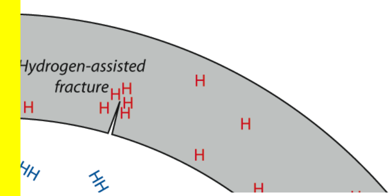

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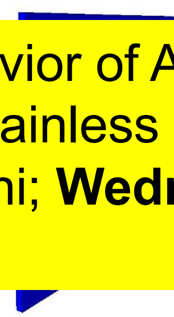
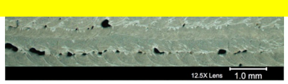
Crack Initiation, Growth and Failure





Fracture and Fatigue Behavior of Additively Manufactured Austenitic Stainless Steel; presenter: Chris San Marchi; **Wednesday 4:10 Room 7B**

Process modeling of LENS manufacturing

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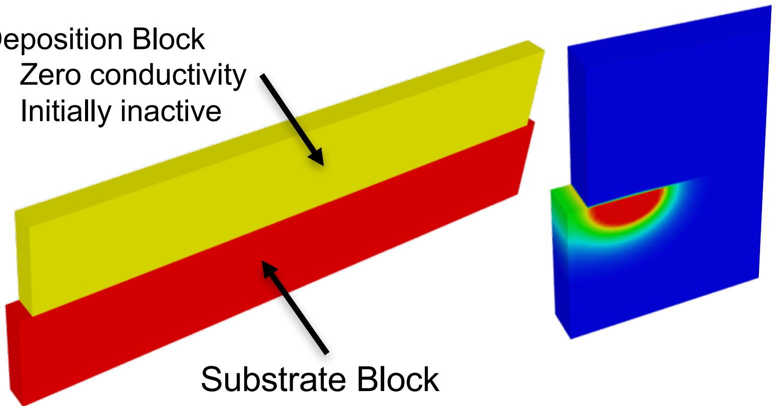
Step 1 Thermal Activation

Initial mesh:

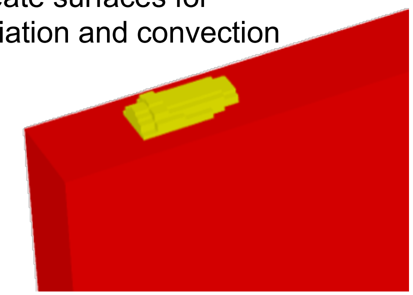
Deposition Block
- Zero conductivity
- Initially inactive



Substrate Block

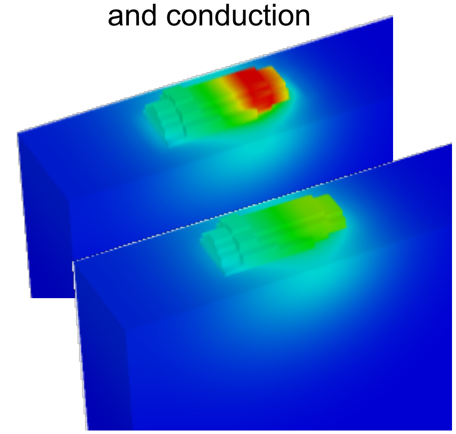
Step 2 Remove Inactive Elements

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



Step 3 Thermal Analysis

- Radiation, convection, and conduction

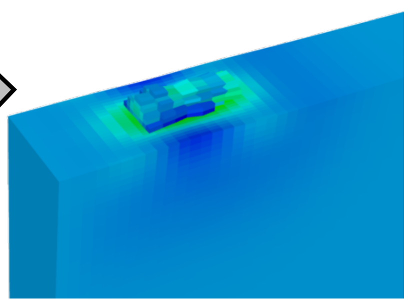


Step 4 Map and/or Initialize Mechanical Variables

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

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



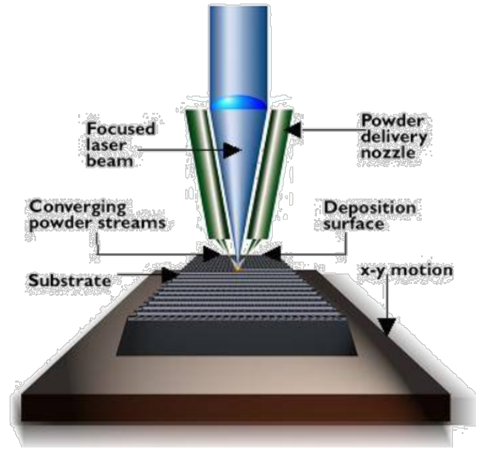
* Displacements shown 15x

Step 6 Map Back to Reference Configuration

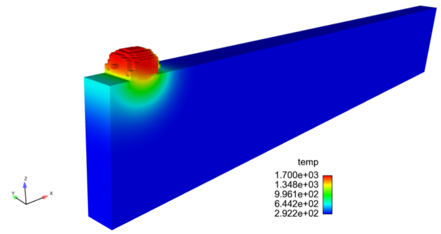
- Map material state variables, displacements, and temperatures back to original mesh

Spherical Moving Heat Source in Aria

- Material is activated via a spherical, volumetric heat source
  - Inputs: raster path, melt temperature, diameter, efficiency, radius and spatial influence factor
  - Activation user variable – toggles conductivity on/off within the sphere



LENS Process



  - Activation and melt pool size based on variable input power

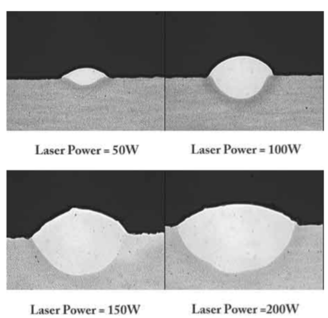
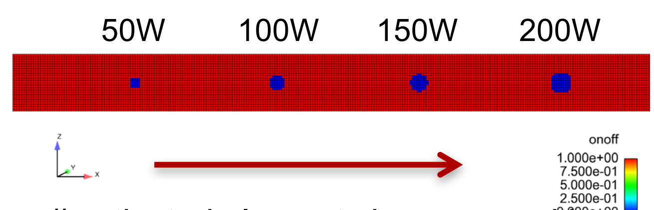
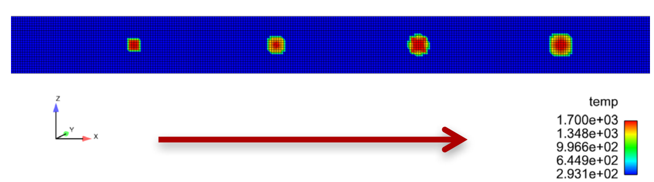


Figure 2: Cross-sectional photographs showing semi-circular type melt pool geometry over a range of laser powers. Travel speed = 5 mm/s, powder mass flow rate = 0.08 g/s.

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



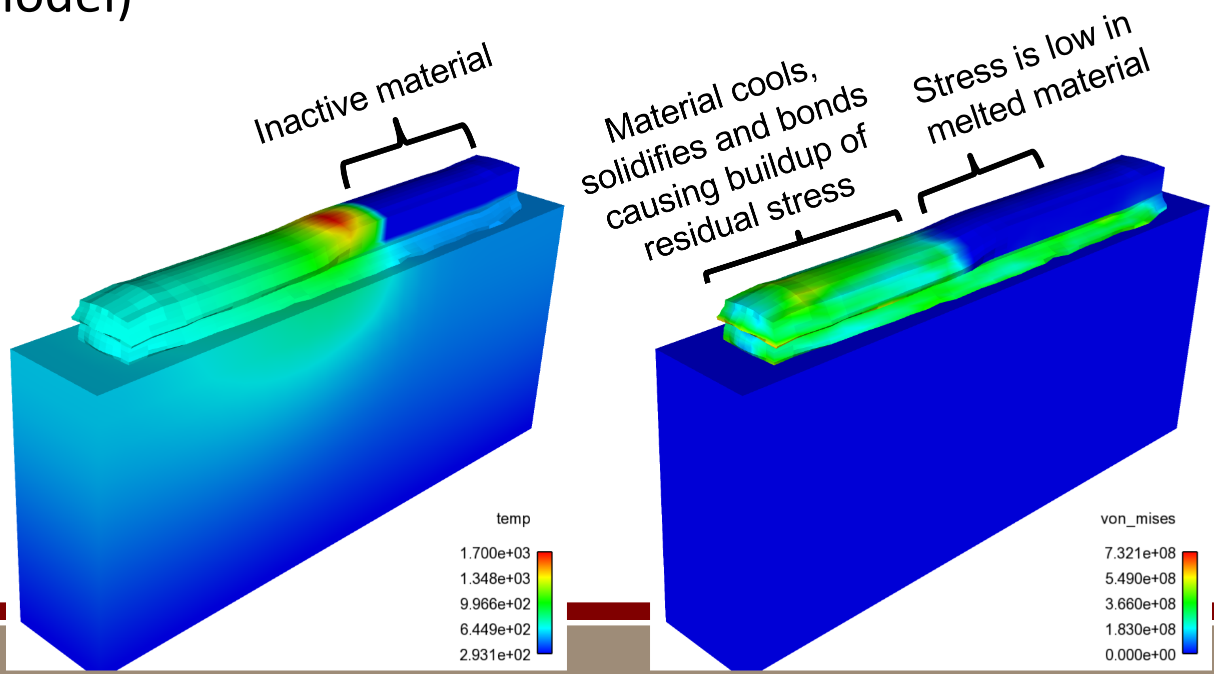
activated elements increases with power



Melt pool size increases with power

Building Models to Birth AM Material: LENS

- Sandia Aria/Presto based code
  - Traveling volumetric heat source based on path (x,y,z), power, efficiency, diameter
  - Element birth from inactive elements: physical properties turn on when interact with traveling heat source
  - Phase transformation ~ 1700k
  - Deformation from gravity
  - Contact transitions from Coulomb to glued (sliding to tied friction model)



Modeling of Material Birthing

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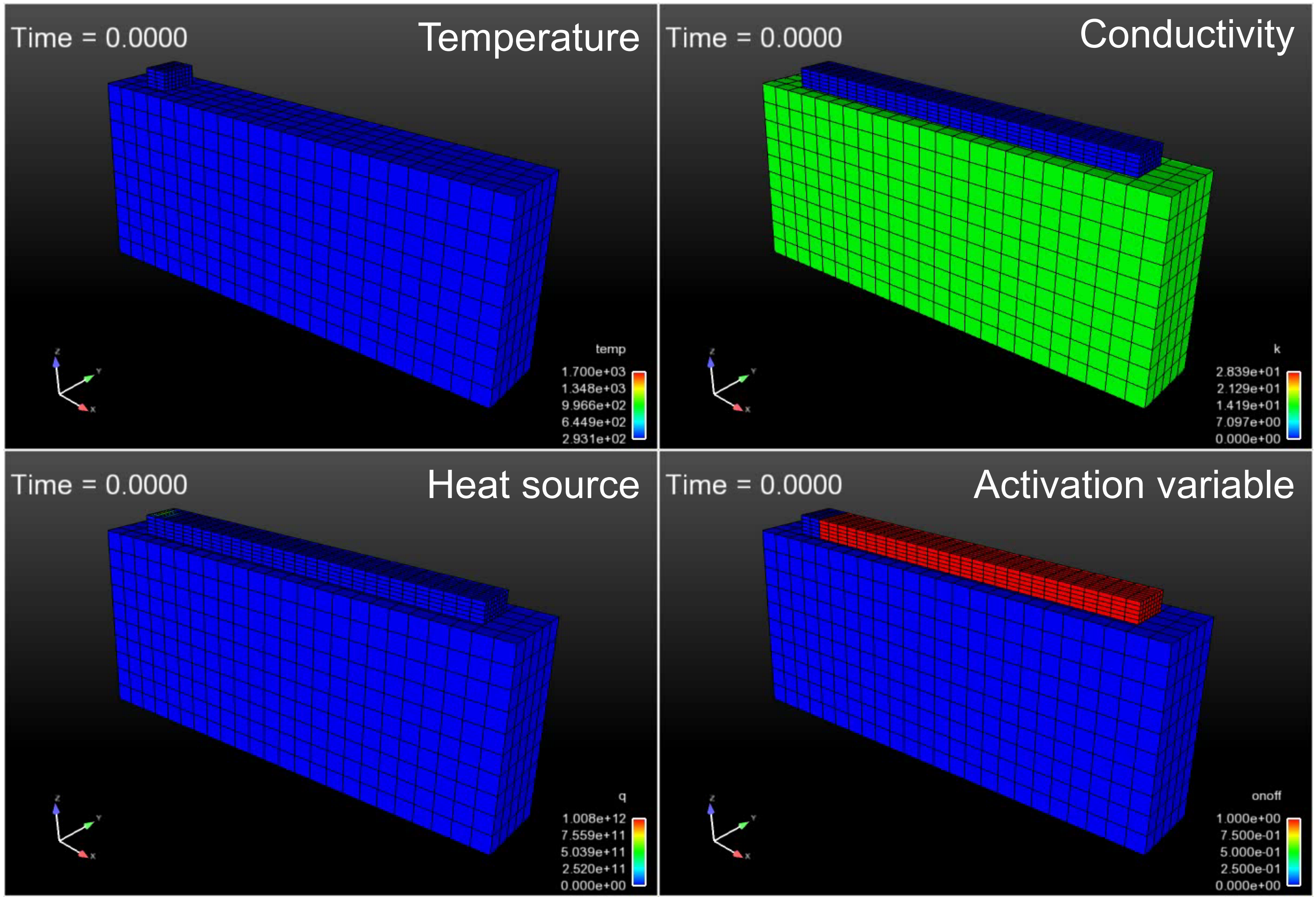
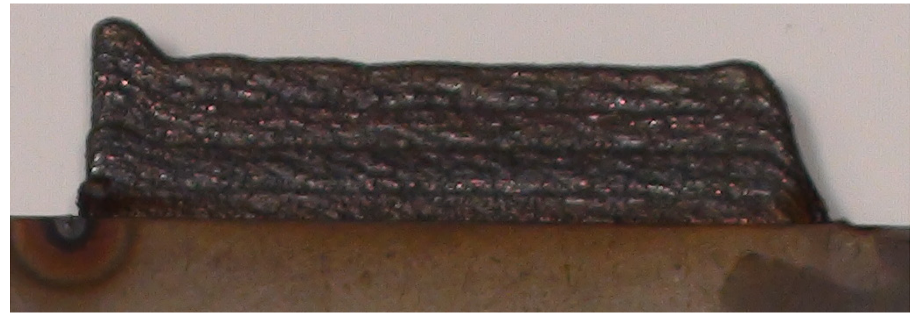
- Coupled Aria/Presto code

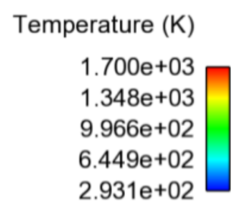


Thermal profiles demonstrate effect of laser power

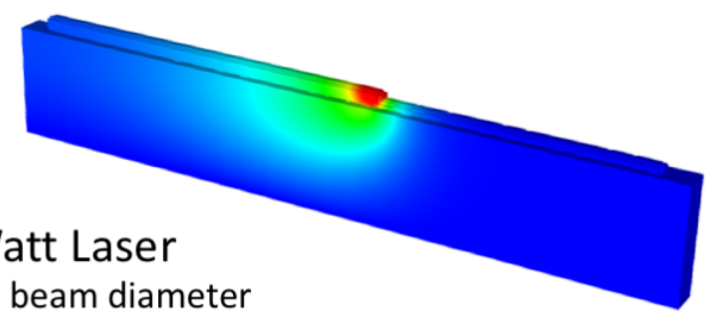
Thin walled LENS part build
- ~1.8 inches long
- Efficiency = 36%
- Print Speed 20 inches/min
- Material melt temperature = 1700 K



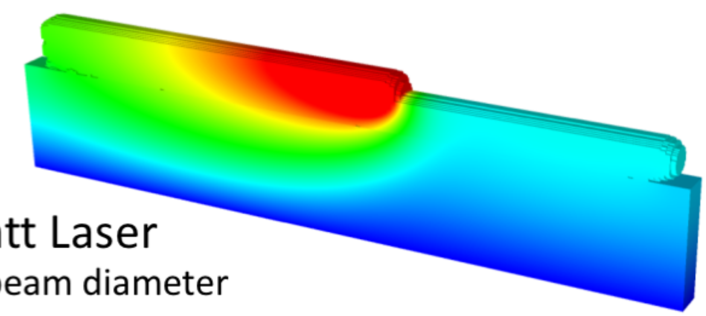
500 W Laser



2 kW Laser



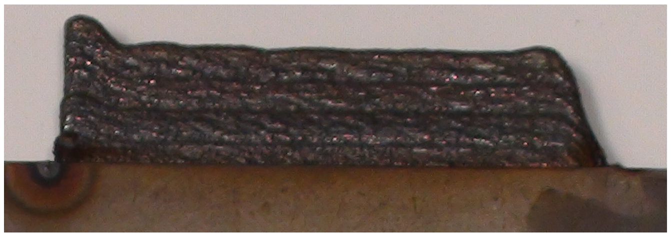
500 Watt Laser
0.001 m beam diameter

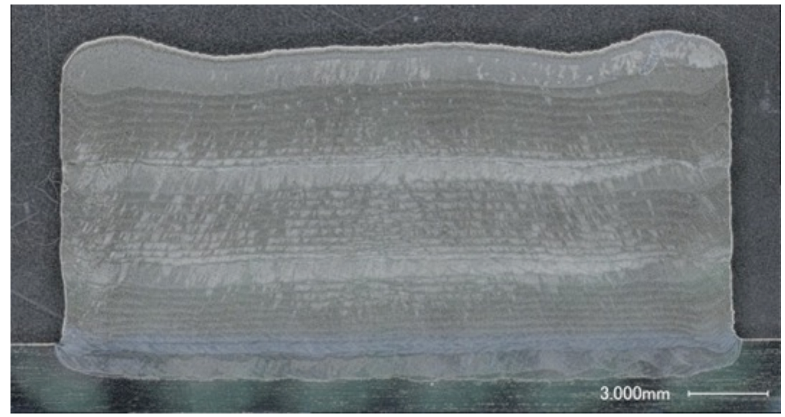


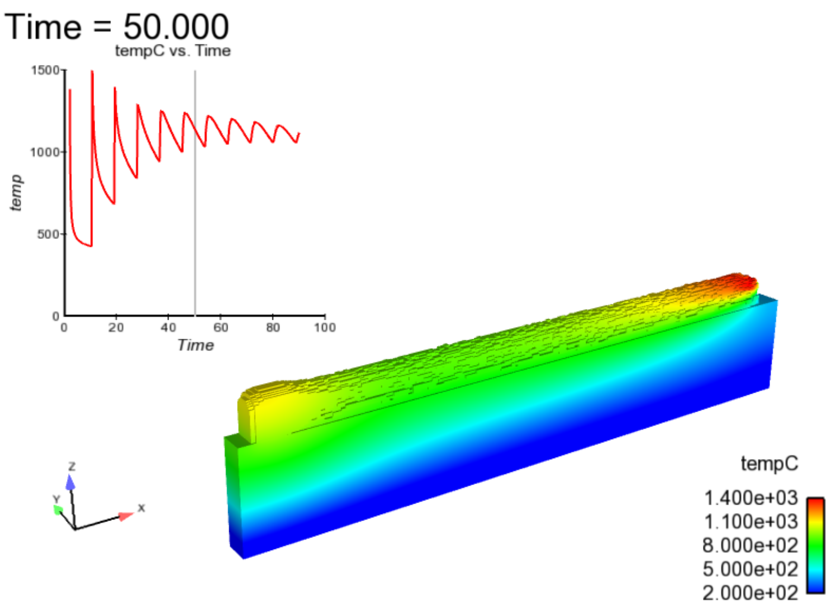
2000 Watt Laser
0.0025 m beam diameter

Models can predict general shape

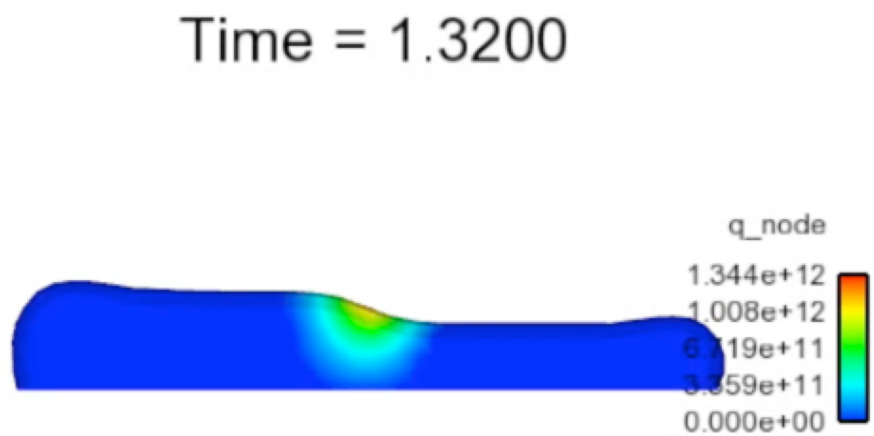
- Validation activities



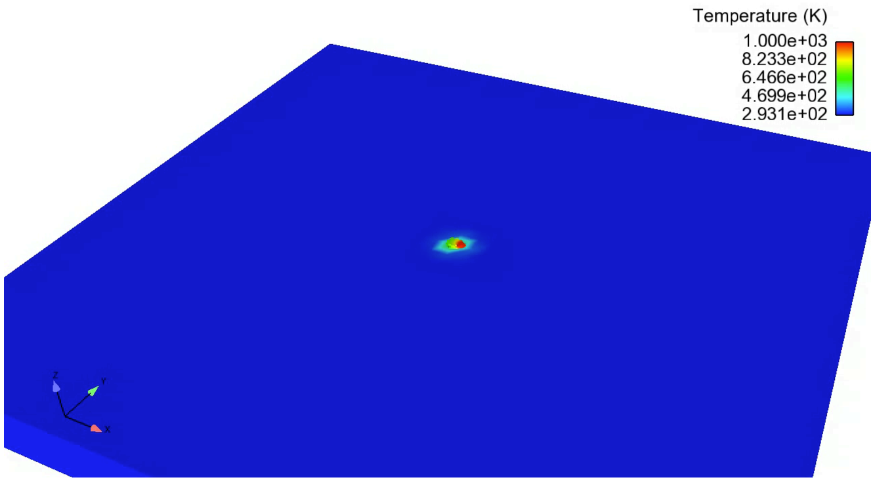


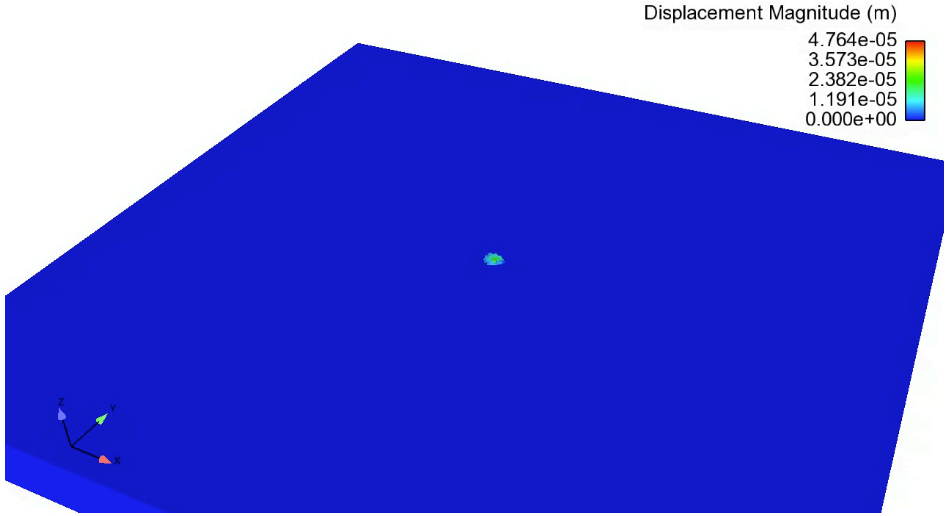


Modeling the thermal history of thin wall build

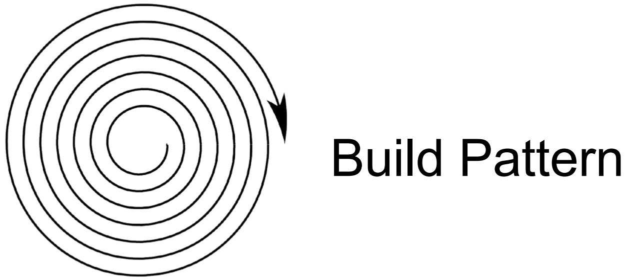


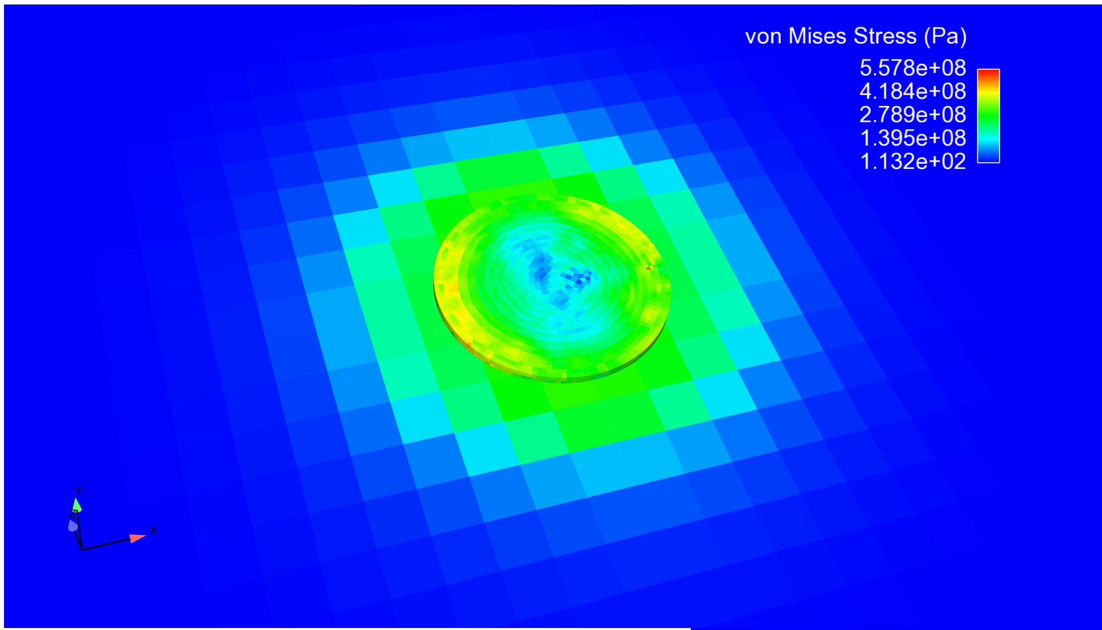
Coupled Thermal and Mechanical Modeling

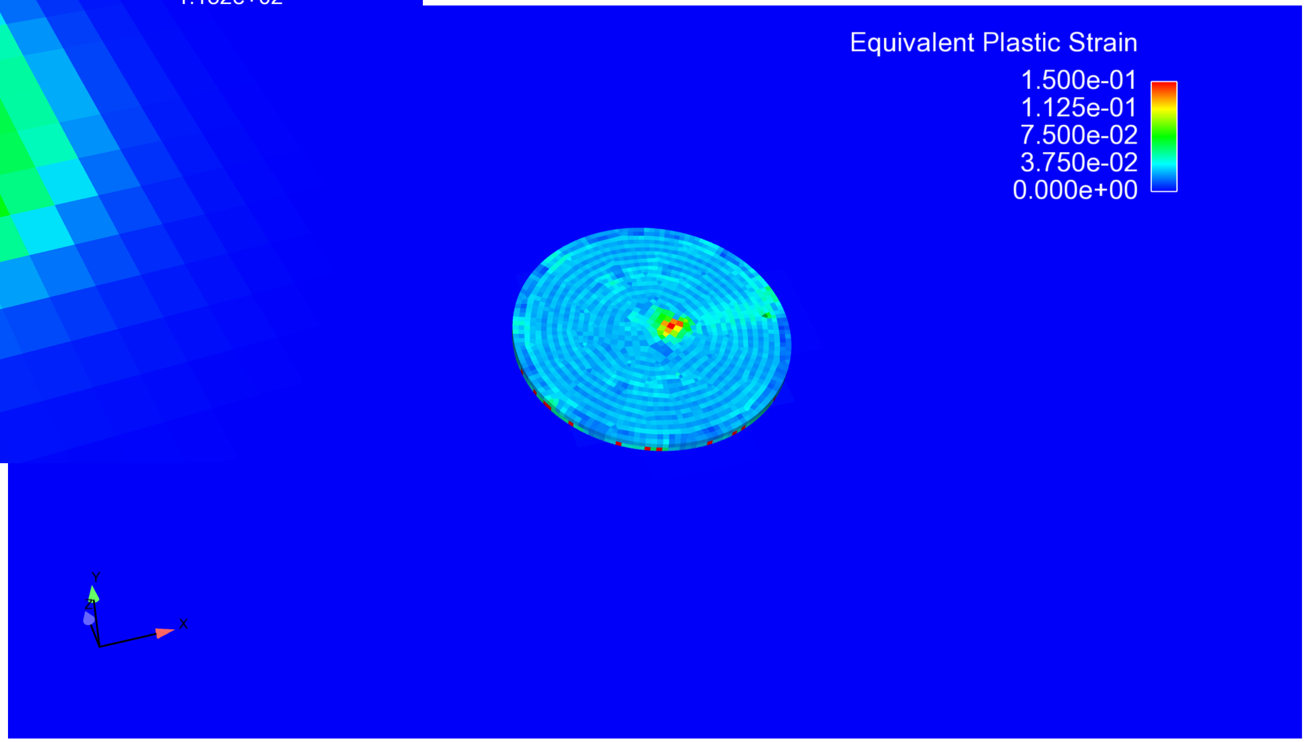




Coupling of Mechanical and Thermal Modeling

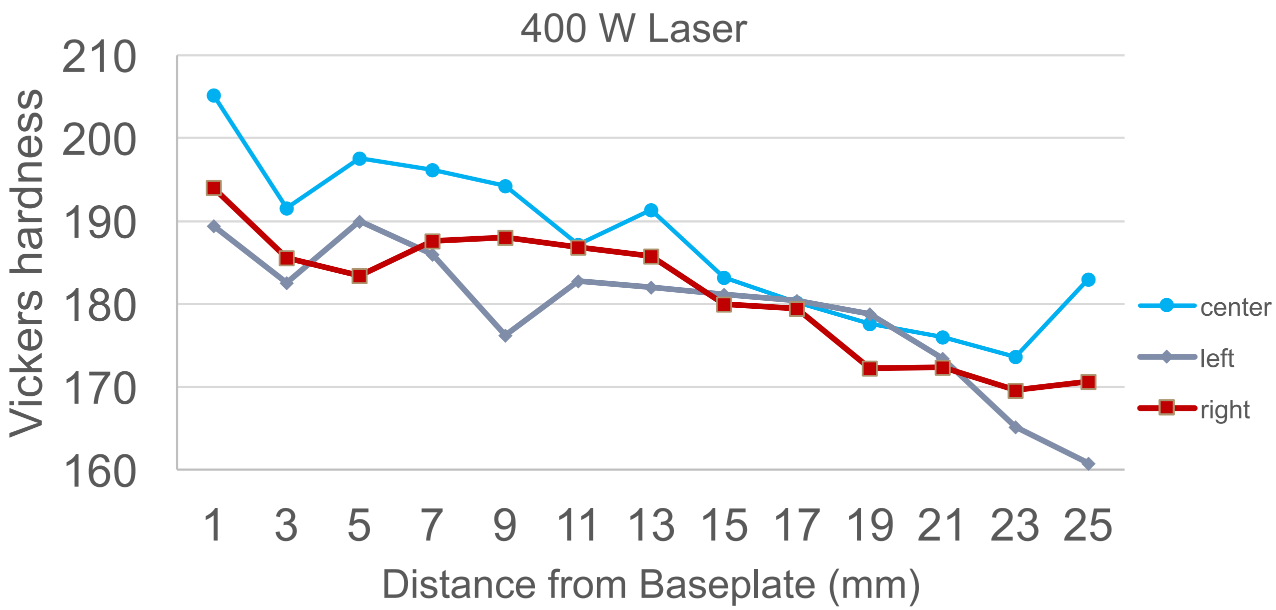


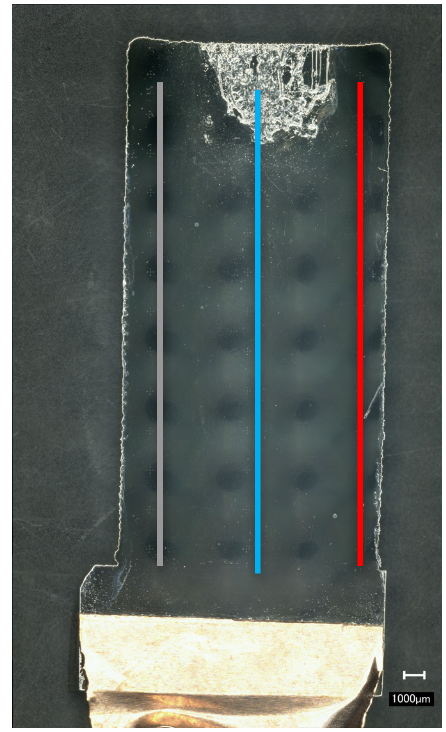


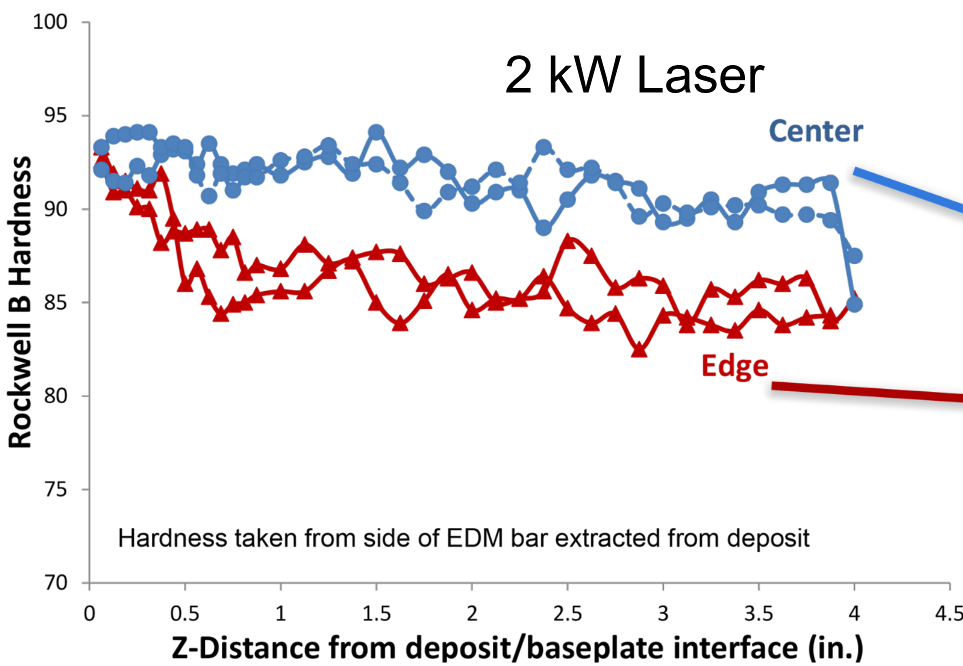


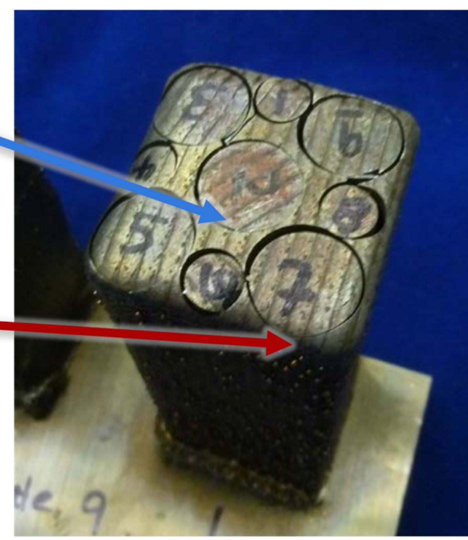
Modeling shows that near the base plate there are inhomogeneous stresses on the part? Do we see any effects of this in the microstructure and properties?

Hardness Values are Higher Near Baseplate

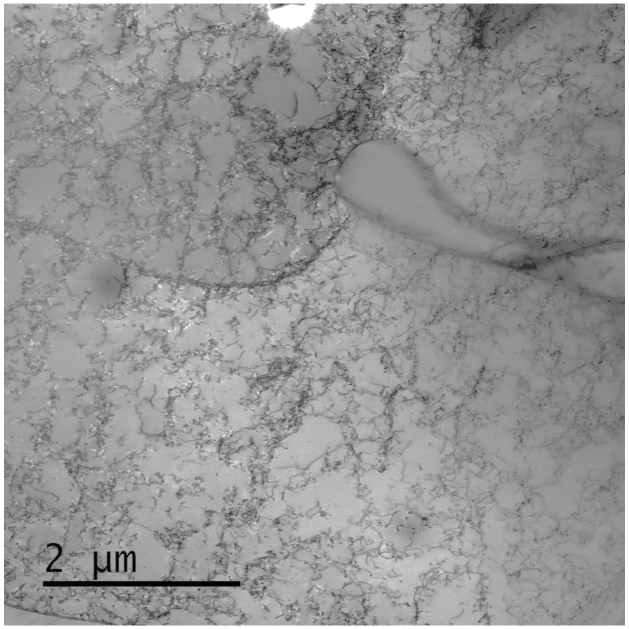




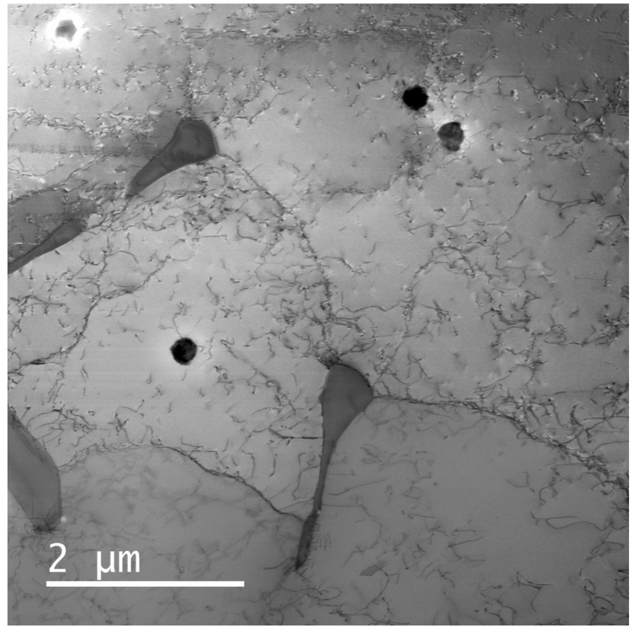




Dislocation Structure Dependent on Location in Build

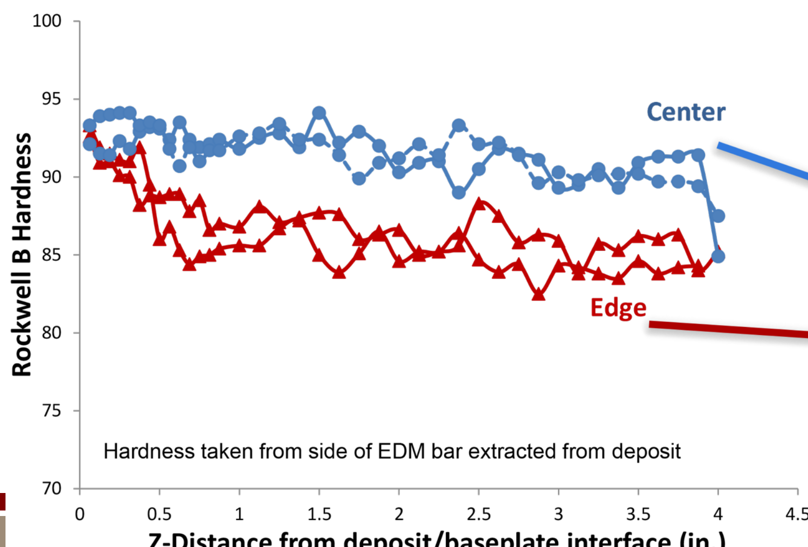


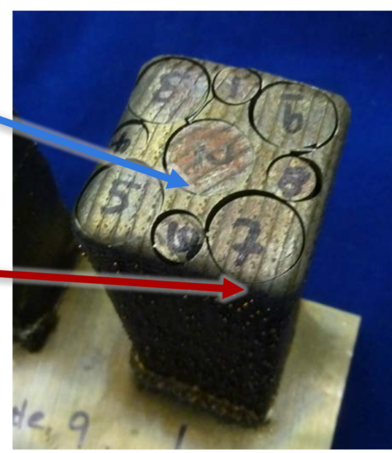
2 mm from Base BF STEM



2 mm from Top BF STEM

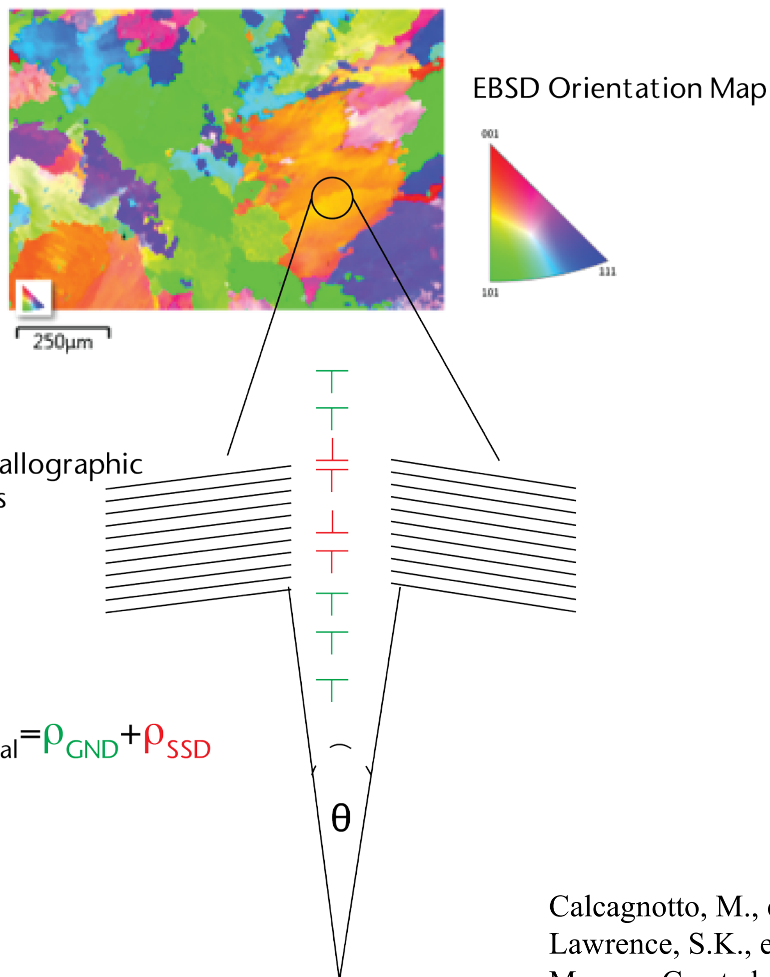
- Qualitatively, there appear to be less dislocations near the top of the build
- This correlates with lower hardness numbers near the top of the build



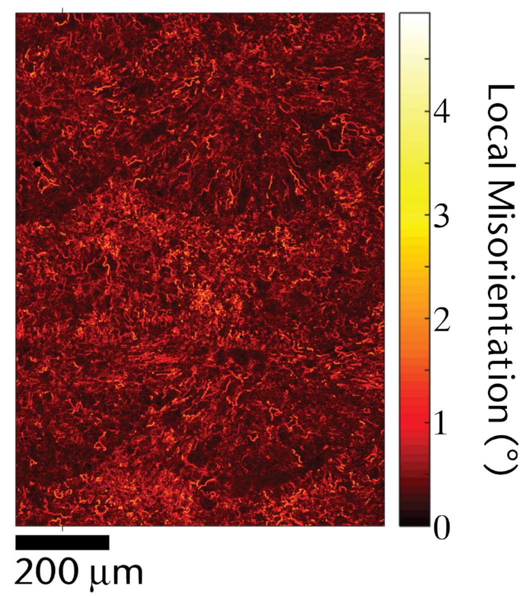


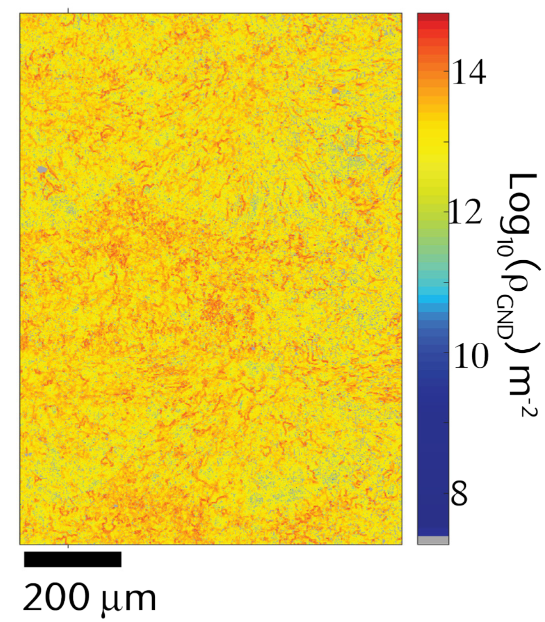
Can we quantify the dislocation structure at a scale larger than what TEM allows?

Measurement of Geometrically Necessary Dislocations with EBSD



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





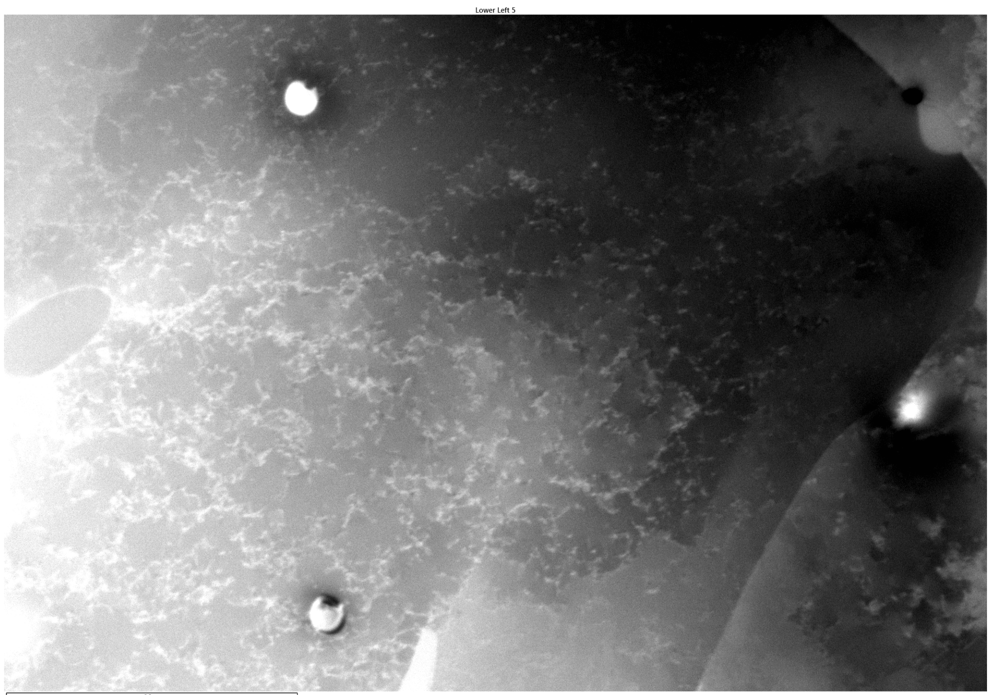
$$\rho_{GND} = \frac{2\theta}{ub} = \frac{2(KAM)}{ub}$$

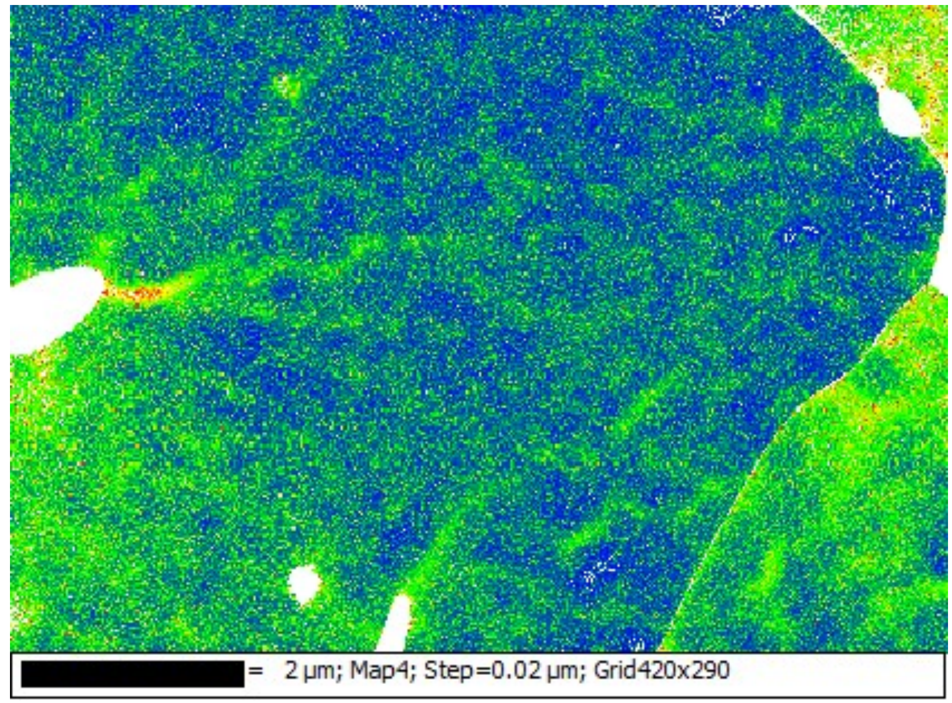
ρ_{GND} = GND density
b = burgers vector
u = unit length

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 Measurements Correlate With STEM Images of Dislocation Structure

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





0° 1°

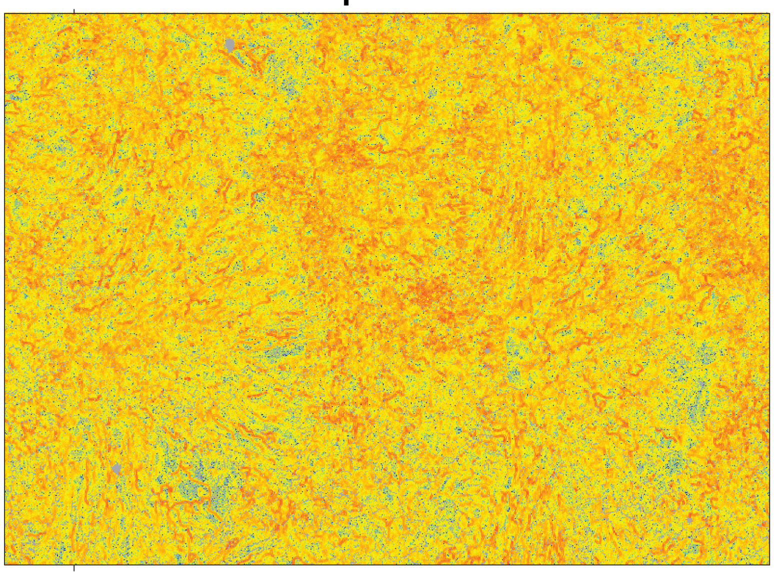
Local Averaged Misorientation

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 dislocations densities.

GND Distribution Varies with Build Location

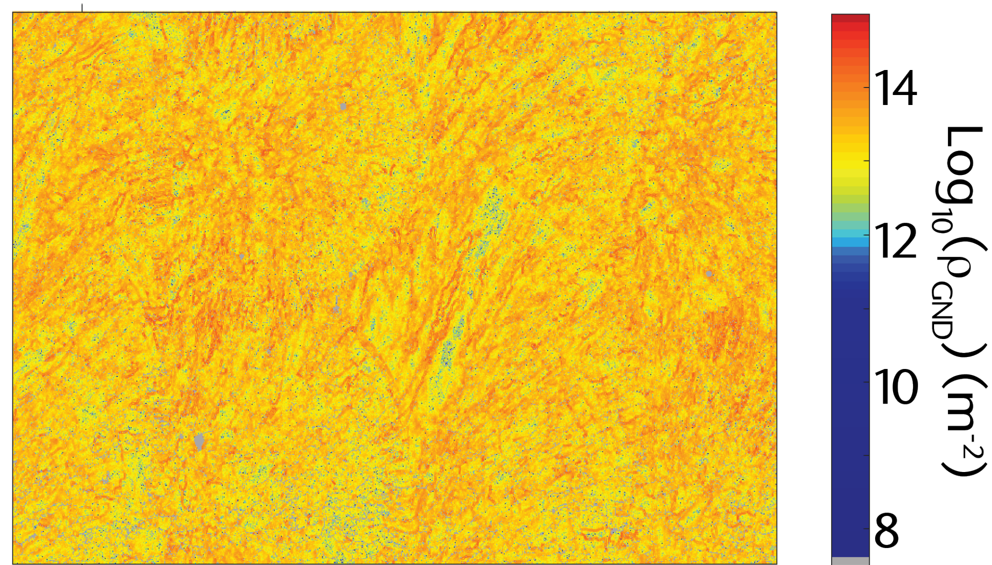
400 W 304L LENS

Top

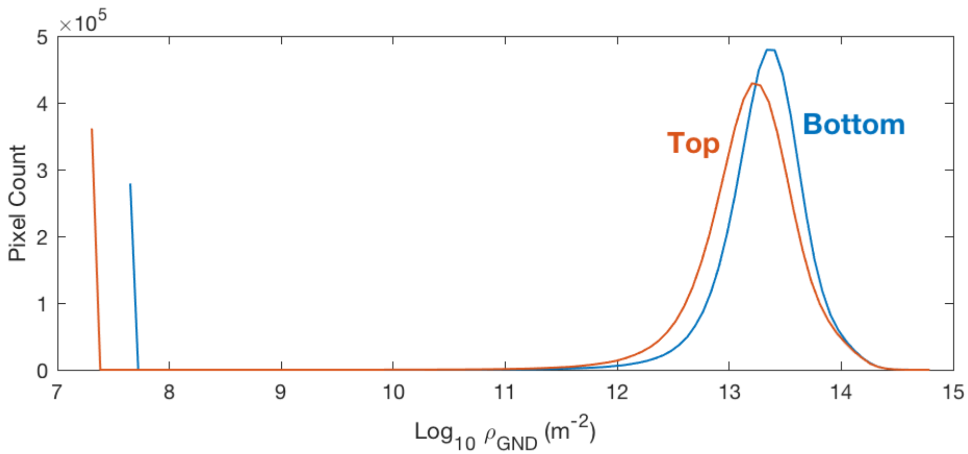


200 µm $\bar{\rho}_{GND} = 2.3\times10^{13}\ m^{-2}$

Bottom



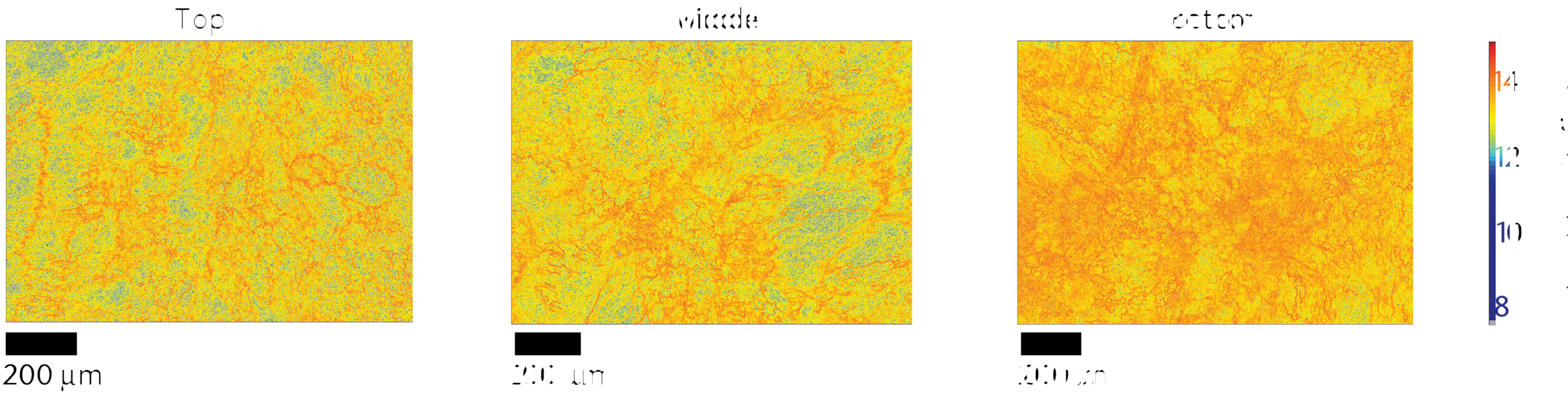
200 µm $\bar{\rho}_{GND} = 2.8\times10^{13}\ m^{-2}$



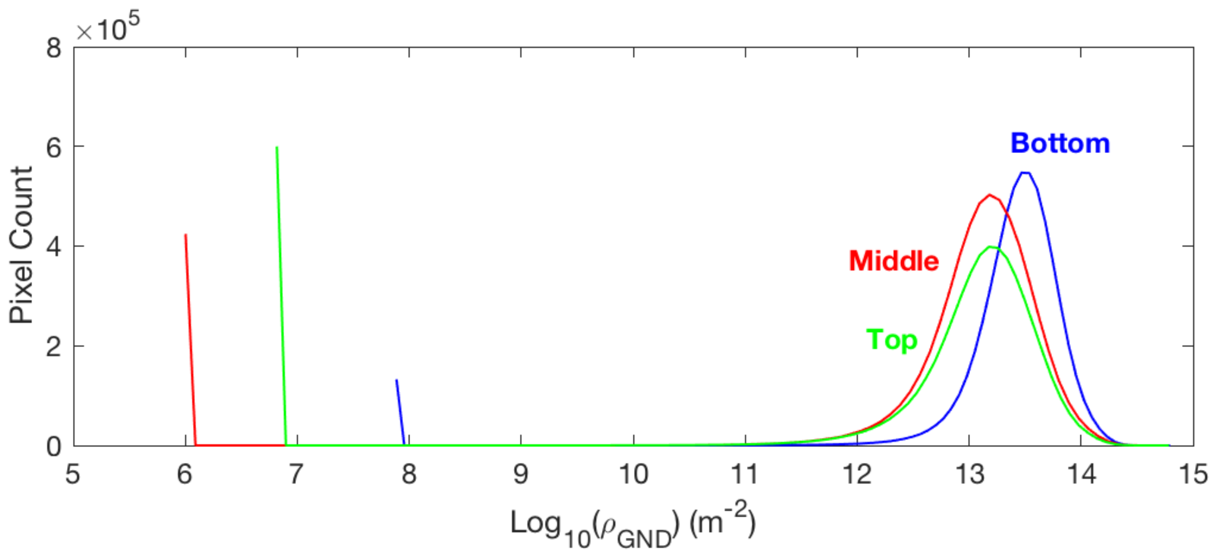
Average GND density and GND distribution show higher densities closer to baseplate

GND Distribution Varies with Build Location

2kW 304L LENS



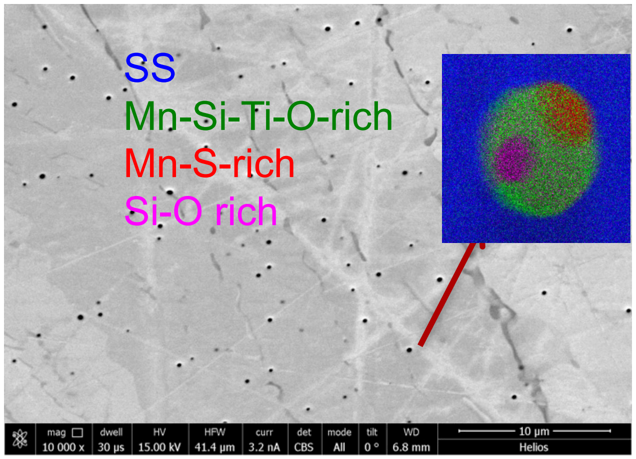
$\bar{\rho}_{GND} = 2.07\times10^{13}\ m^{-2}$ $\bar{\rho}_{GND} = 2.09\times10^{13}\ m^{-2}$ $\bar{\rho}_{GND} = 3.62\times10^{13}\ m^{-2}$



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

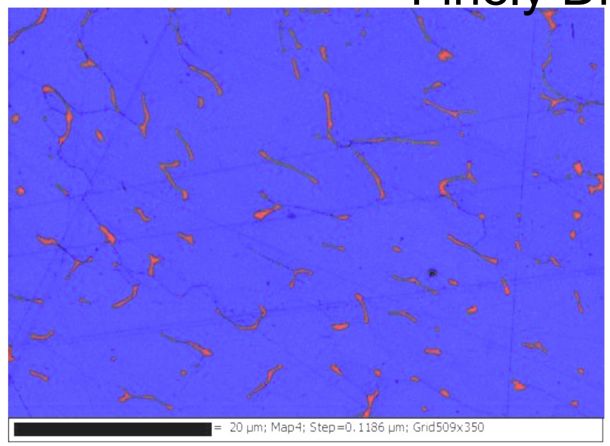
Several Other Fine-Scale Features to Consider in the Overall Microstructural Picture

Sandia National Laboratories



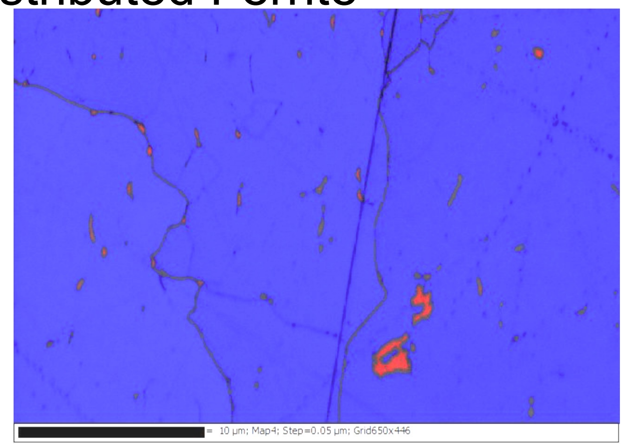
2 kW PSU 304

Finely Distributed Ferrite



20 µm

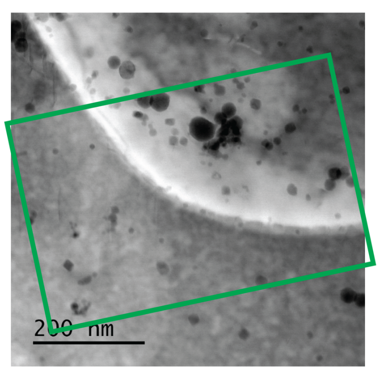
2 kW PSU 304L

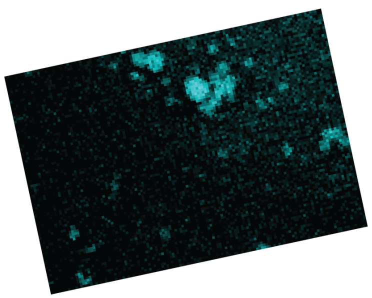


10 µm

400 W UCD 316

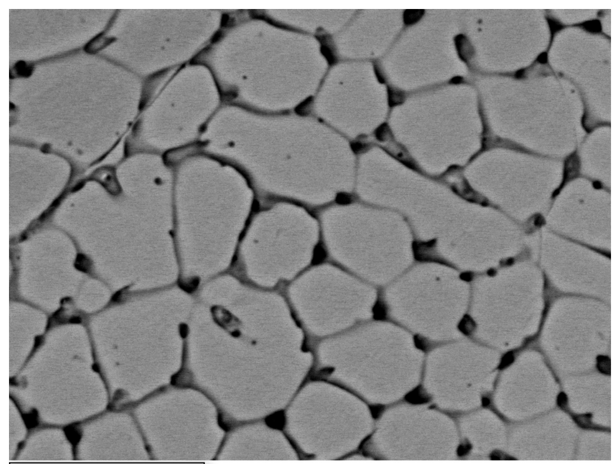
Oxide Particles



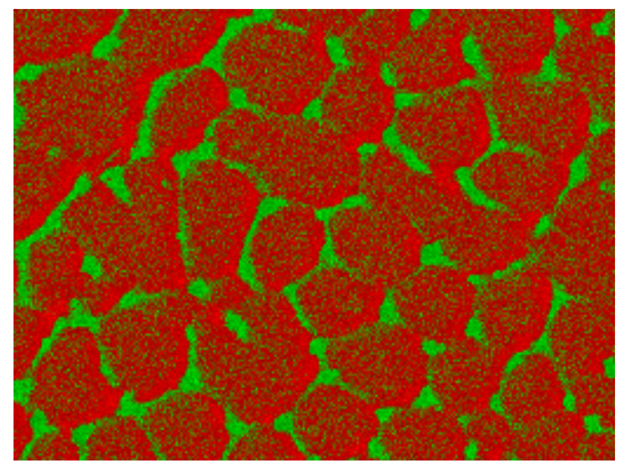


Cr-O rich

400 W UCD 316



10 µm

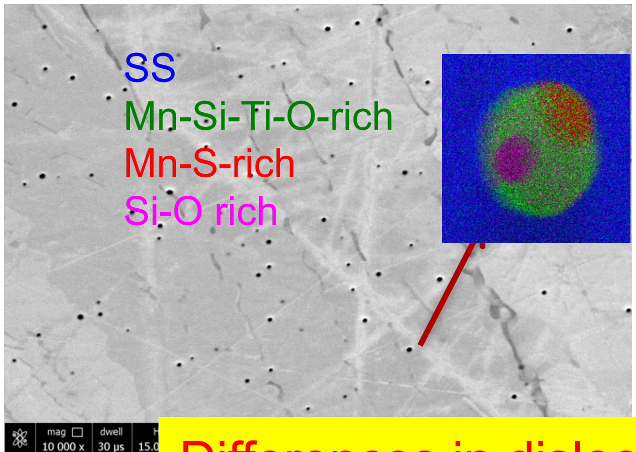


Cellular Solidification Structure

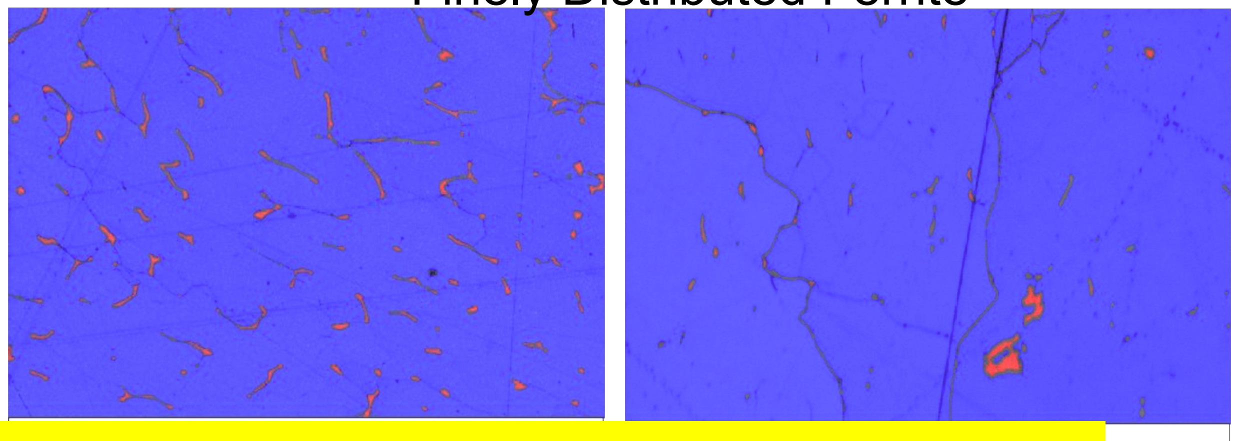
Cr-rich

Ni-rich

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

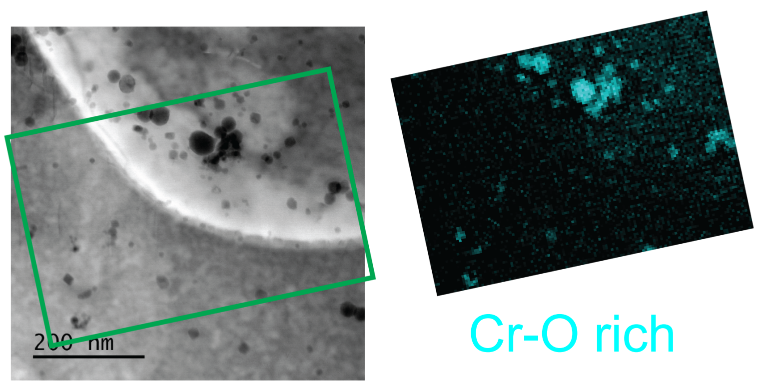


Finely Distributed Ferrite

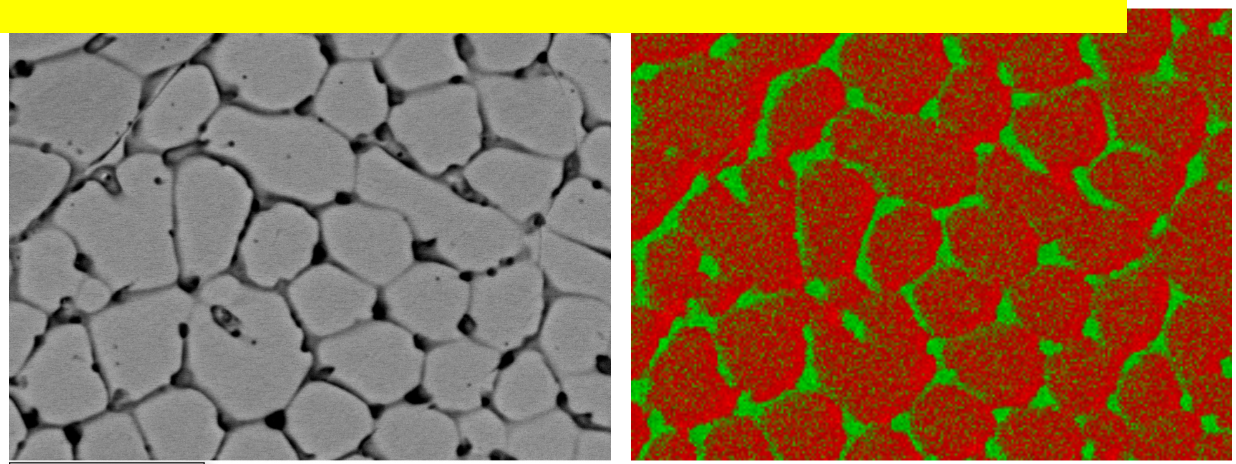


Differences in dislocation structure near the base plate and away from base plate are sufficient to explain the variation in mechanical properties with build location

Oxide Particles



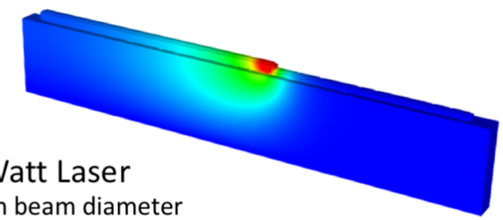
400 W UCD 316



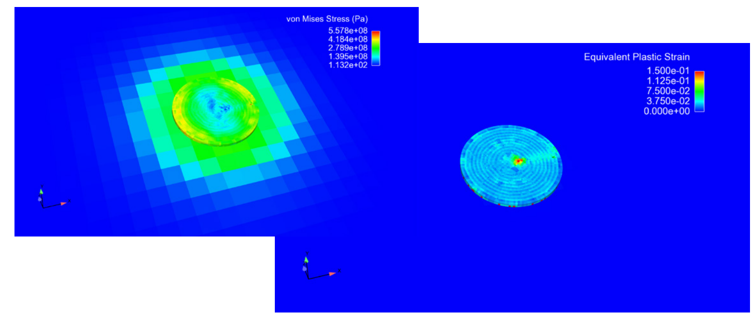
Cellular Solidification Structure

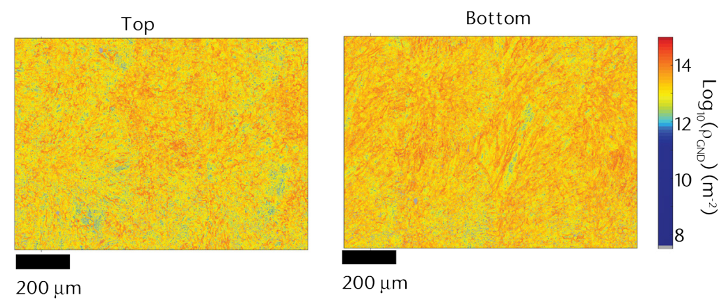
Summary

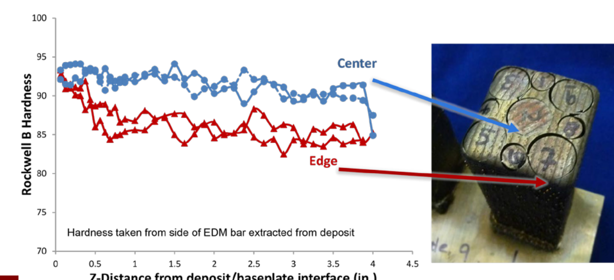
- Moving heat source has been developed that enable multiphysics thermal and mechanical modeling of the LENS process for part-scale builds
- We can perform coupled simulations that predict residual stresses at values near the yield strength 304L
- The prediction of yielding and plastic strain near the baseplate is consistent with microstructural measurements of dislocation density
- Measurements of higher GND density near the baseplate is consistent with our measurements of higher hardness values near the baseplate



500 Watt Laser
0.001 m beam diameter

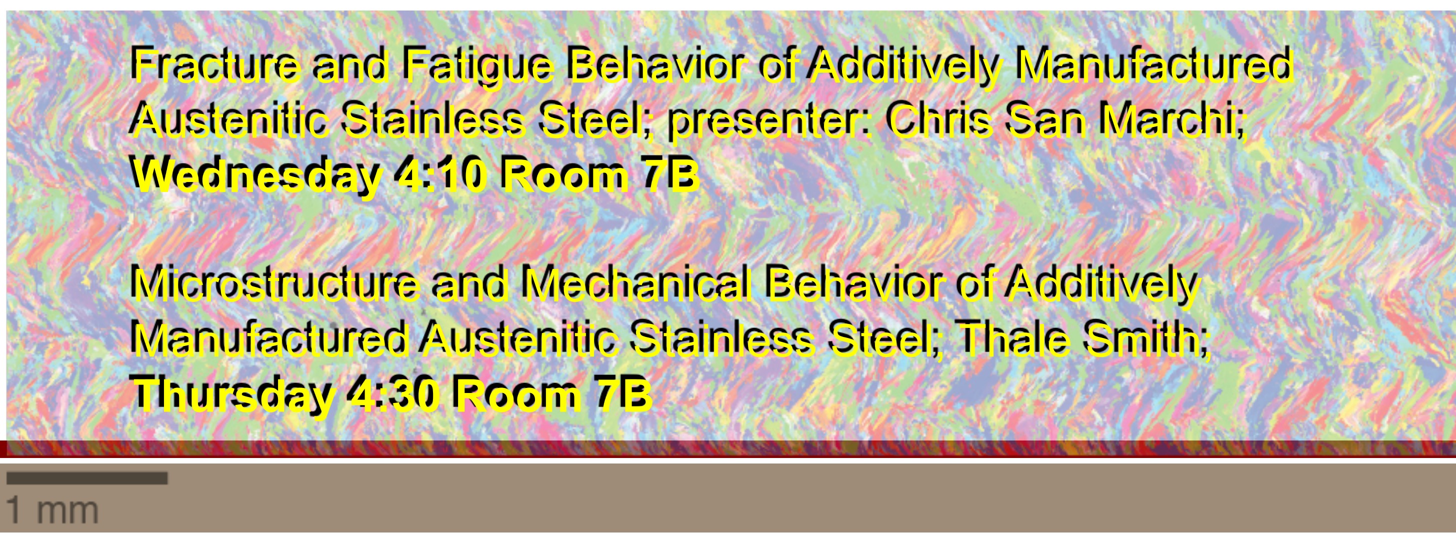






Conclusions

- Dislocation structure is an important microstructural parameter to consider for understanding variations in mechanical properties within a single build
  - The effect of the base plate as a heat sink and a constraint is significant in the development of microstructure and properties of a build
- 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)



LENS 304L
400 W Laser