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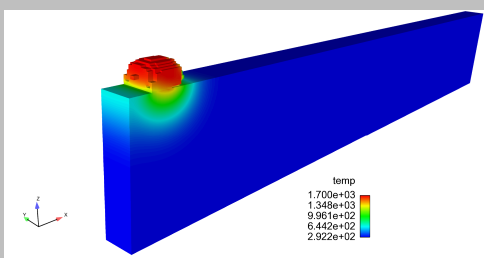

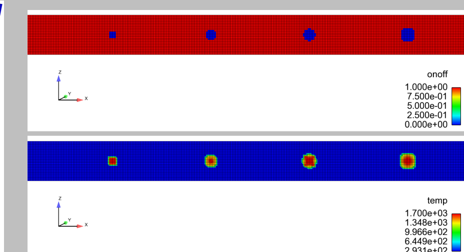

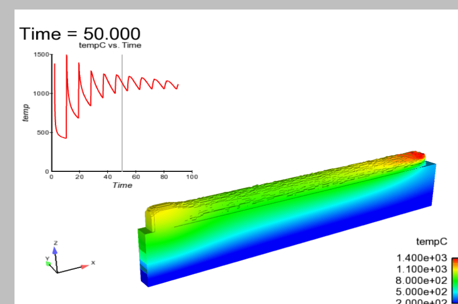

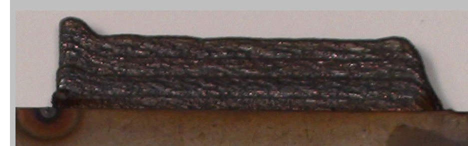

A workflow for thermal-mechanical modeling of additive manufacturing

M. Veilleux, M. Stender, L. Beghini, C. Alleman, J. Sugar, S. Subia

USNCCM14; Montreal, Canada; July 17th, 2017

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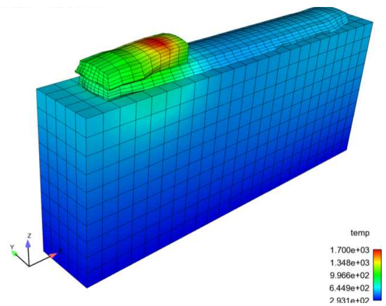
Lifecycle analysis of additively manufactured parts

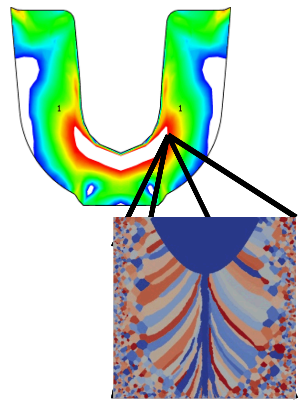
Sandia National Laboratories

Process Design and Simulation

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

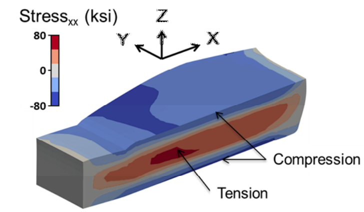


Microstructure and Properties



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

Residual Stresses

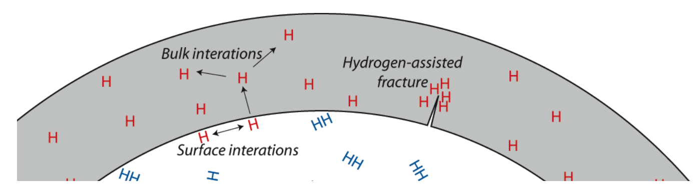


Solidification and thermal history result in strong residual stresses, which can impact performance

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

Assembly and Service

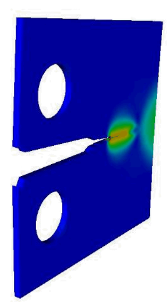
Multiphysics approaches for fully coupled simulation of chemical/thermal transport, mechanical loading, etc. to predict performance



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

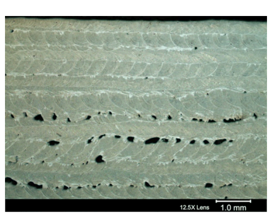
Fracture and Failure

Depends on microstructure, residual stresses, service environment history, mechanical loading, etc.



Margin/Uncertainty → Design Life

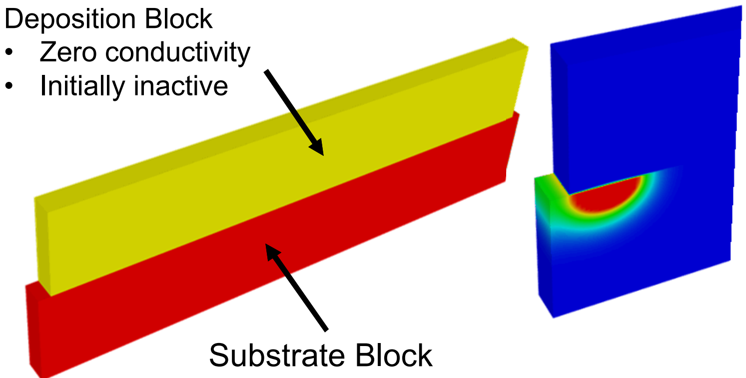
Service requirements may dictate design iteration to assure sufficient margin based on predictive uncertainties.
The lifecycle analysis provides a tool to enable design optimization to meet the requirements.



Modeling workflow for LENS manufacturing

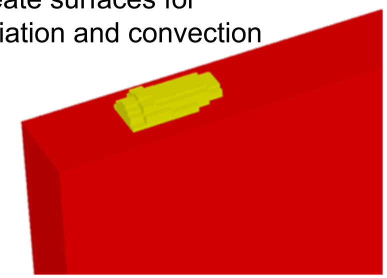
Sandia National Laboratories

Step 1 Thermal Activation



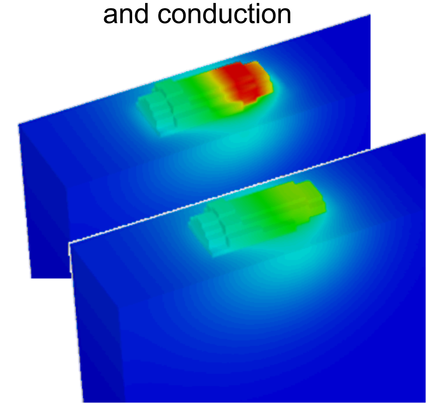
Step 2 Remove Inactive Elements

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



Step 3 Thermal Analysis

- Radiation, convection, and conduction

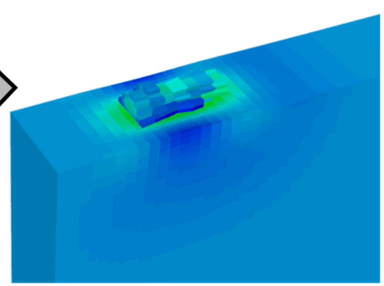


Step 4 Map and/or Initialize Mechanical Variables

- 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



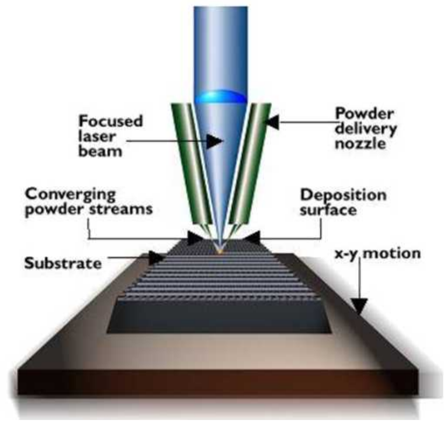
* Displacements shown 15x

Step 6 Map Back to Reference Configuration

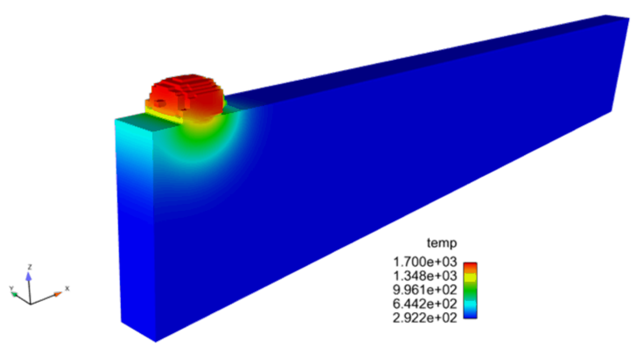
- Map material state variables, displacements, and temperatures back to original mesh

Material deposition modeling

- Laser heating represented by spherical, volumetric heat source
  - Inputs: raster path, melt temperature, diameter, efficiency, radius and spatial influence factor
  - Laser heat absorbed by specific heat of deposition material within the laser spatial influence
  - Zero conductivity in deposition block
- Material activates at melt temperature



LENS
Process



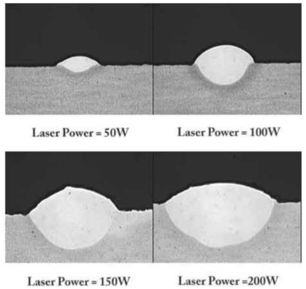
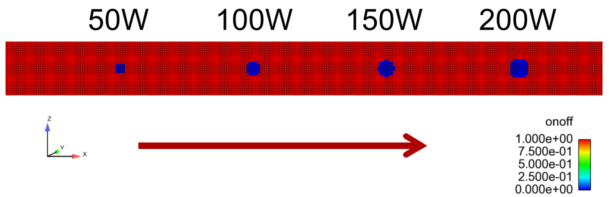
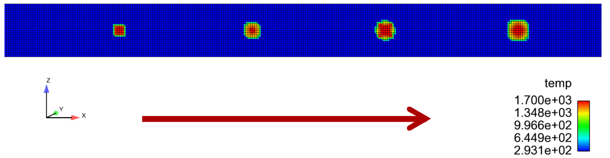


Figure 2: Cross-sectional photographs showing semi-circular type melt pool geometry over a range of laser powers. Travel speed = 5 mm/s, powder mass flow rate = 0.08 g/s.

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

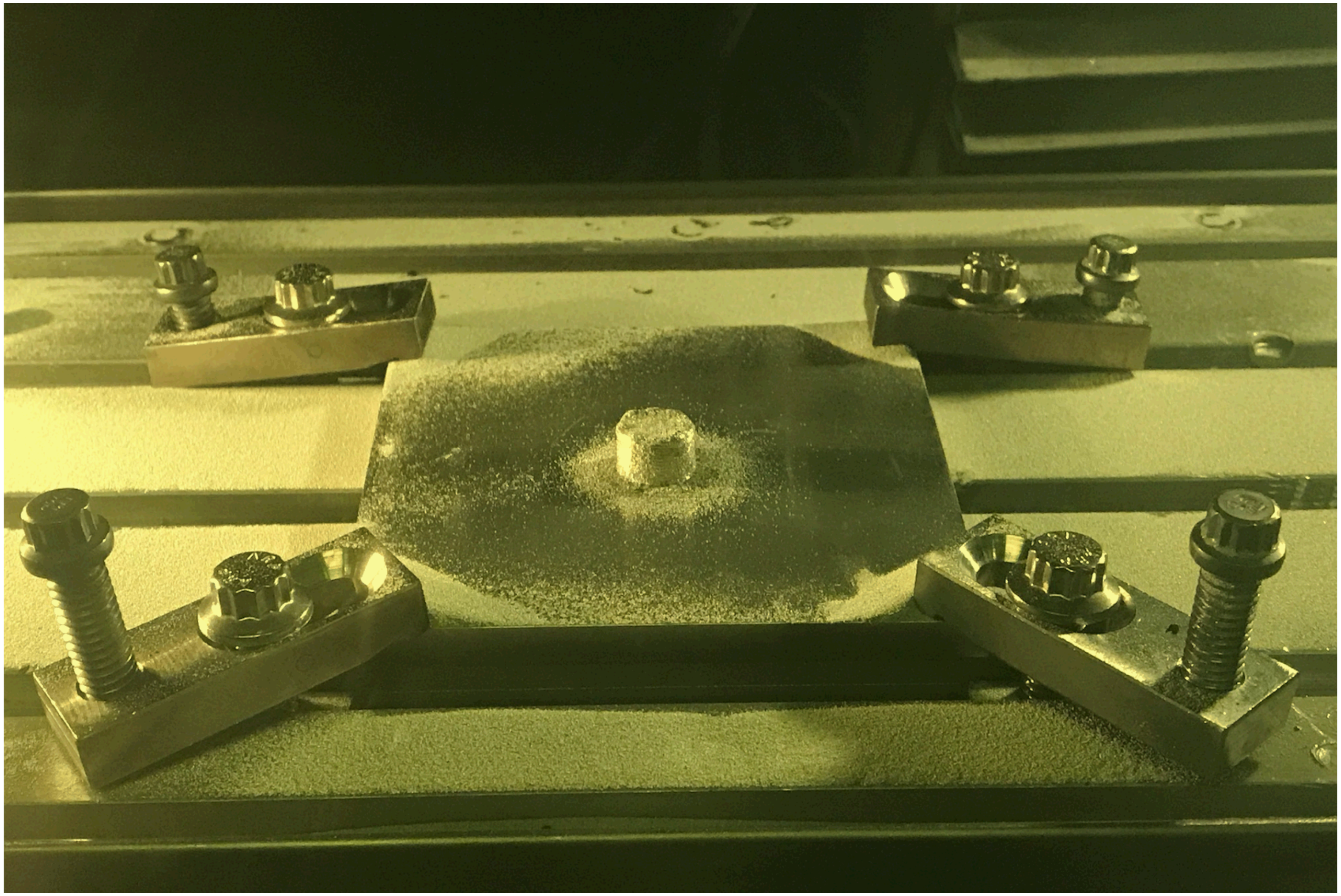


activated elements increases with power



Melt pool size increases with power

Benchmark problem: LENS button

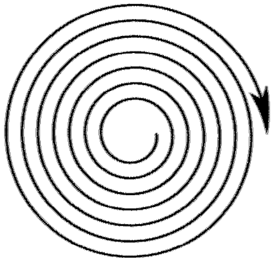


Material
- 304L

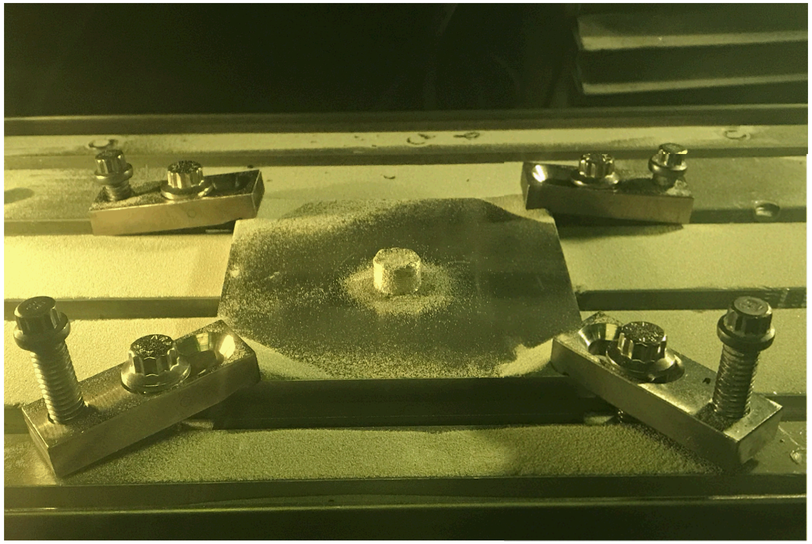
Button
- ½” high
- ½” diameter

Build plate
- 4” x 4” x 1/4”

Build Pattern

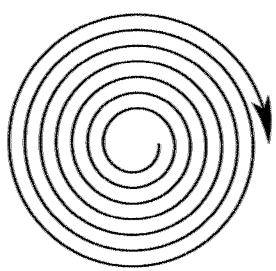


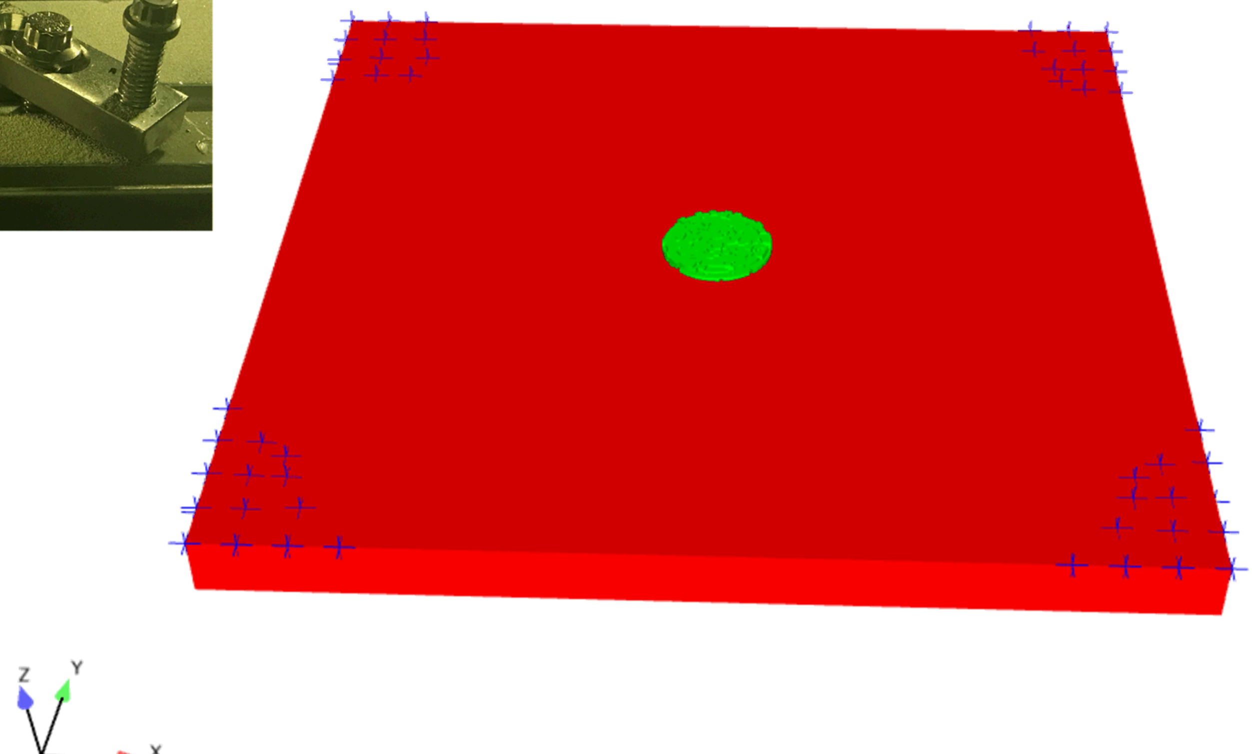
LENS button: Boundary conditions



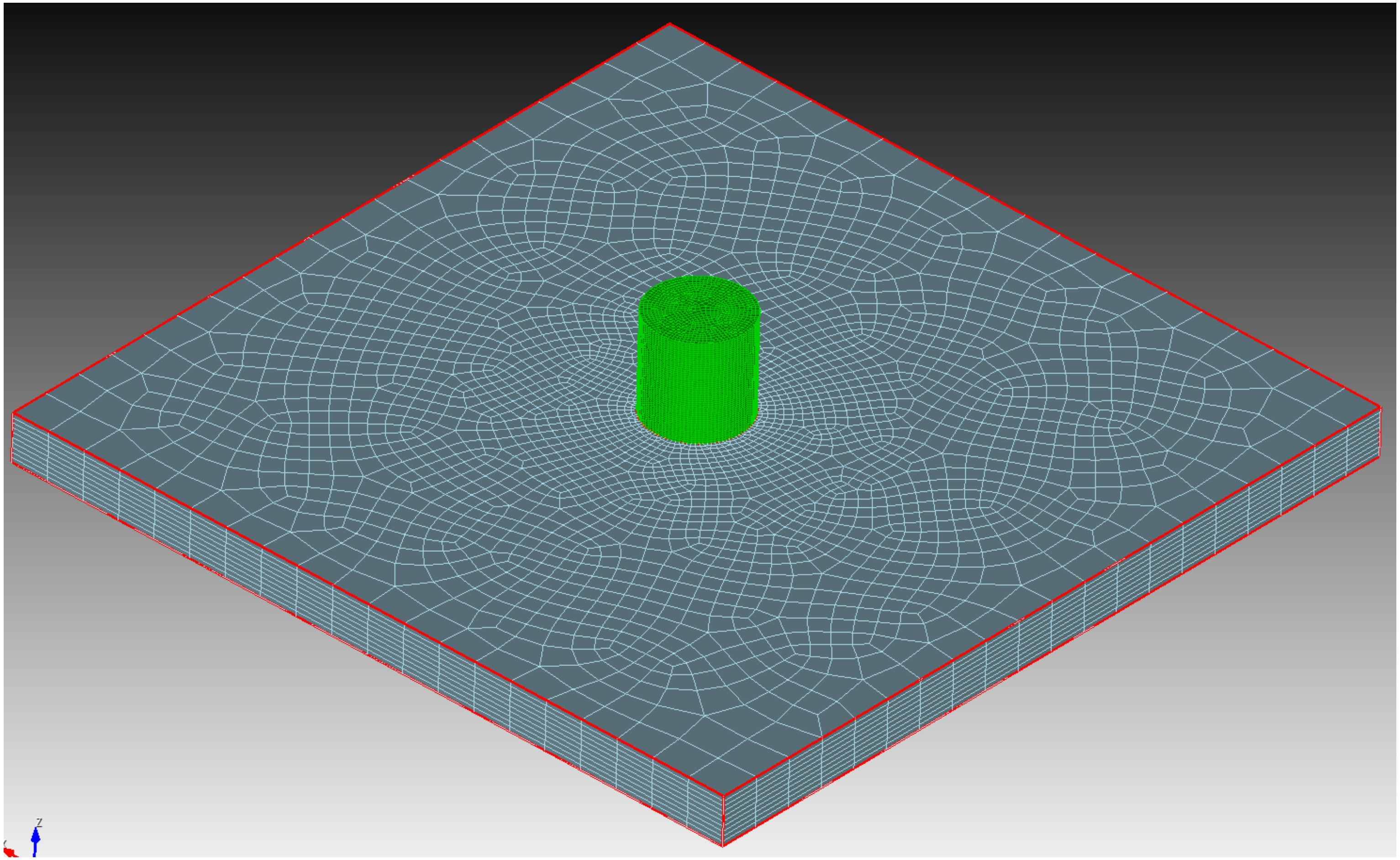
- Blue checks are fixed displacement nodes
  - Represents clamping
  - Allows warping as observed in builds
- Original model fixed bottom of build plate
  - Did not allow warping

Build Pattern



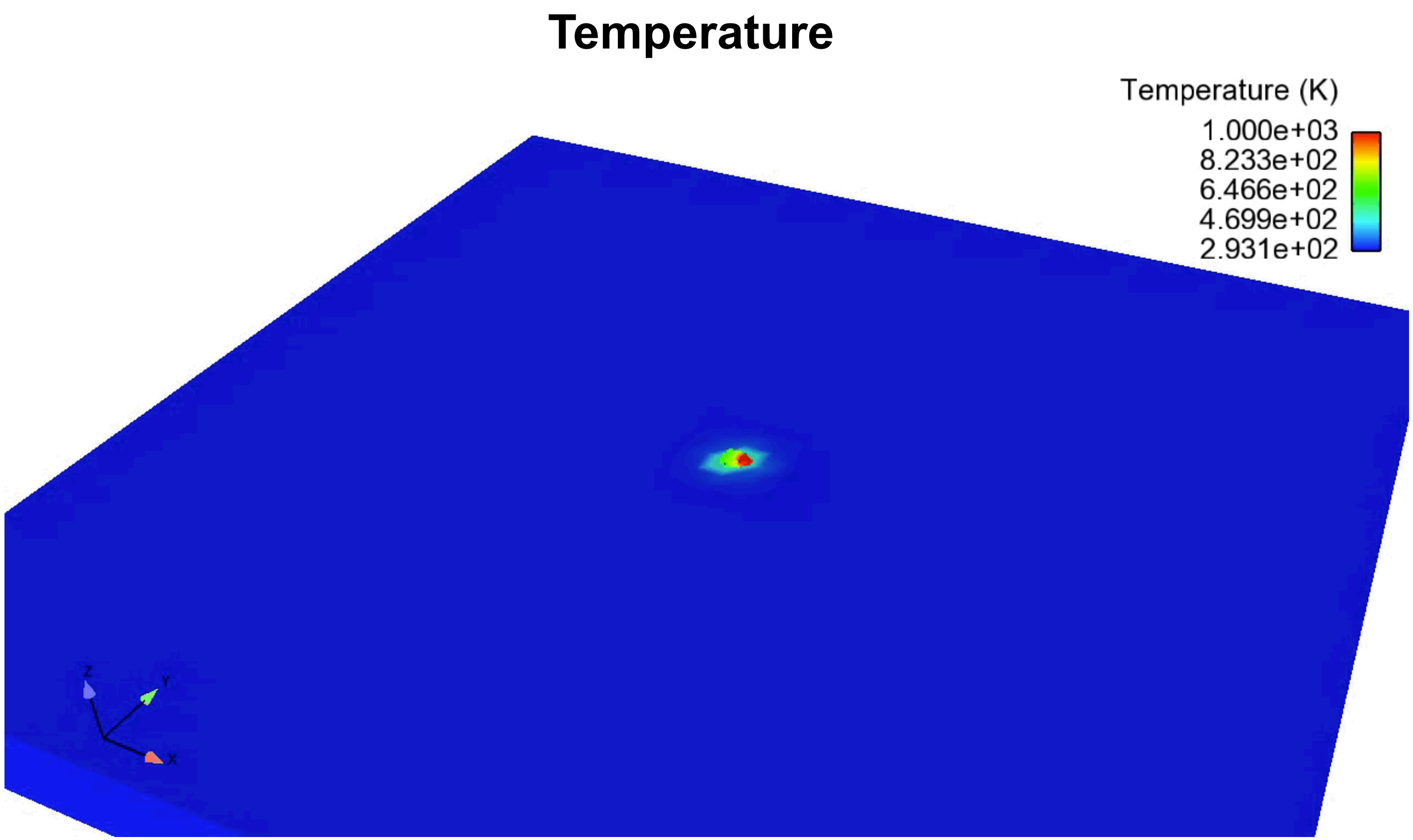


LENS button: Finite element mesh



Linear hexahedral elements:
- Full integration of deviatoric stress response
- Volume-averaging of hydrostatic stress response

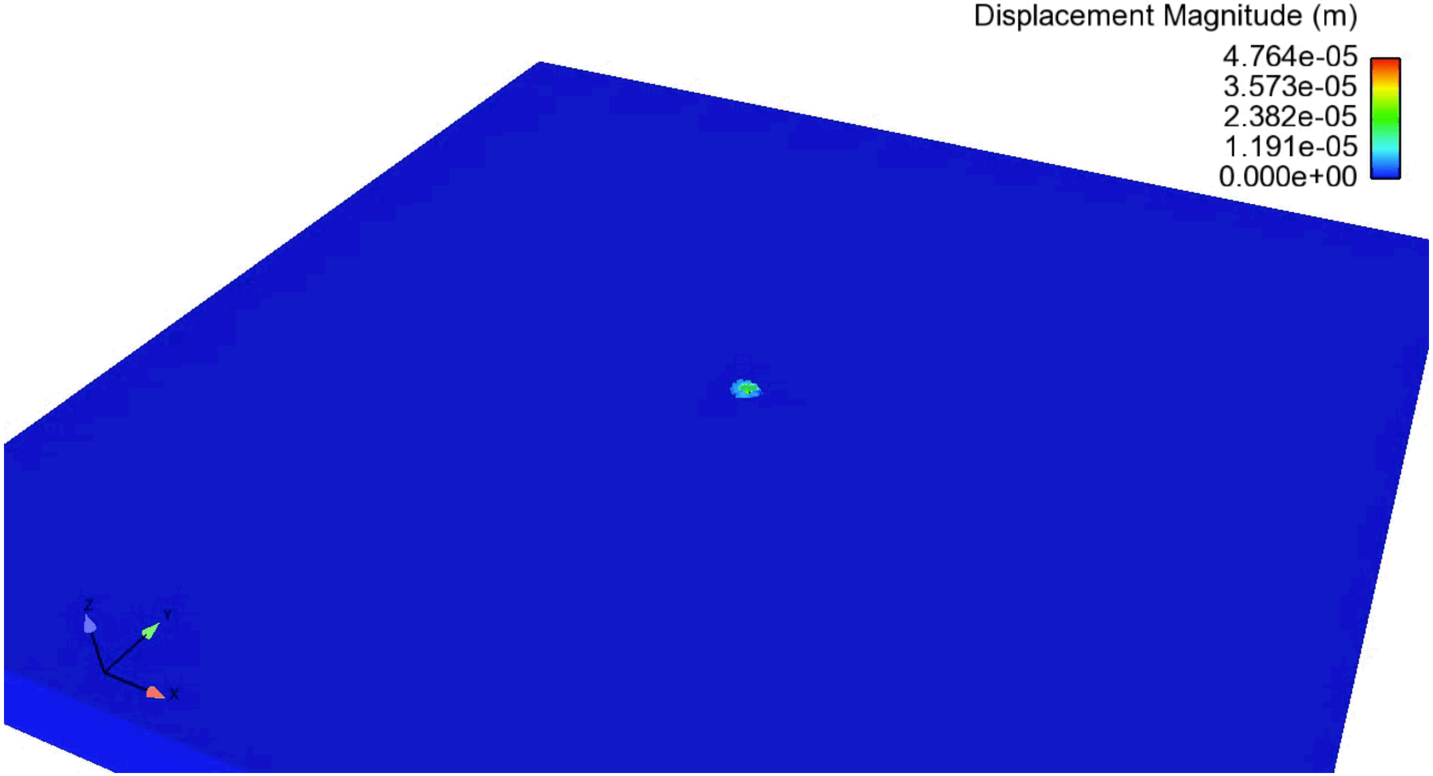
LENS button: Thermal solution during build



- First layer of deposition
- Build pattern matches experimental raster path

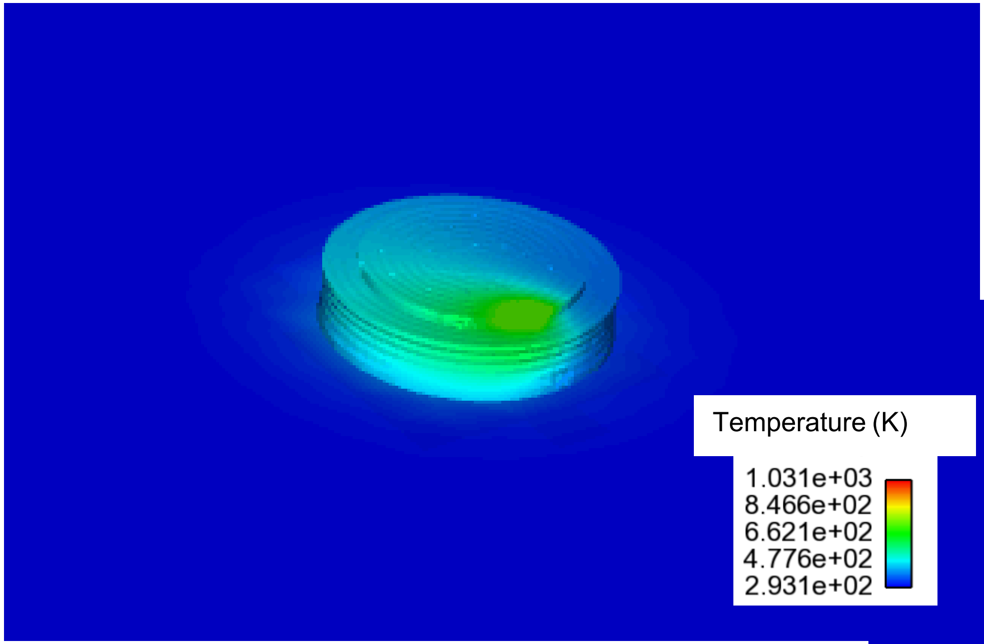
LENS button: Mechanical solution during build

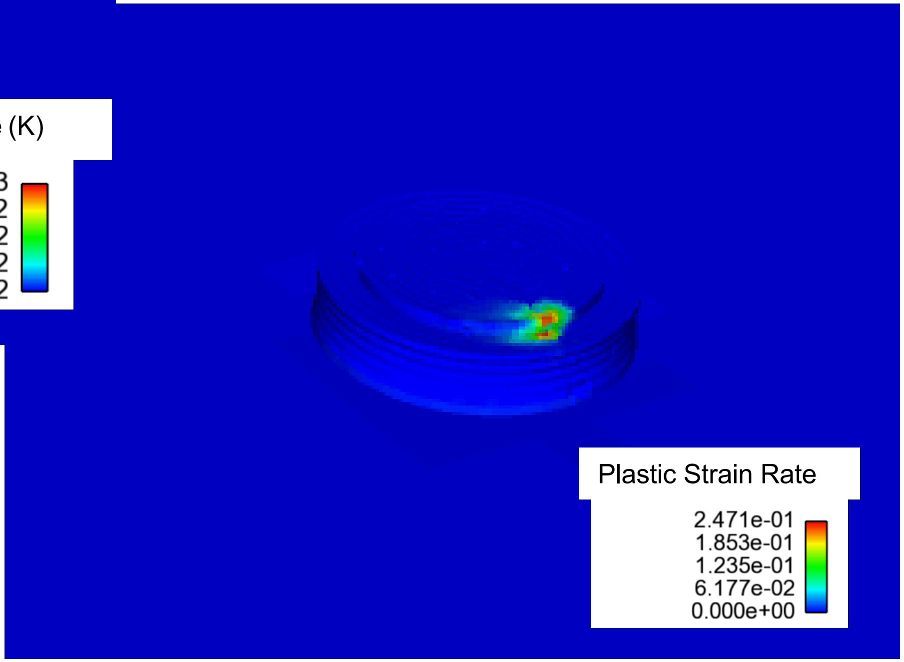
Displacement Magnitude



- First layer of deposition
- Explicit transient dynamics solution

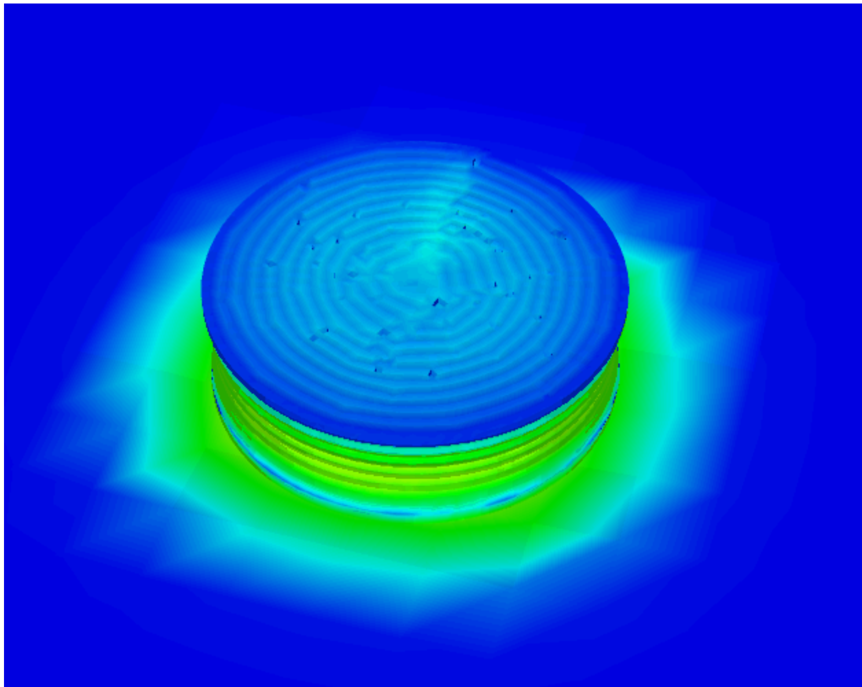
LENS button: Plastic strain rate during build



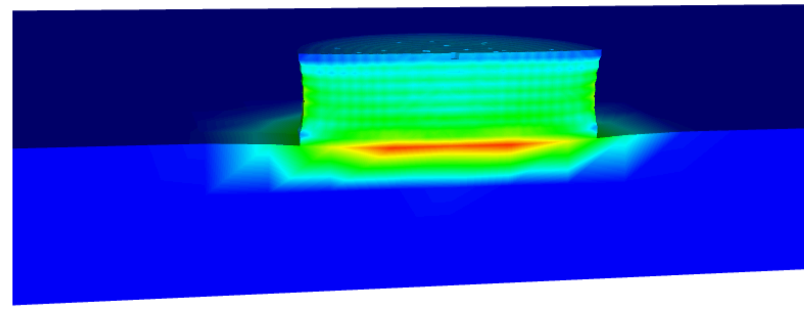


Nonzero plastic strain rates are in high temperature regions

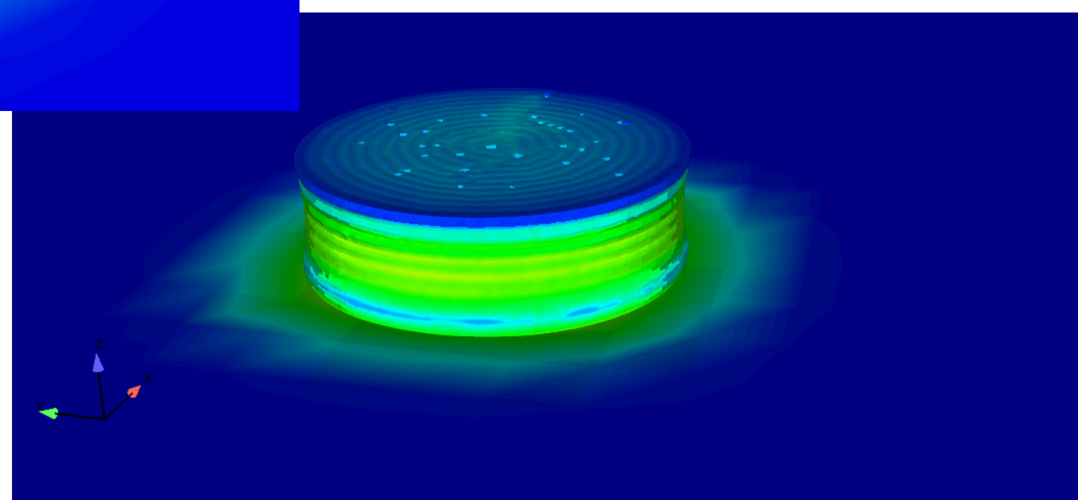
LENS button: @ 50% of build height



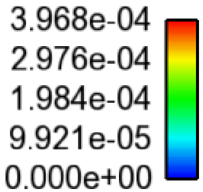
Peak displacements are at part/plate interface



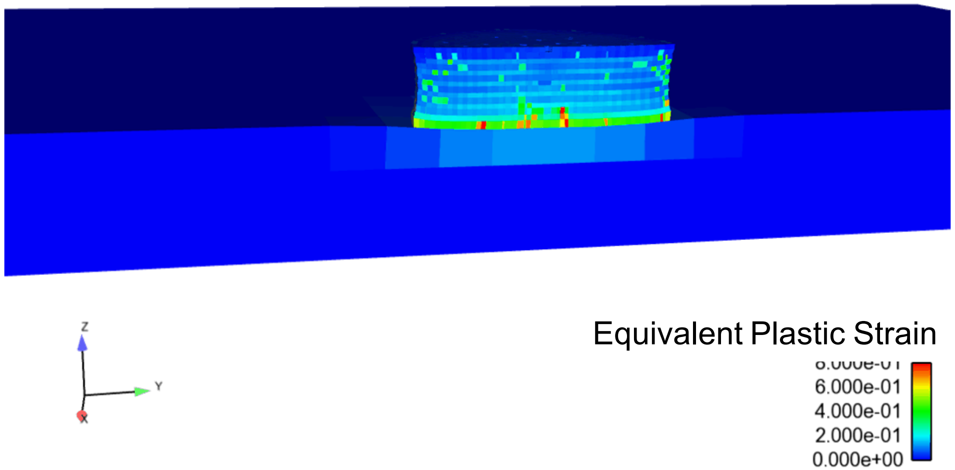
"spots" are elements that never activated



Displacement Magnitude (m)

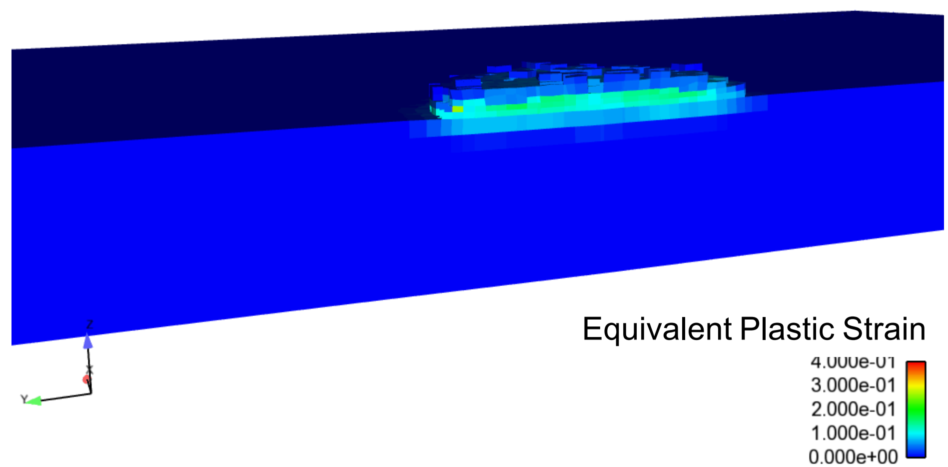


LENS button: Plastic strain



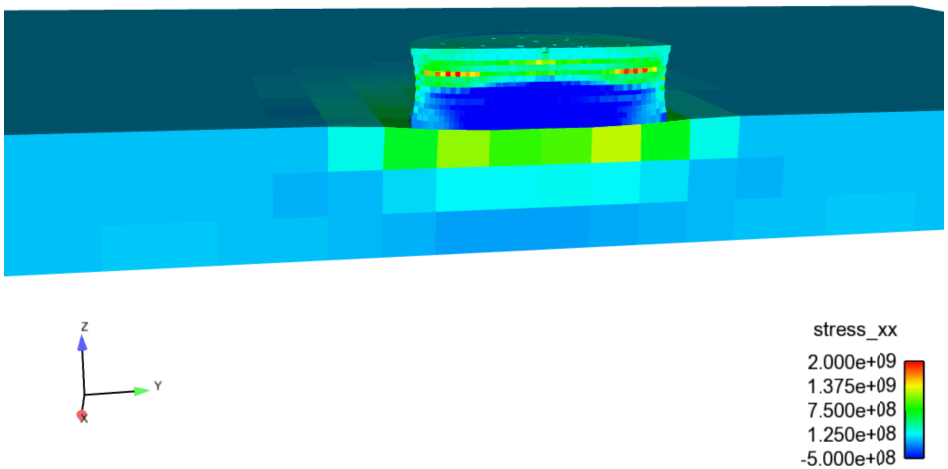
Model Setup #1
- Explicit transient dynamics
- Tied contact to base plate
- Fixed bottom of base plate

Model Setup #2
- Implicit quasi-statics
- Contiguously meshed to base plate
- Clamped corners of base plate



Note difference in plastic strain magnitude between model setups

LENS button: Residual stress

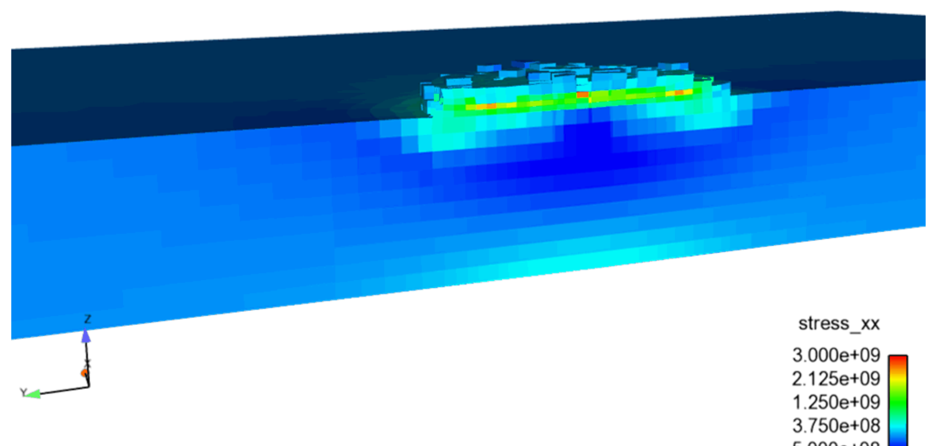


Model Setup #1

- Explicit transient dynamics
- Tied contact to base plate
- Fixed bottom of base plate

Model Setup #2

- Implicit quasi-statics
- Contiguously meshed to base plate
- Clamped corners of base plate



Note difference in stress at bottom of build plate between model setups

LENS button: Baseplate deformation

Initial results show deformation patterns in build plate consistent with experimental builds and measurements

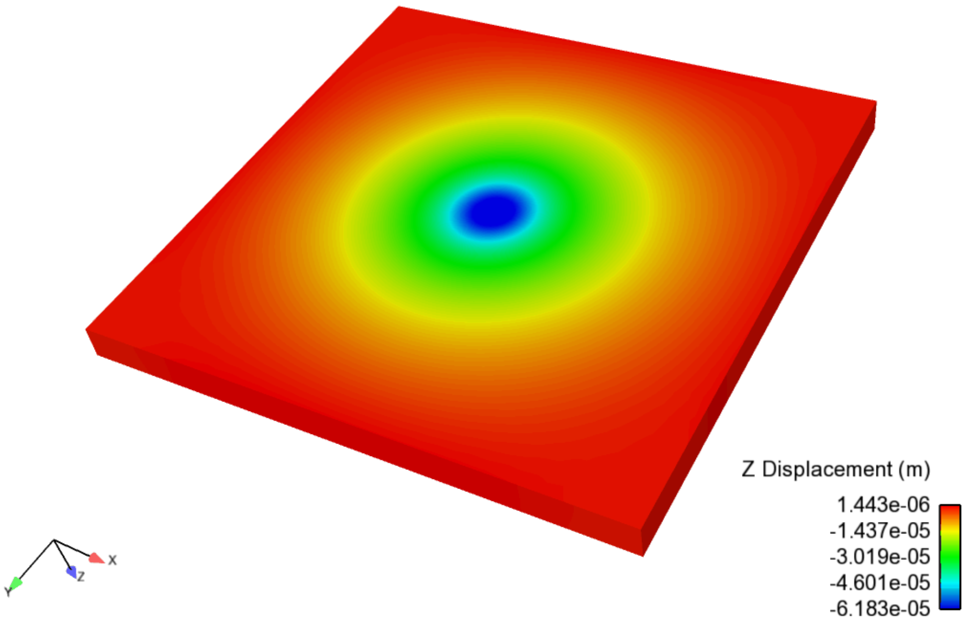
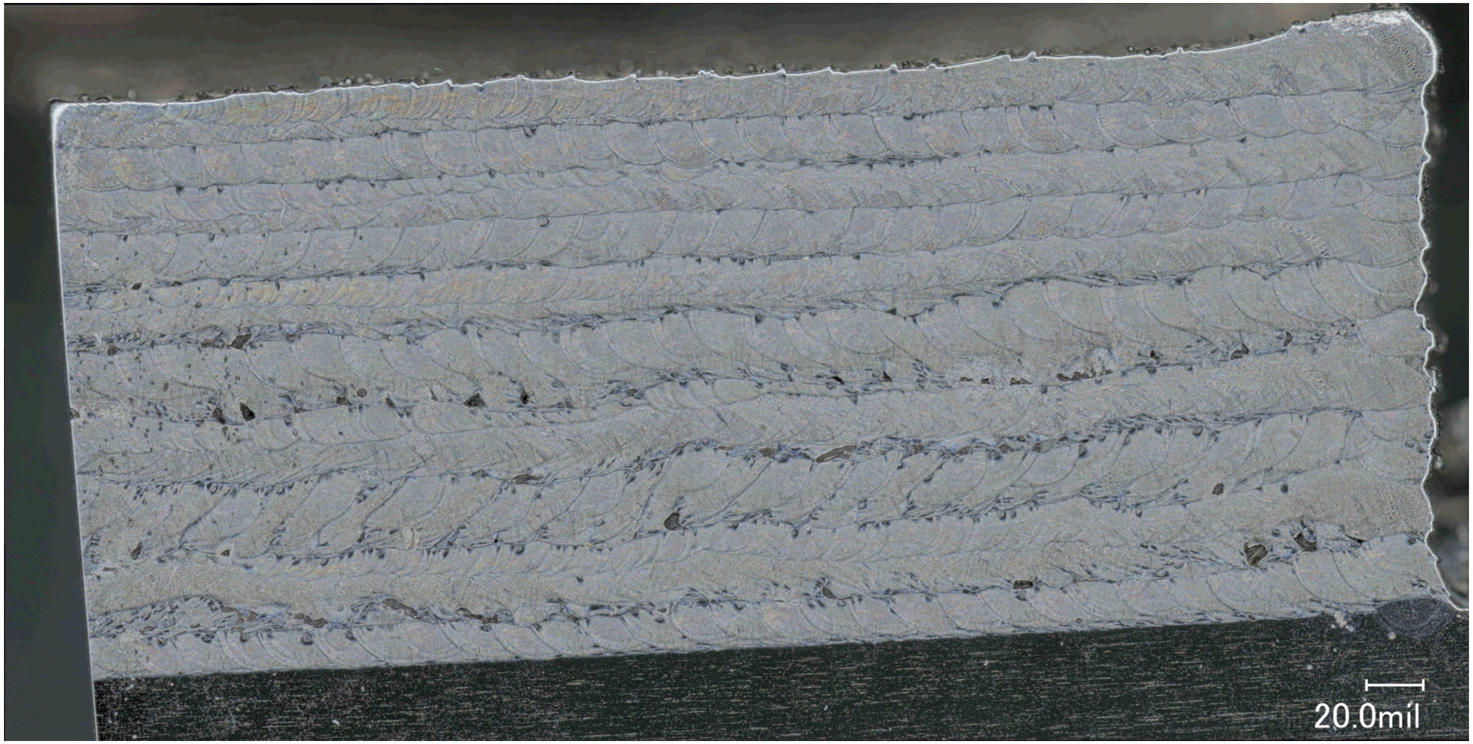


Plate deformation in vertical direction after 2 deposition layers

**** Displacements shown 50x ****

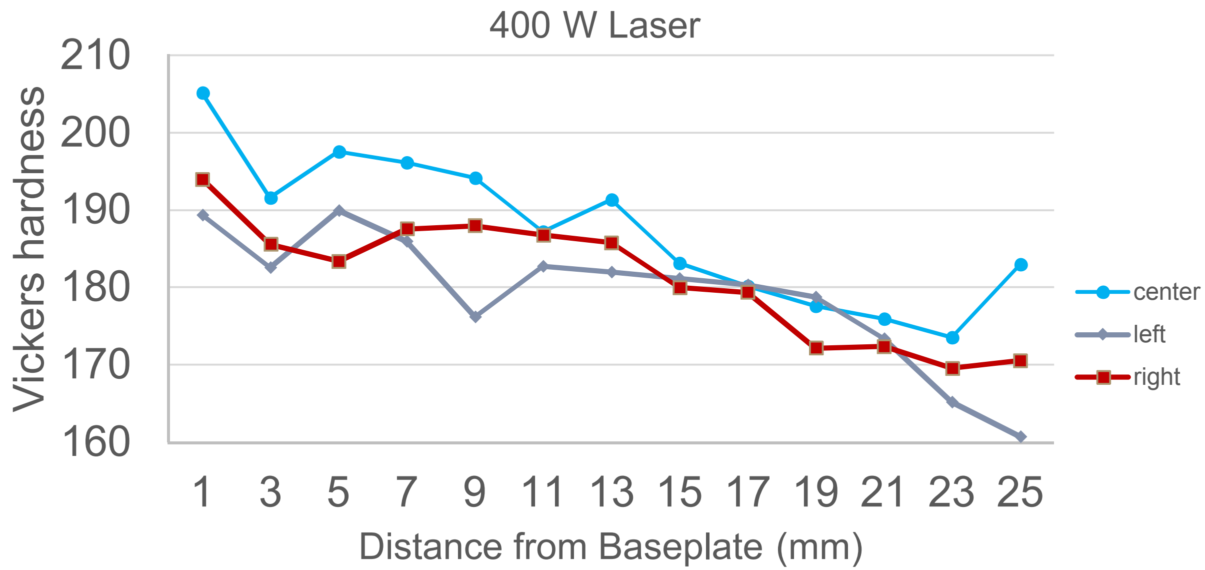
Thermally Induced Plasticity During Processing is Critical

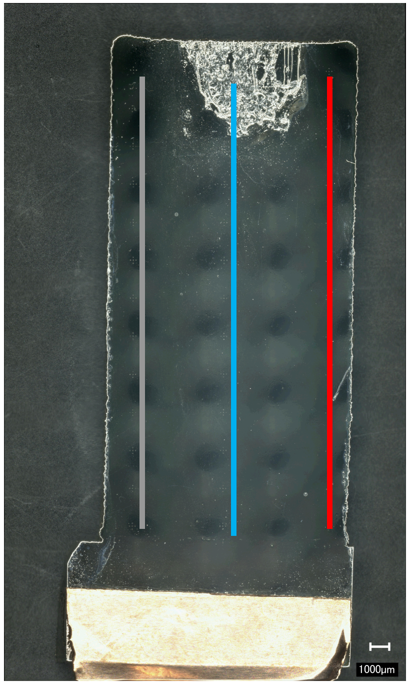


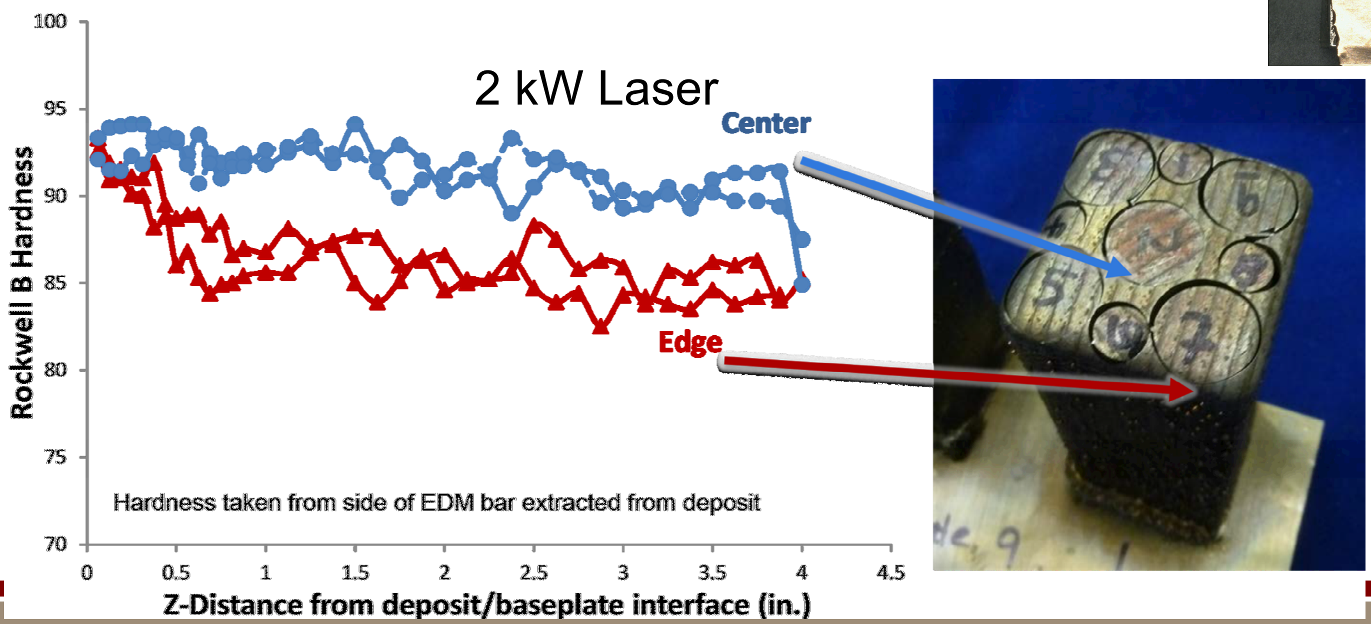
The constraint of the baseplate and thermally induced plasticity during processing make a difference in the dislocation structure and distribution of hardness in LENS 304L stainless steel

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

Hardness Values Highest Near Baseplate

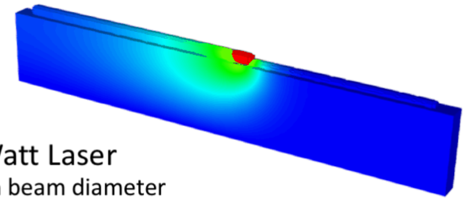




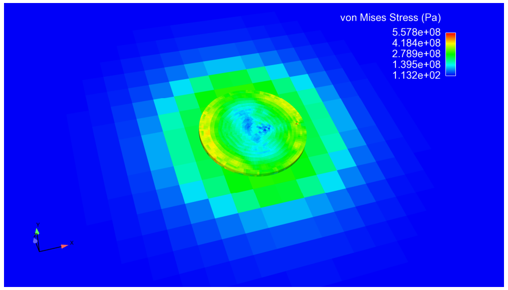


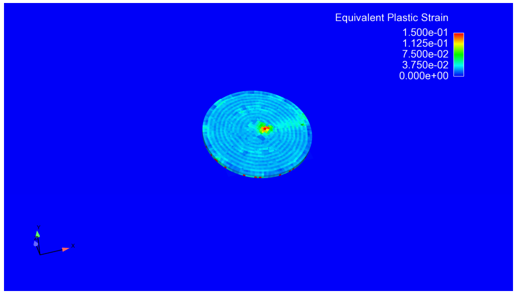
Summary and Current Status

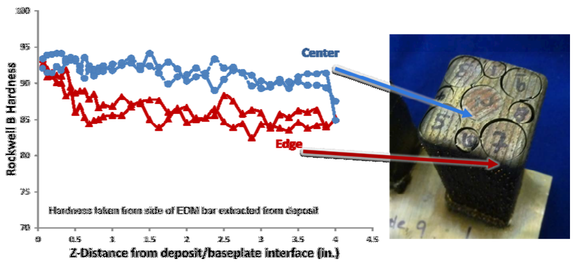
- Implementation of a multi-step, multi-physics workflow for additive manufacturing process modeling to predict residual stresses
- Increasing effort is being applied toward part scale builds and improving simulation turnaround time
- Coupled thermal-mechanical simulations predict residual stresses values near the material yield strength of 304L stainless steel
- The predicted yielding and plastic strain near the baseplate is supported by observations and measurements
- Experimental validation is ongoing
- Simulations of more complex geometries are currently underway



500 Watt Laser
0.001 m beam diameter

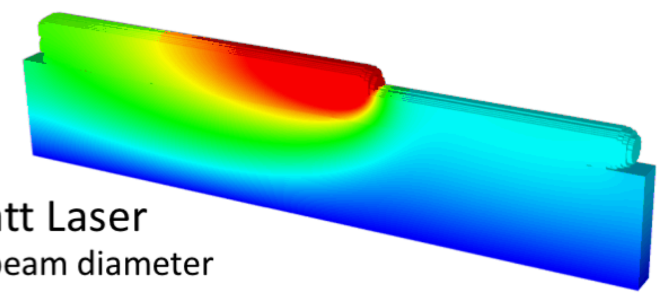






Conclusions

- 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)



2000 Watt Laser
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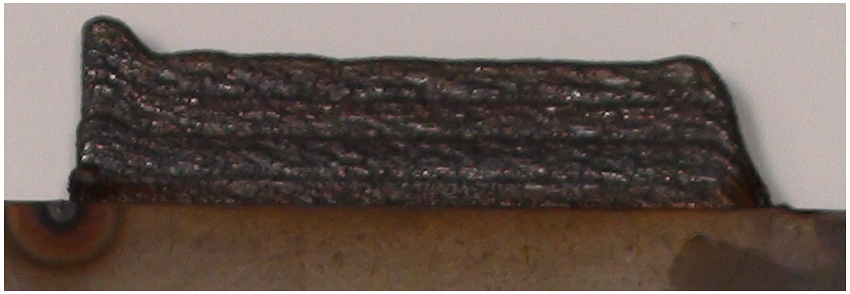

Extra Slides

- Varying build orientation in dog bone tensile specimens shows differential response in post-processing residual strain