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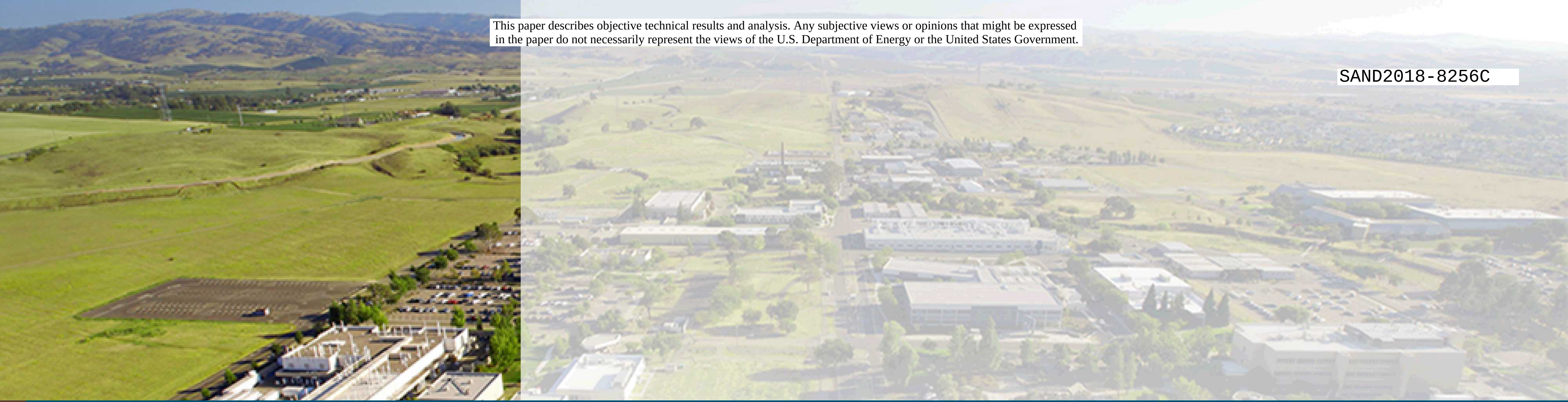

Process Modeling of LENS Manufacturing; Effects of Laser Scan Path on Residual Stress

Michael E. Stender, Lauren L. Beghini, Michael G. Veilleux, Joshua D. Sugar, Samuel R. Subia

World Congress of Computational Mechanics 2018

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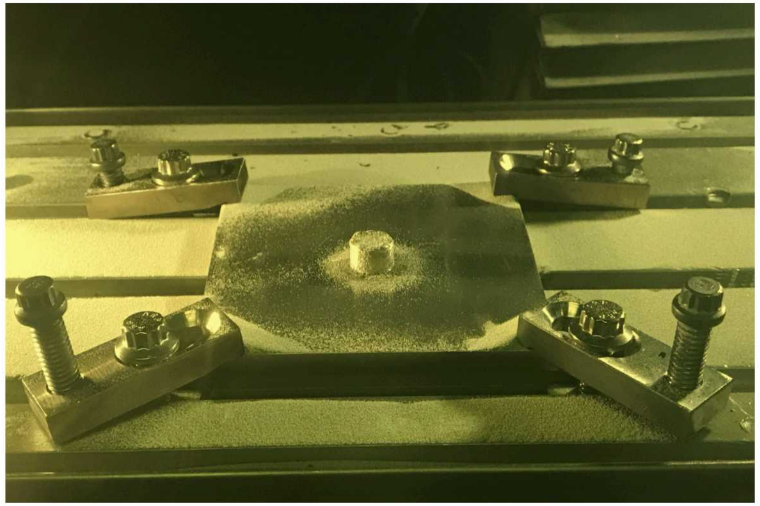
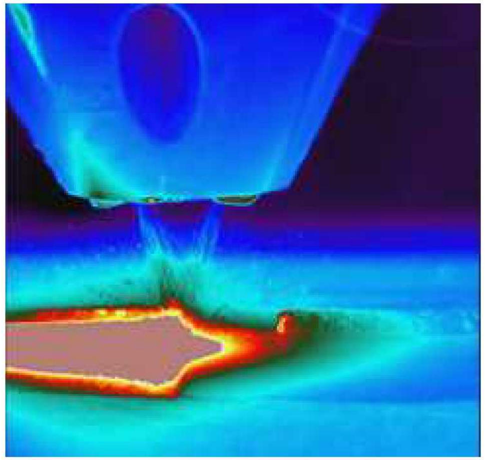
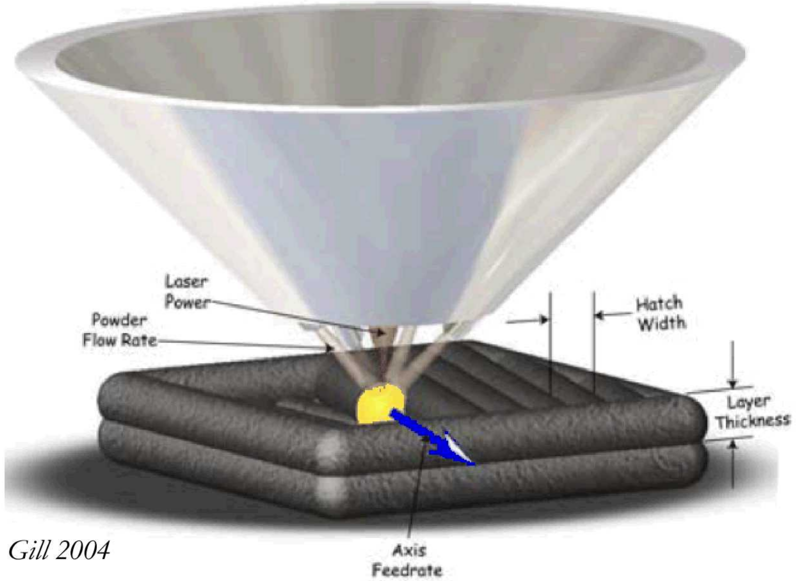
LENS Modeling Overview

- Overview of modeling efforts – integration into lifecycle analysis
- Part scale thermal-mechanical LENS modeling results
  - Experimental validation efforts
  - Effect of laser scan pattern and baseplate size on residual stress
- High fidelity coupled solid/fluid simulations
  - Methodology and development
  - Initial results





Daryl Dagel

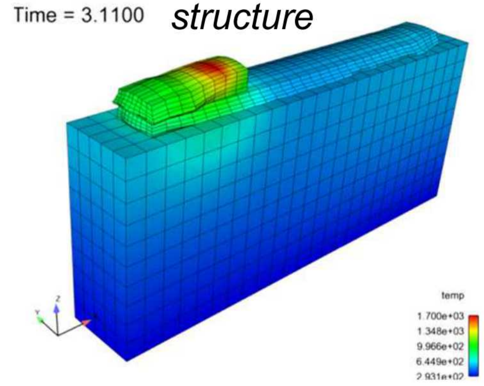


Gill 2004

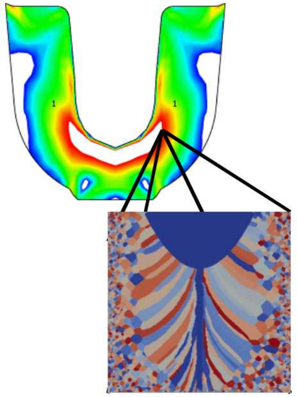
Lifecycle Analysis of Manufactured Components

Process Design and Simulation

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

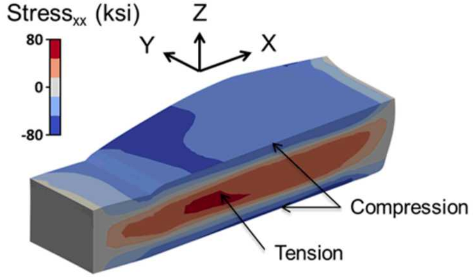


Microstructure and Properties



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

Residual Stresses

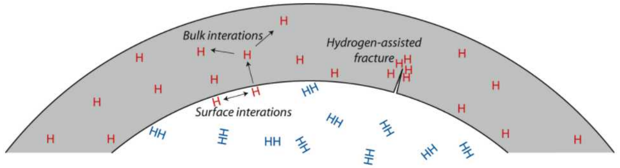


Solidification and thermal history result in strong residual stresses, which can impact performance

- 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

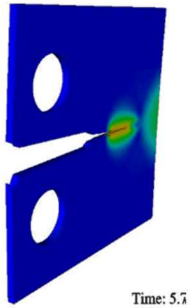
Multiphysics approaches for fully coupled simulation of chemical/thermal transport, mechanical loading, etc. to predict performance



(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



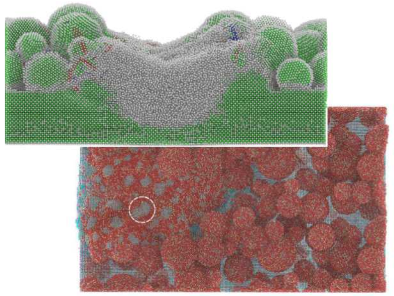
Margin/Uncertainty Design Life

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.

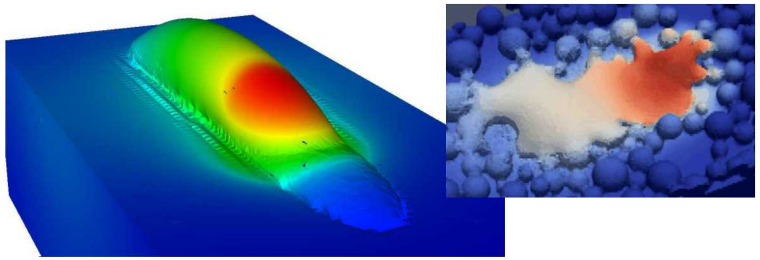
Additive Manufacturing Modeling at Sandia

Much of this work shown belongs to Sandia's Born Qualified project

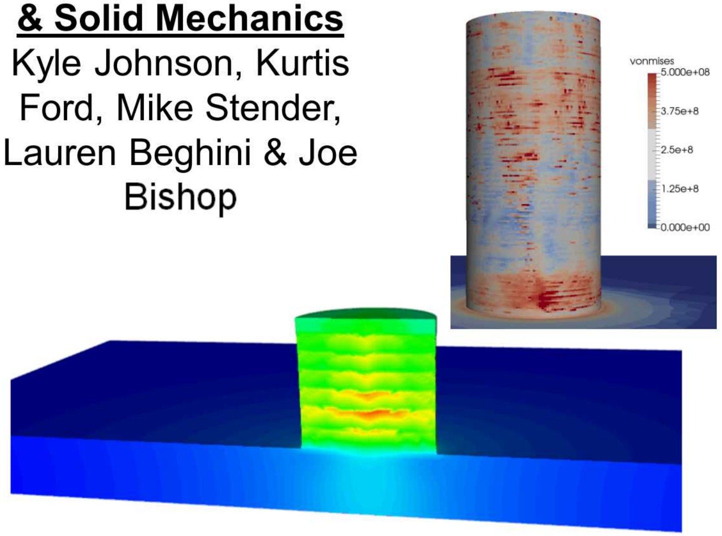
Powder Behavior
Mark Wilson



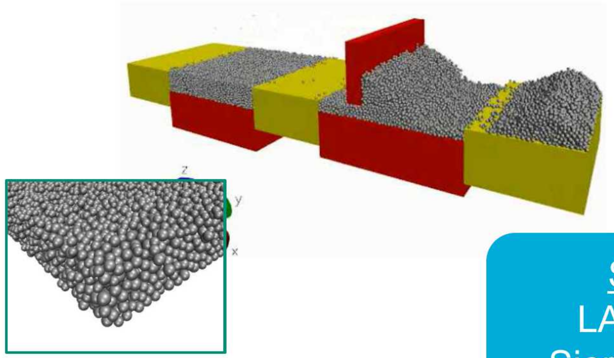
Mesoscale Thermal/Fluid Behavior
Brad Trembacki, Dan Moser & Mario Martinez



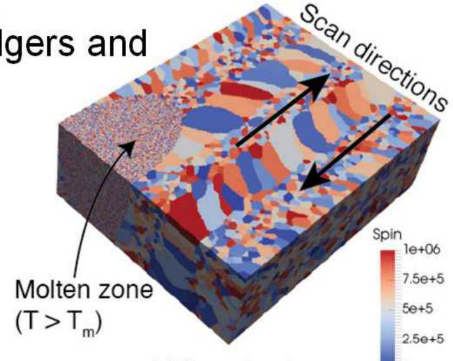
Part-Scale Thermal & Solid Mechanics
Kyle Johnson, Kurtis Ford, Mike Stender, Lauren Beghini & Joe Bishop



Powder Spreading
Dan Bolintineanu



Mesoscale Texture/Solid Mechanics/CX
Judy Brown, Theron Rodgers and Kurtis Ford



a) Microstructure

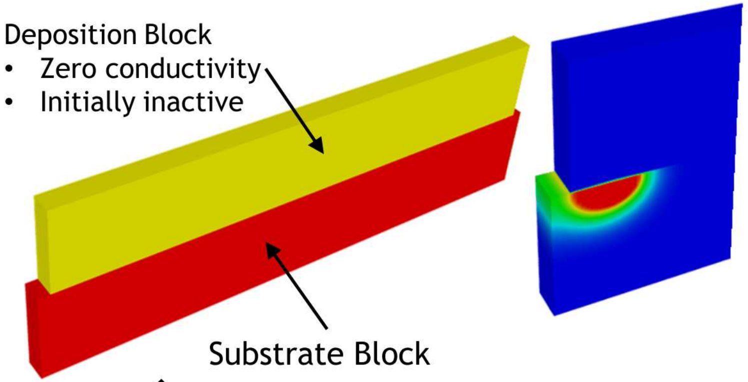
Part-Scale Microstructure
Theron Rodgers

Simulation Codes:
LAMMPS, SPPARKS, Sierra/Aria, Sierra/Adagio

Process Modeling of LENS Additive Manufacturing

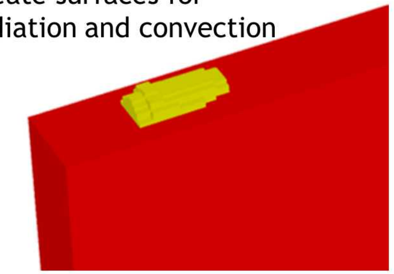
Step 1 Thermal Activation

Initial mesh:



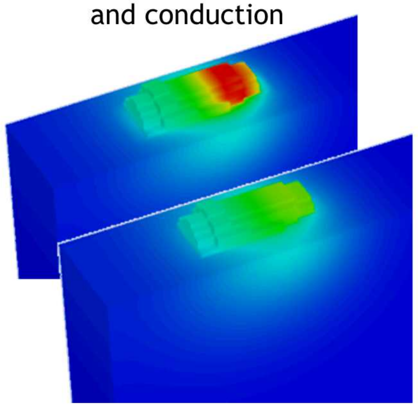
Step 2 Remove Inactive Elements

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



Step 3 Thermal Analysis

- Radiation, convection, and conduction

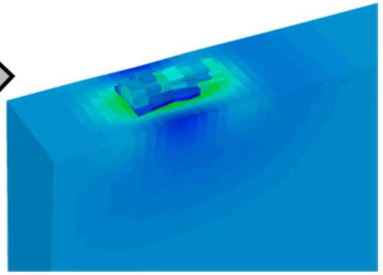


Step 4 Map and/or Initialize Mechanical Variables

- 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
- Fluid elements
  - Newtonian fluid material model



* Displacements shown 15x

Step 6 Map Back to Reference Configuration

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

Constitutive Model 304L Stainless Steel

- Elastoviscoplastic temperature dependent material model calibrated for 304 L (BCJ mem)
  - Calibrated for room temperature to forging temperatures (< 1200 K)
  - Continuing work into higher temperature calibration up to near melt (~1700 K)
  - Temperature dependent thermal and mechanical properties

Flow rule

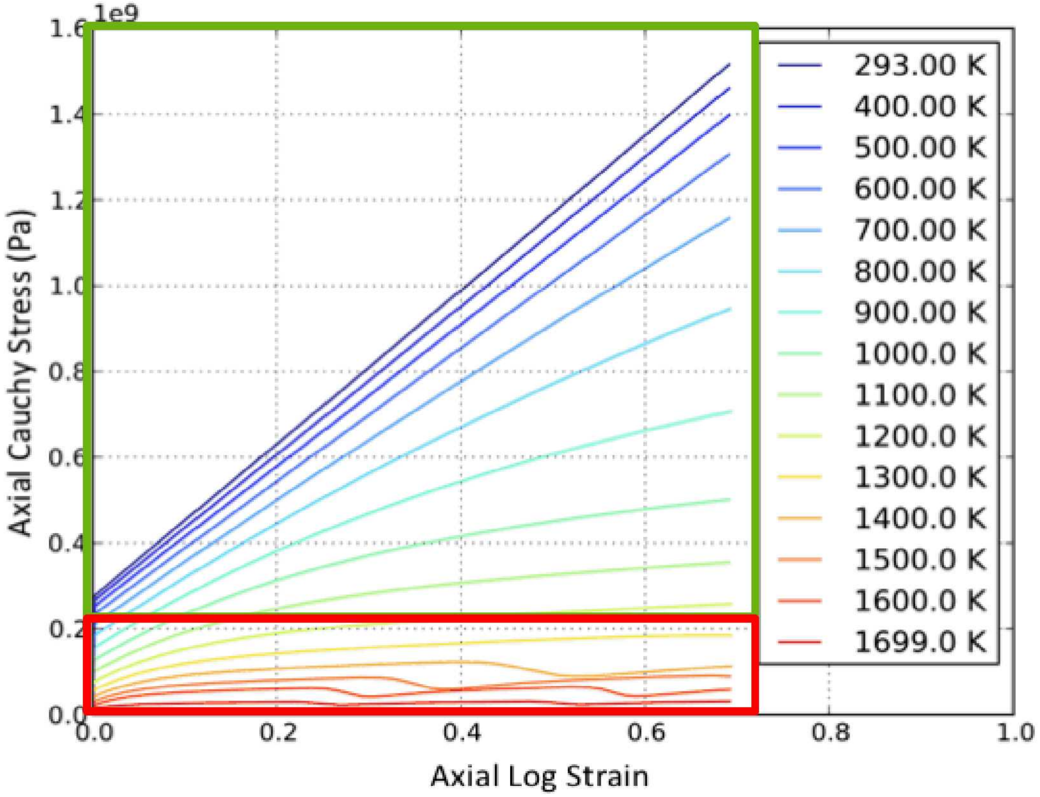
$$\dot{\epsilon}_p = f_1 \mathrm{e}^{-f_2/\theta} \sinh^{n_1+\frac{n_2}{\theta}} \left\langle \frac{\sigma}{\kappa + Y(\theta)} - 1 \right\rangle$$

Temperature dependent yield stress

$$Y(\theta) = \frac{1}{2} \frac{Y_0}{Y_4 + e^{\left(-\frac{Y_1}{\theta}\right)}} [1 + \tanh\{Y_2(Y_3 - \theta)\}]$$

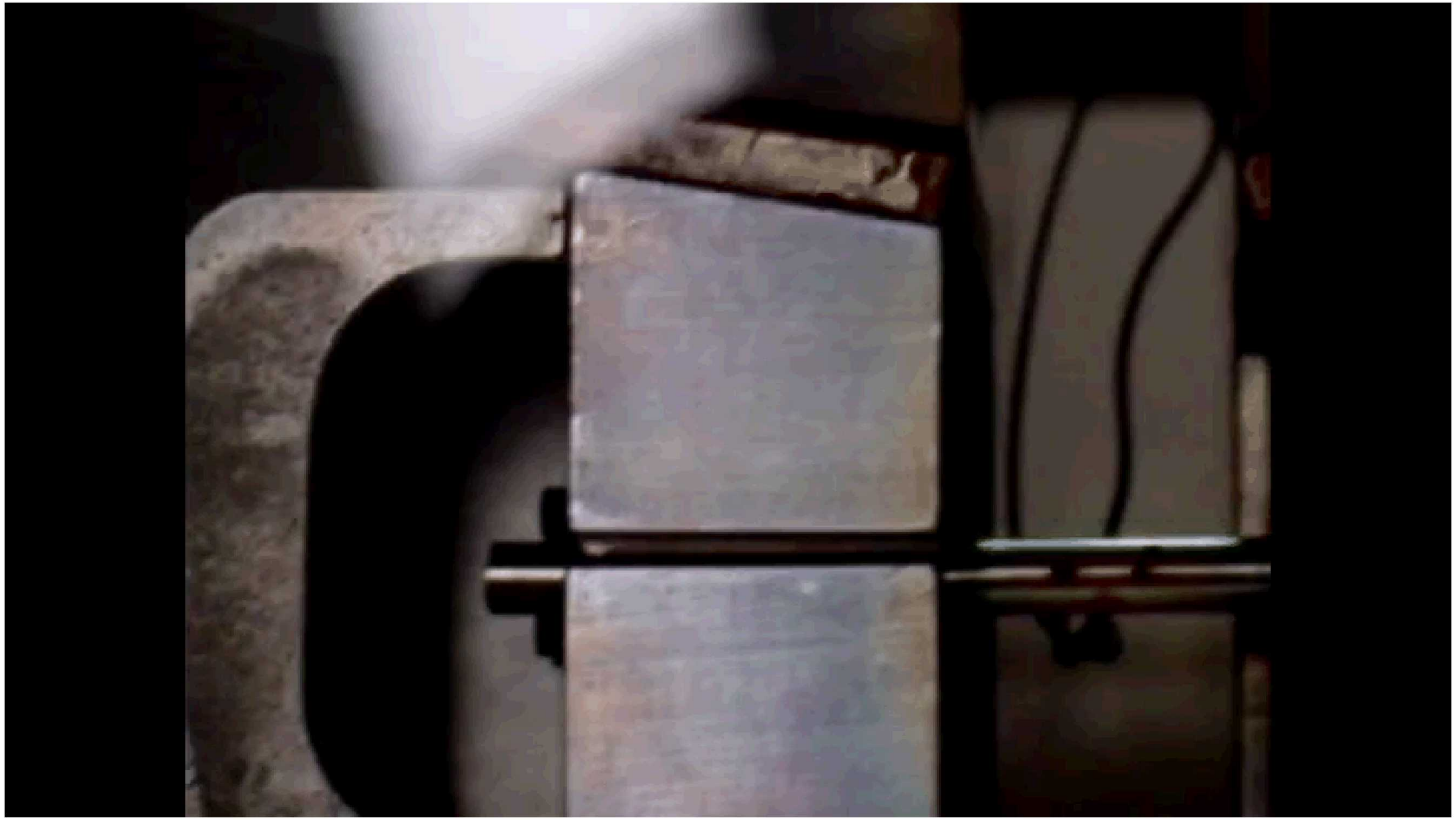
If $T > T_{melt}$ then,

$$T_{ij} = -p\delta_{ij} + \mu_{melt}\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right)$$

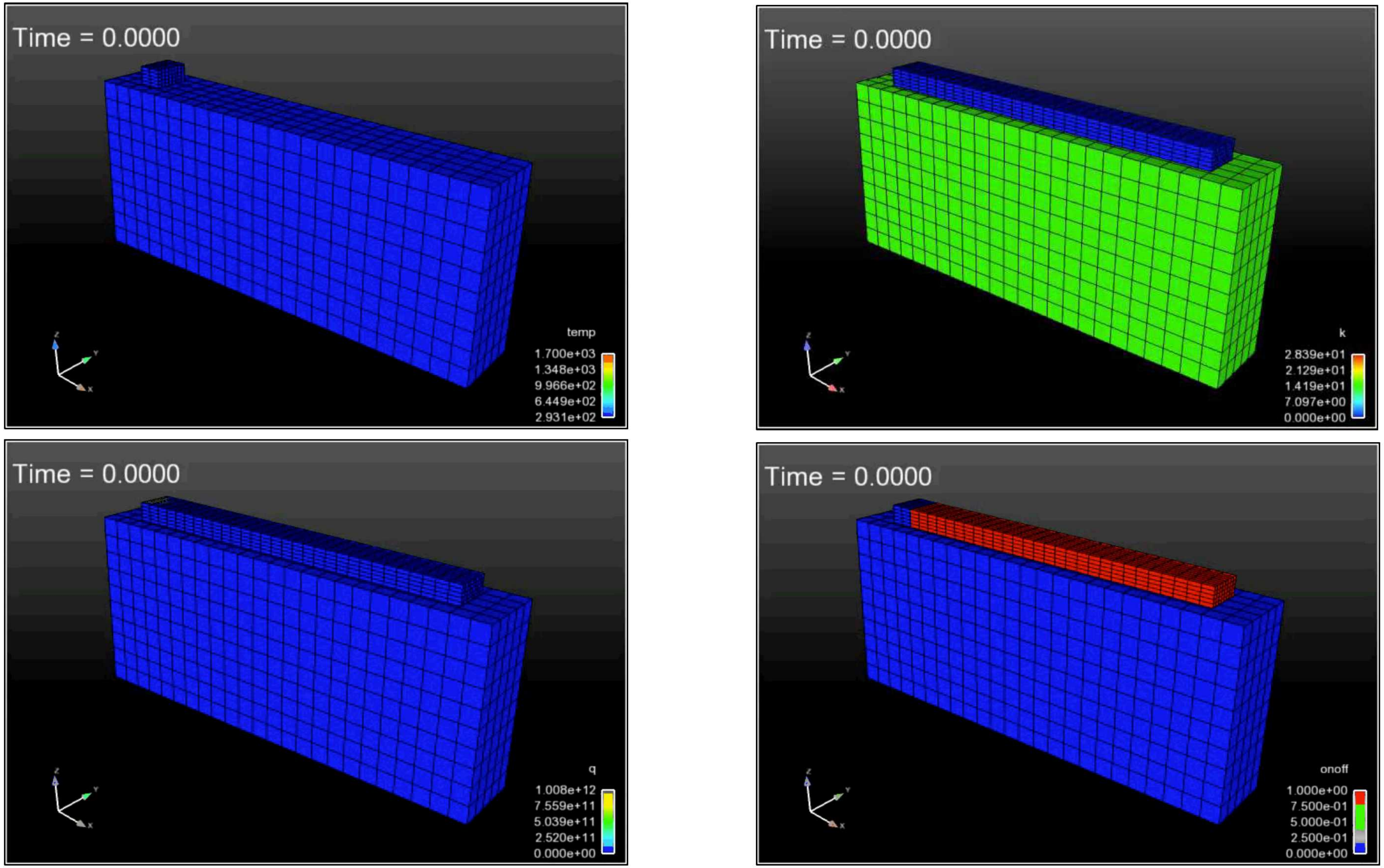


High Temperature Material Testing

- Gleeble tests underway to calibrate high temperature material parameters

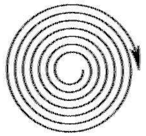


Example - Single Pass LENS Deposition

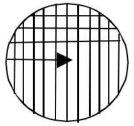


Effect of Scan Pattern and Baseplate Size

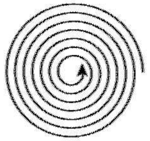
- All builds of a ½" diameter ¼" high cylinder
- 3 Scan Patterns



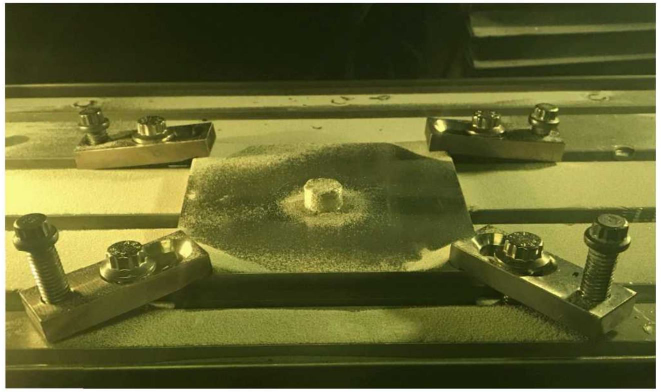
Spiral Out



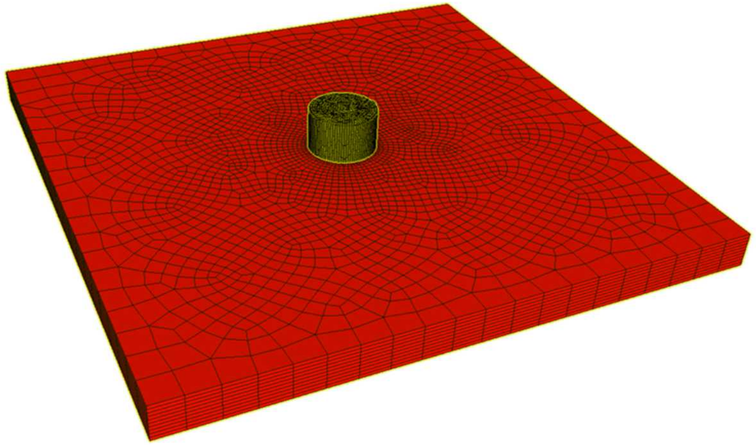
90 Degree Cross Hatch



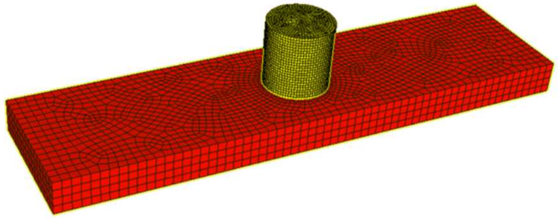
Spiral In



- 2 Baseplate Sizes



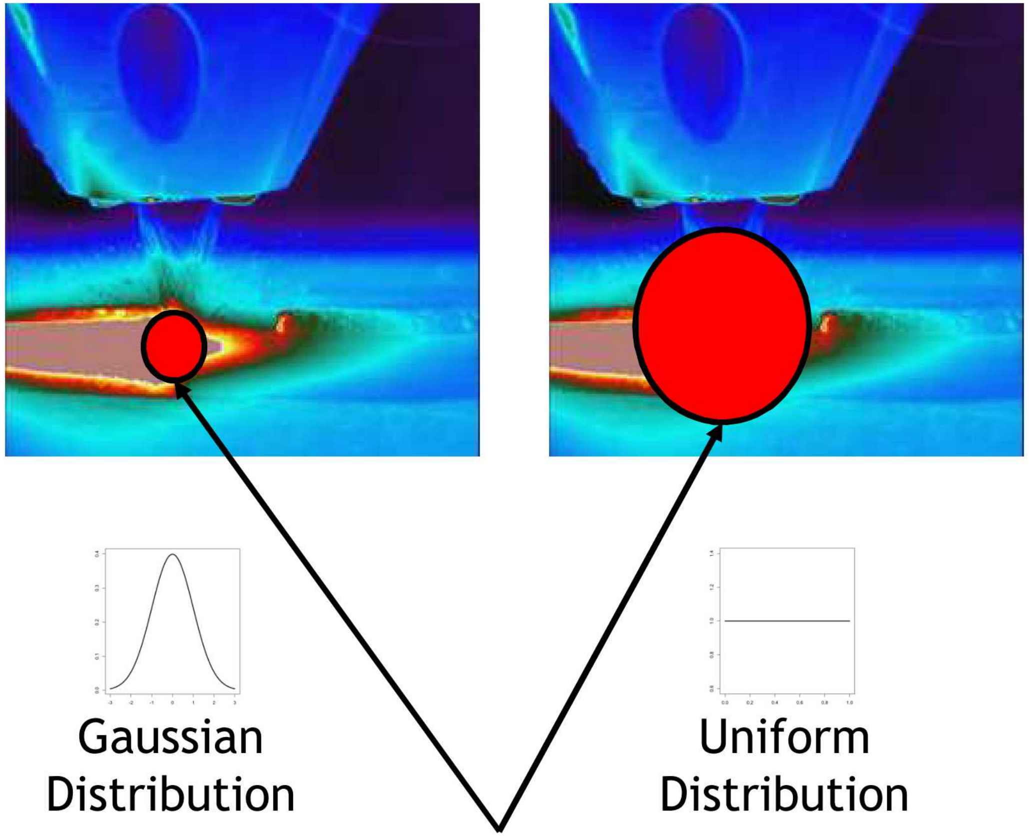
4" by 4" by ¼" baseplate



1" by 4" by ¼" baseplate

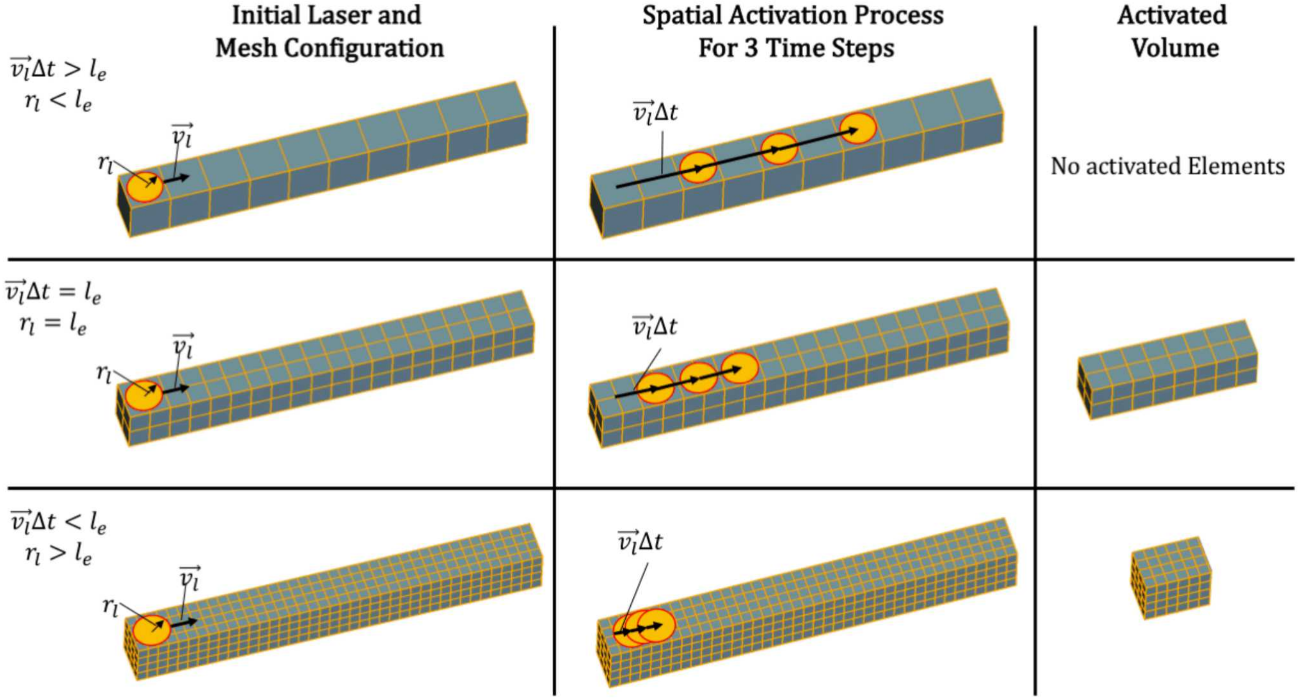
Lumped Laser Method

- Computational throughput remains a primary challenge for process simulation
- ”Lumped laser method” employed to improve computational efficiency



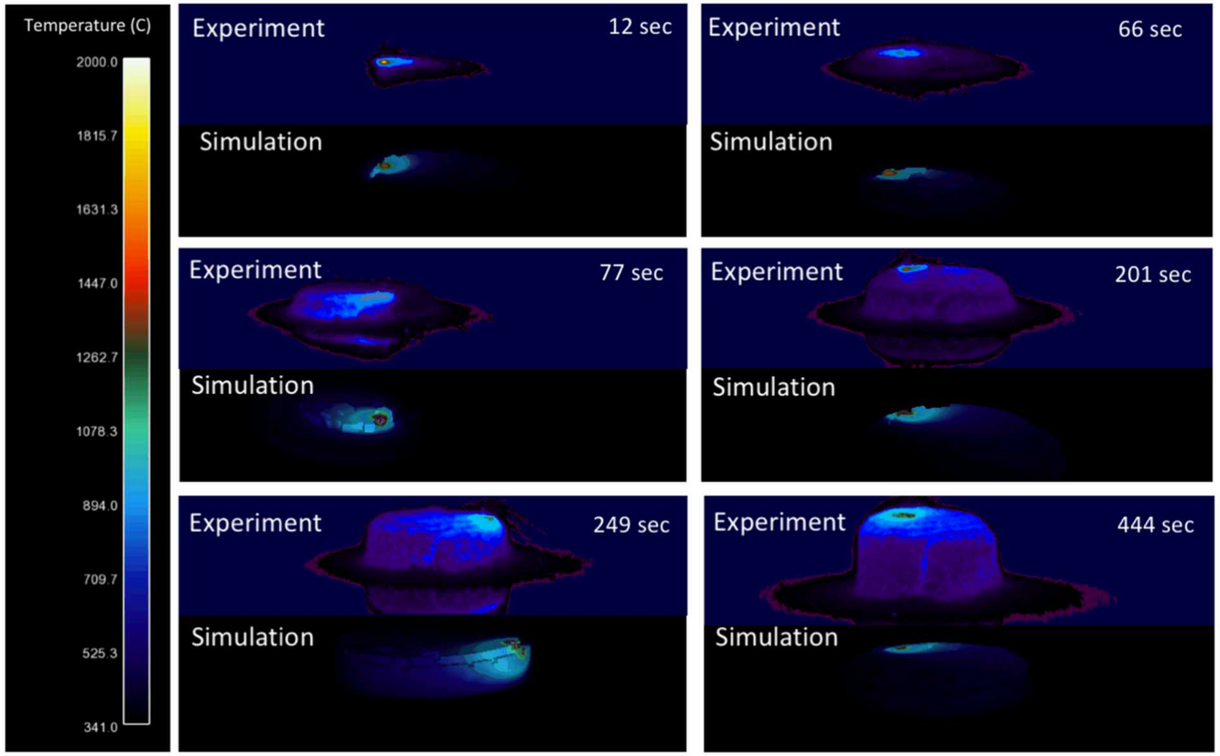
Laser beam spot size
Enlarged to increase material
activation rate

This method is inherently mesh dependent
Mesh size, laser spot size, and laser velocity
must be appropriately defined

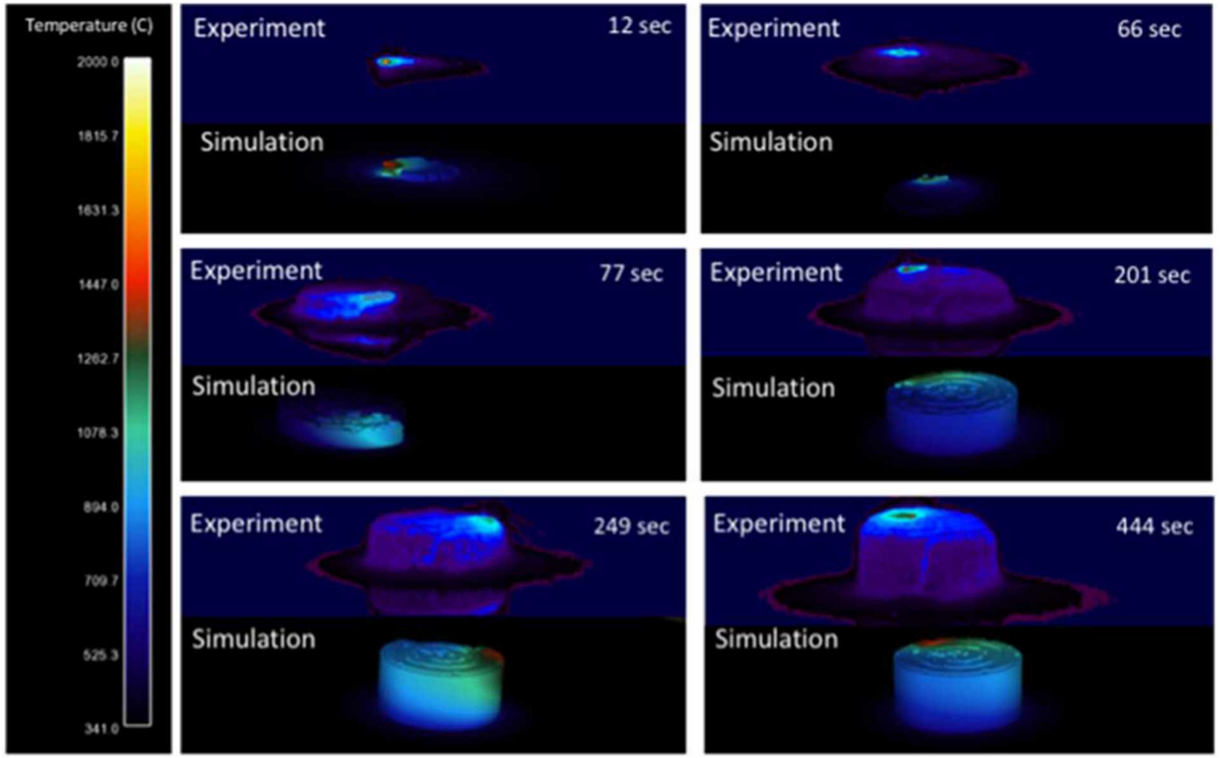


LENS Cylinder Build Thermal Comparisons

- Comparisons between simulation and experimental FLIR camera measurements

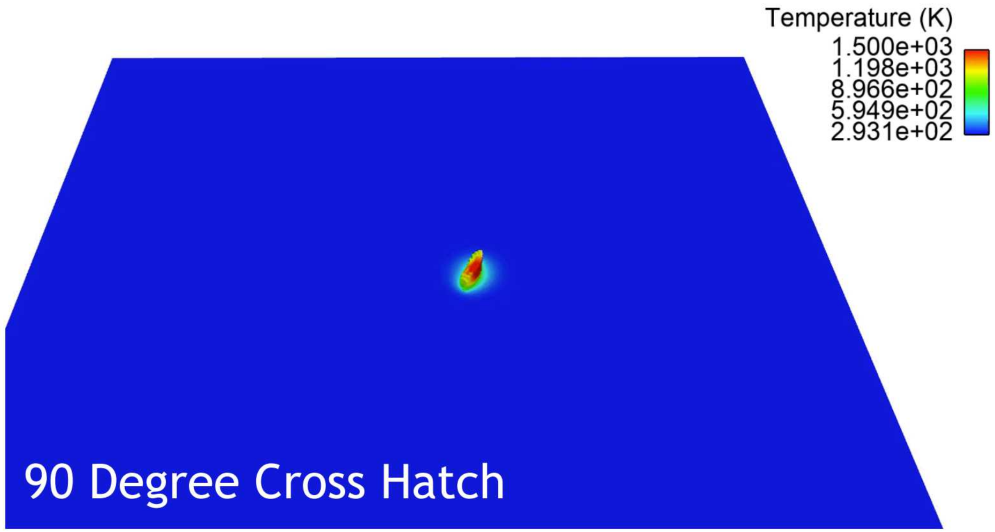


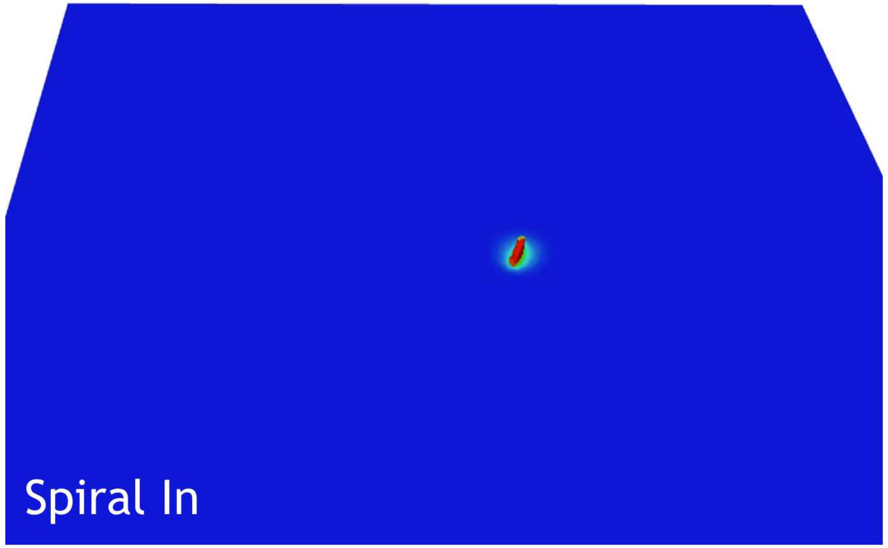
Actual Laser Beam Model

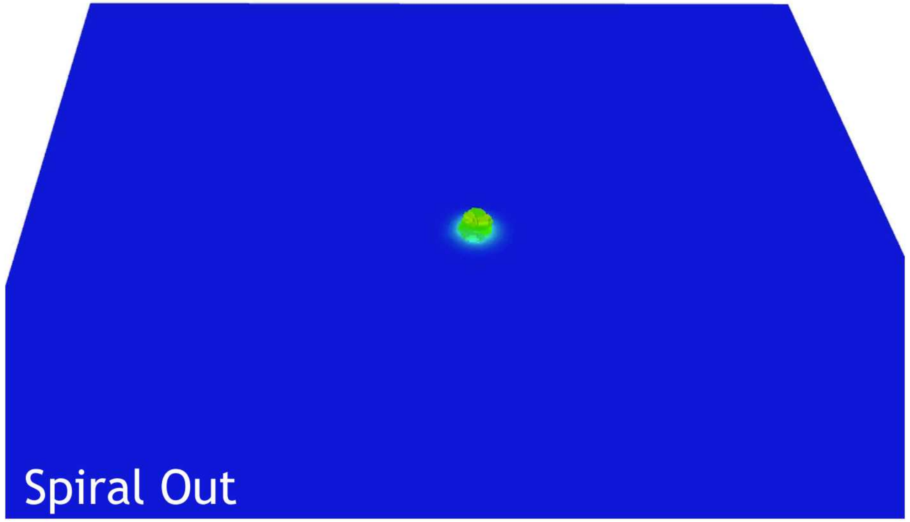


Lumped Laser Beam Model

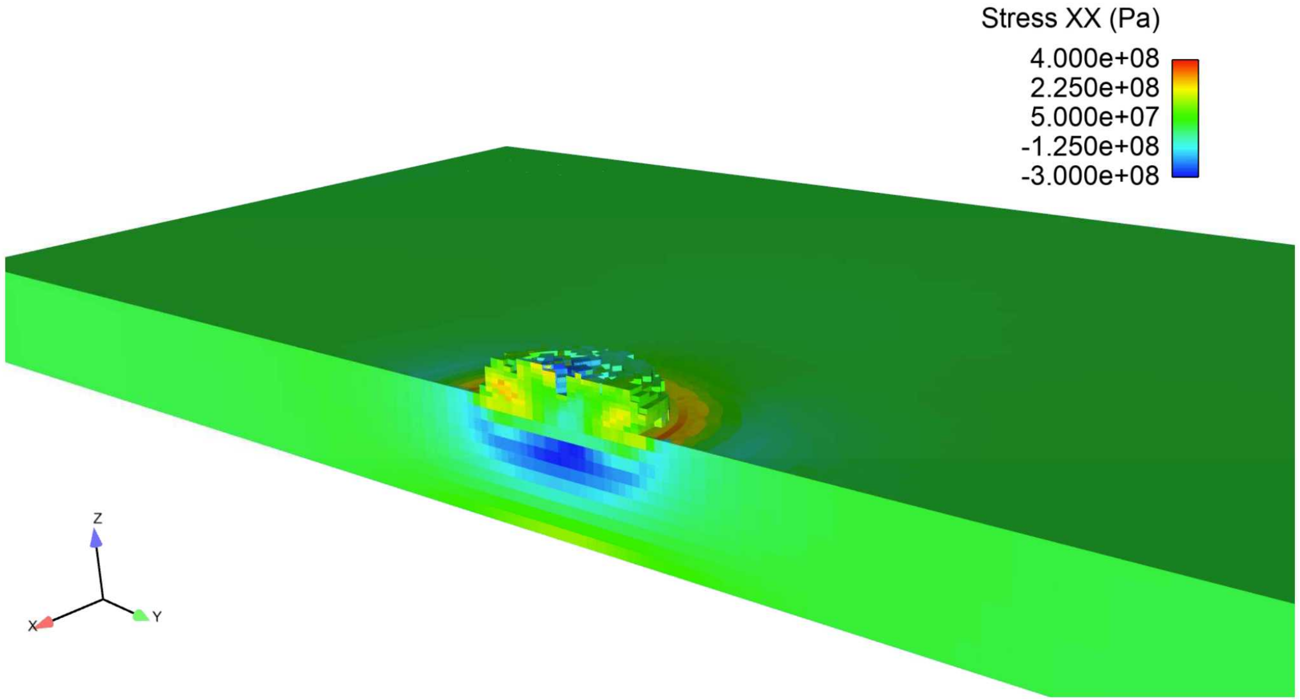
Influence of Differential Laser Scan Patterns

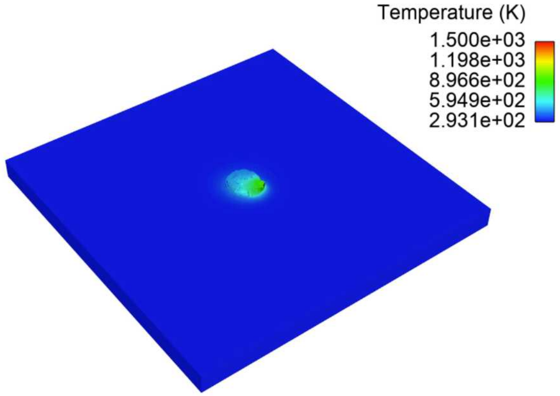


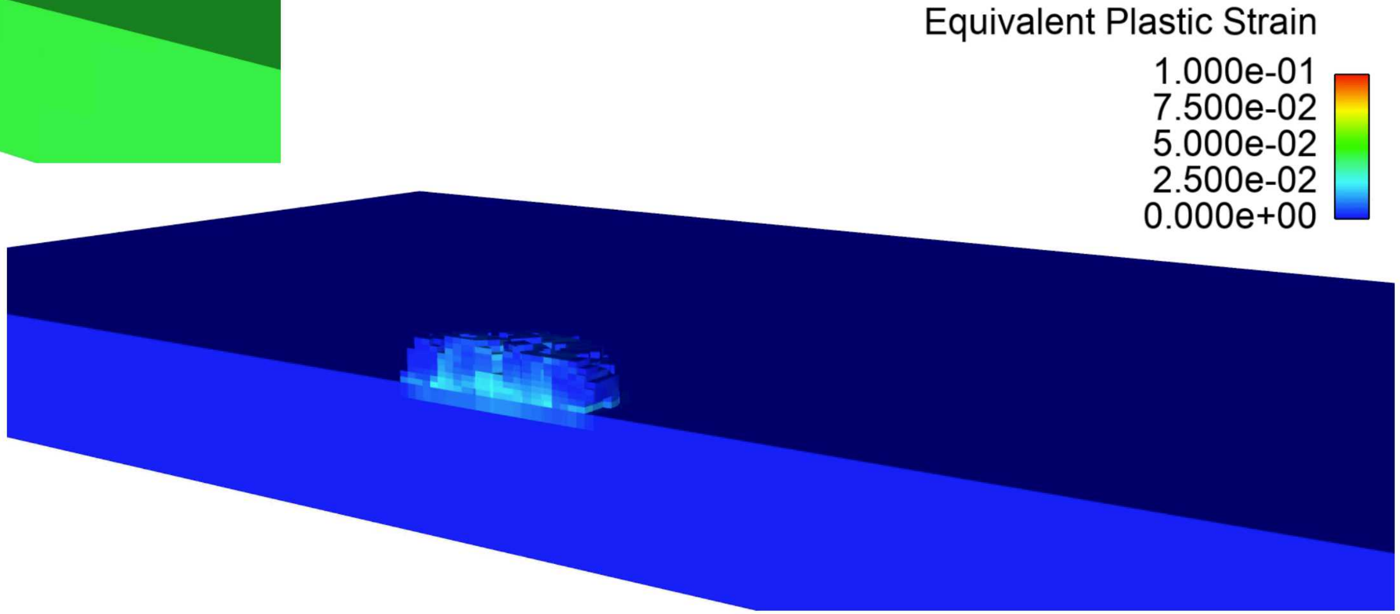




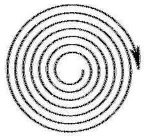
Residual Stress and Plastic Strain Evolution



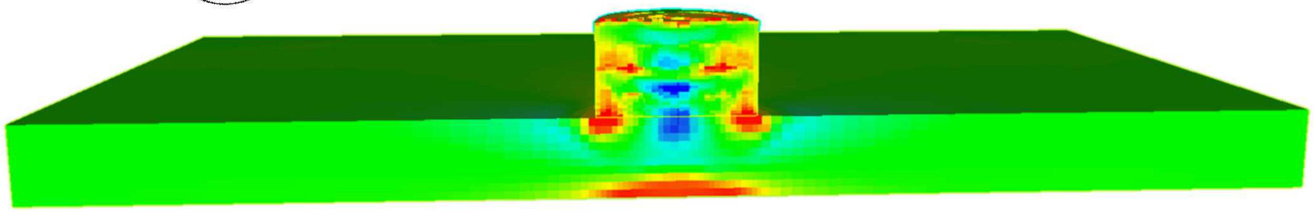


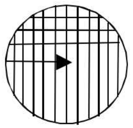


Residual Stress Predictions

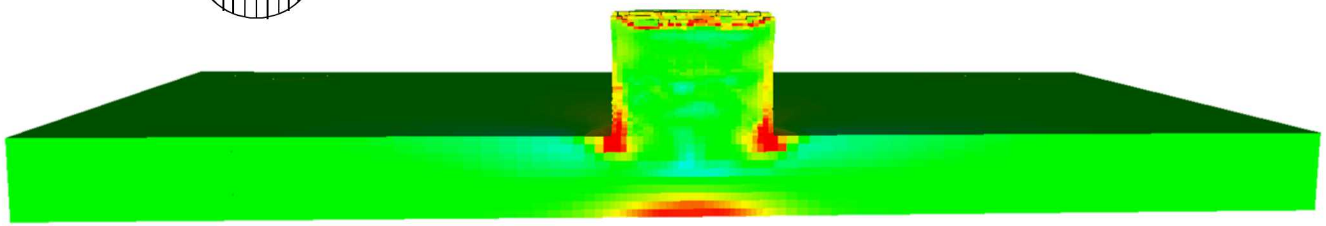


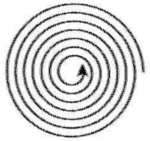
Spiral Out Large Plate



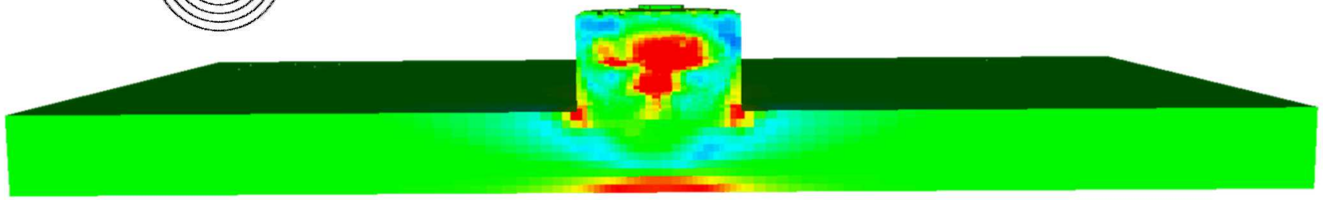


Cross Hatch Big Plate

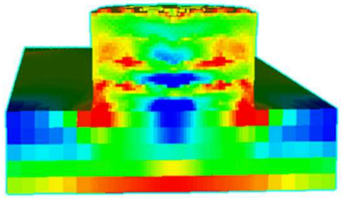




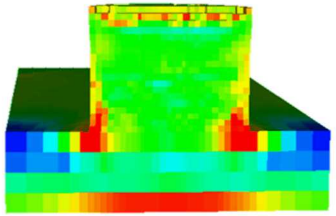
Spiral In Big Plate



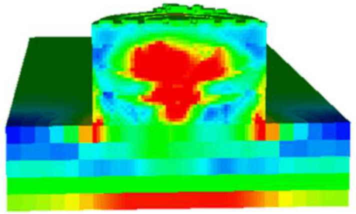
Spiral out Small Plate

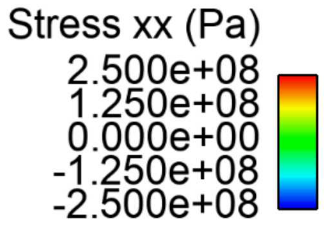


Cross Hatch small Plate



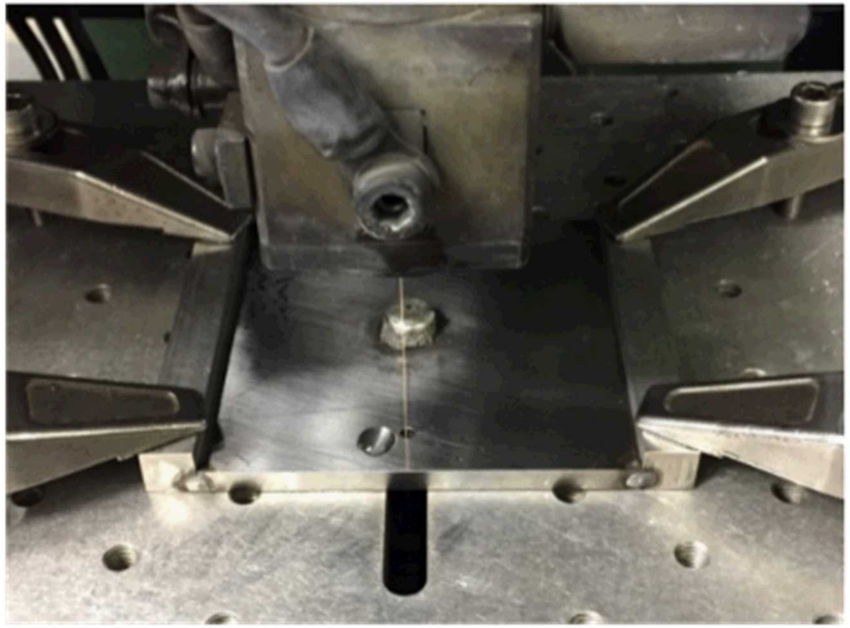
Spiral In Small Plate



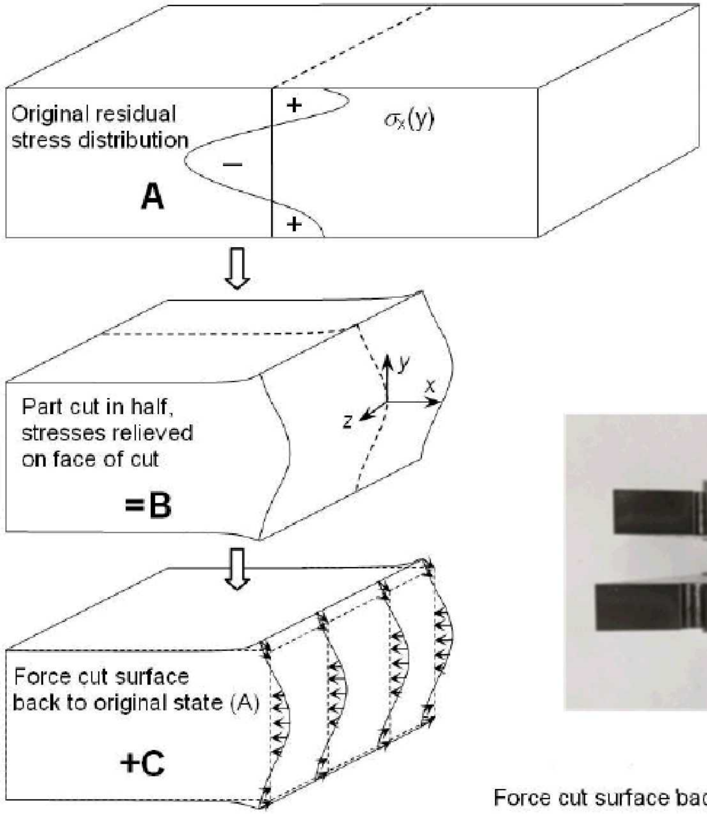


Contour Measurements – UC Davis

- Contour method measurements conducted to determine residual stresses
  - Inverse problem to back out tractions on surfaces to return deformed shape back to pre cut condition



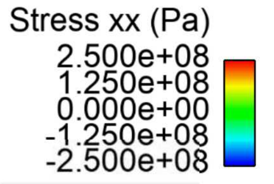
Contour measurement data provided by M. Hill and C. D'Elia, UC Davis



Pagliaro et al., 2010

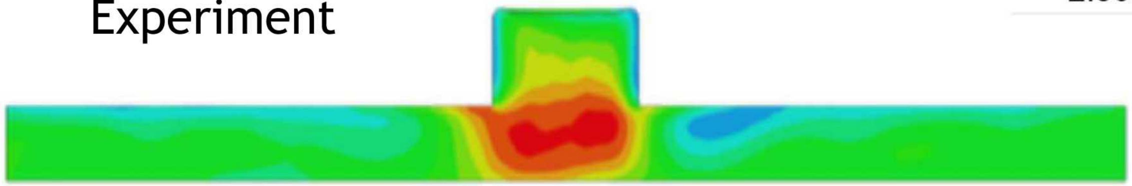
Force cut surface back to original state

Comparison to Contour Measurements

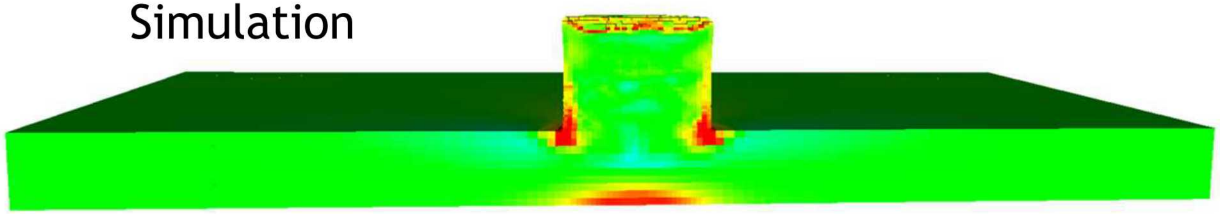


90 Degree Cross Hatch Big Plate

Experiment

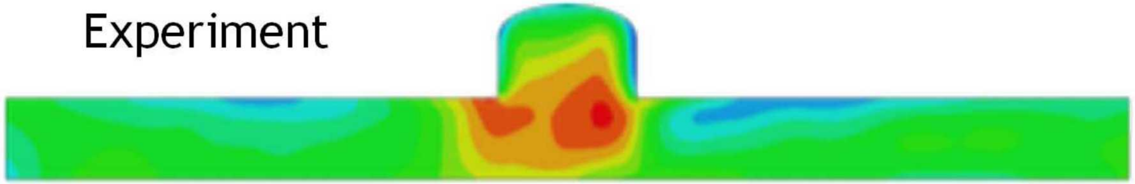


Simulation

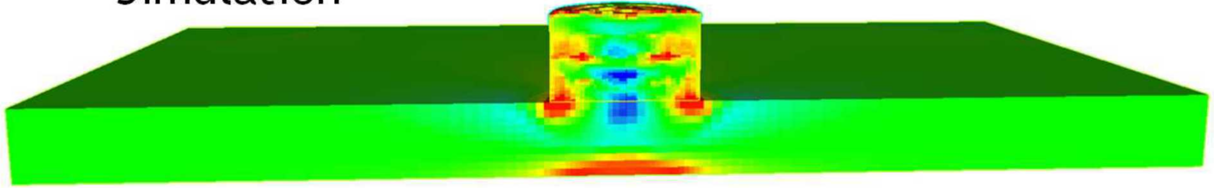


Spiral Out Big Plate

Experiment

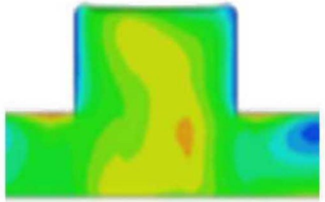


Simulation

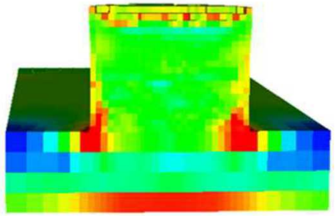


90 Degree Cross Hatch Small Plate

Experiment

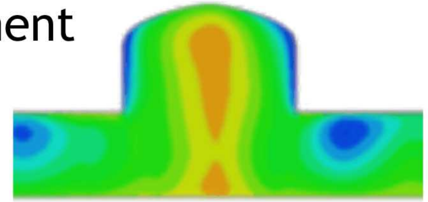


Simulation

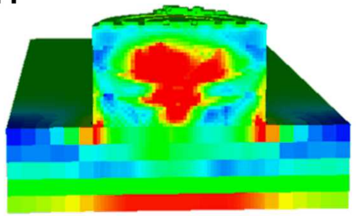


Spiral In Small Plate

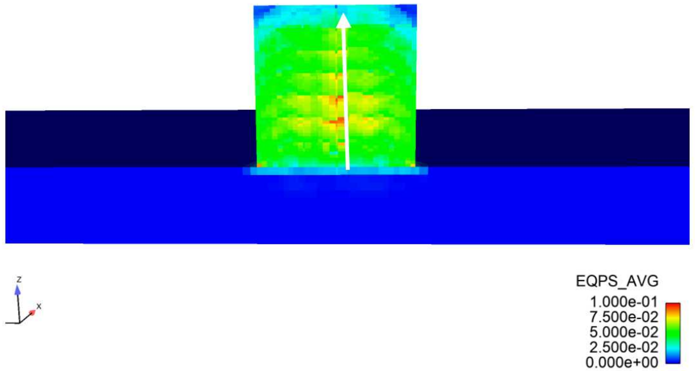
Experiment

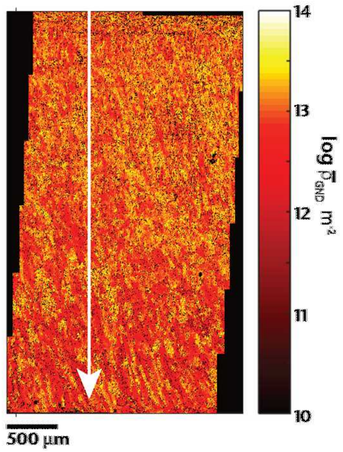


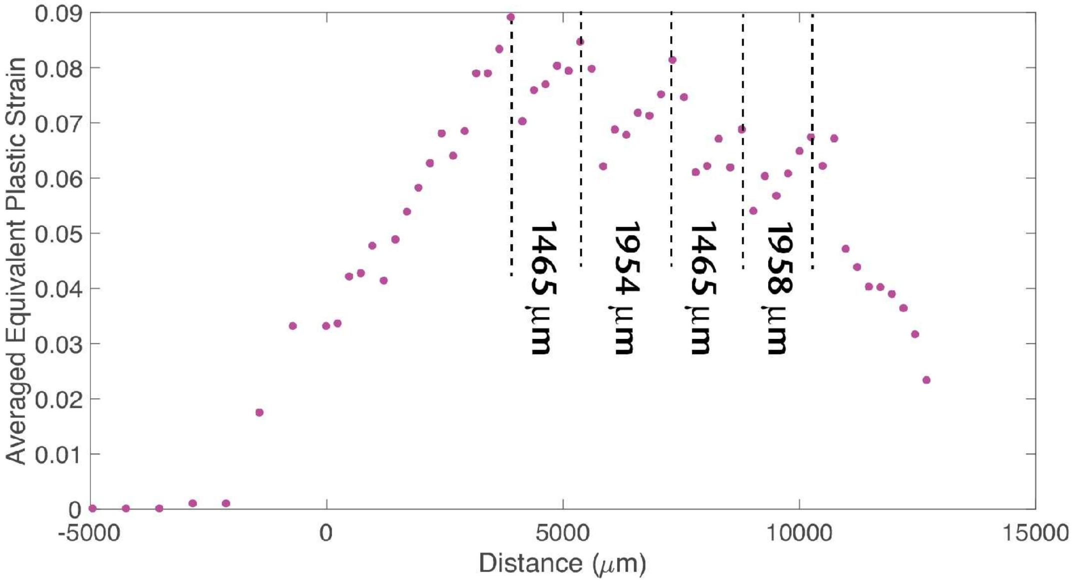
Simulation

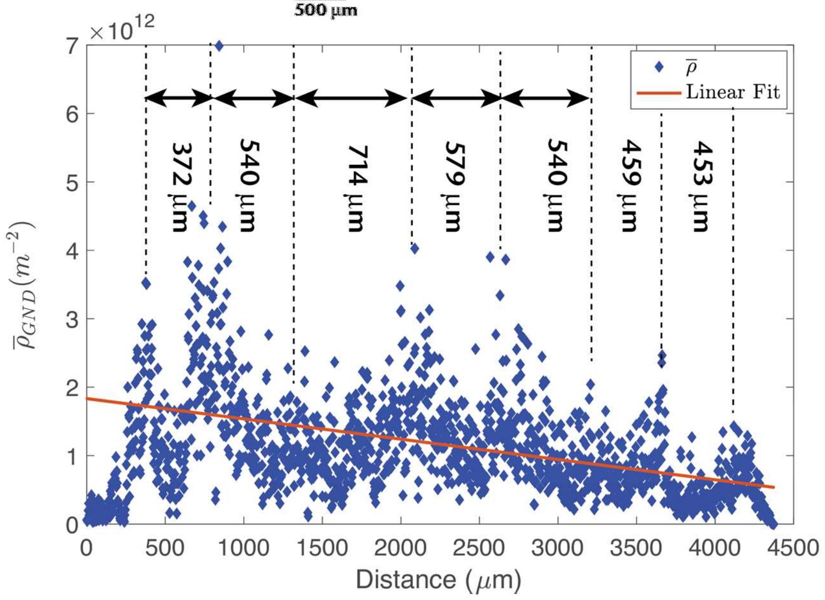


Model and Experiment Exhibit Oscillations Consistent with Layer Height





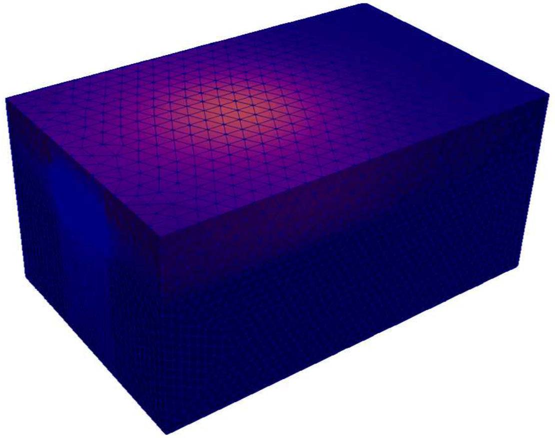




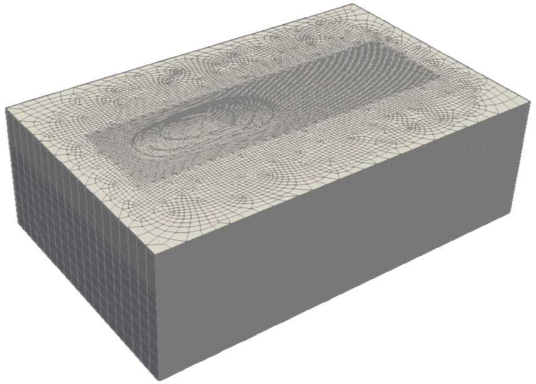
Simulation results and experimental build had different layer heights, but show similar trends

Fluid Mapping Onto Solid Mechanics Mesh

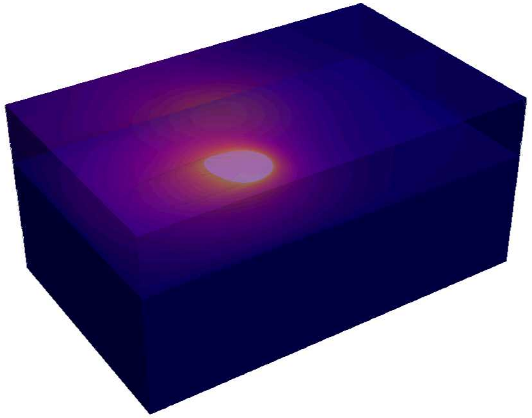
- Using SIERRA Adagio, map the field data from the fluid model to initialize the solid mechanics run:



Fluid model results (tet4 elements)



Hex8 mesh to conduct the solid mechanics

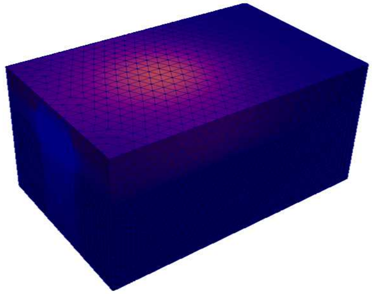


Mapping of fluid results on Hex8 mesh to compute residual stress

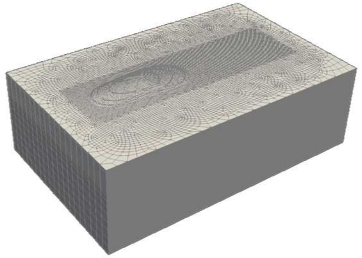
Now, we have a thermal history and topology from the thermal/fluid model as an input to the solid mechanics to compute the residual stresses with only the “active” elements…

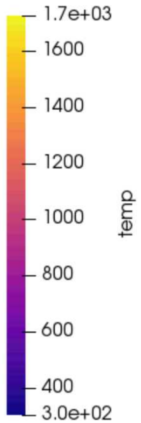
New Fluid/Solid Workflow Provides Enhanced Fidelity

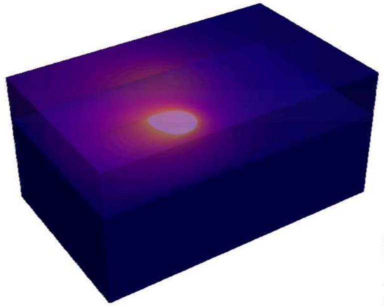
Run fluid model to get the thermal history and topology for the full build (~8M tetrahedral elements)



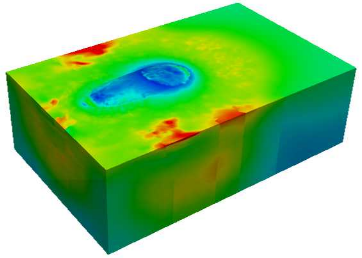
Using CUBIT's sculpt algorithm, mesh the "active" regions of material (fluid/solid) (~300,000 hex8 elements)



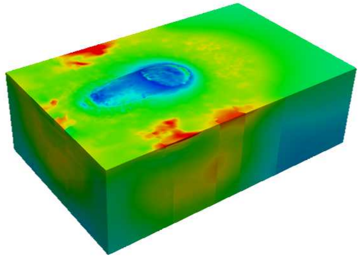




ap the thermal ory onto the hex mesh to use for solid mechanics input for that topology

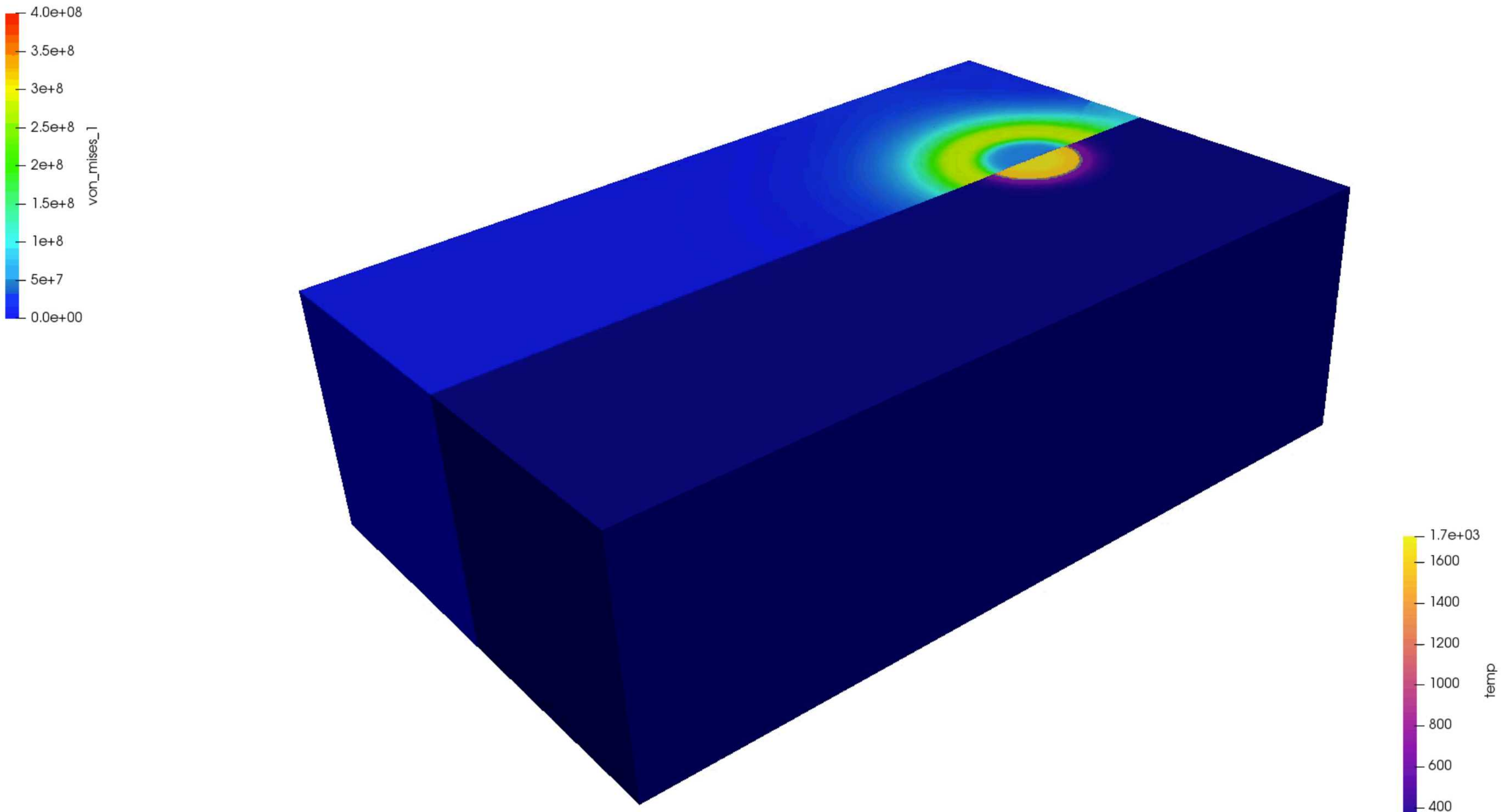


. previous iteration's state variables onto the new hex mesh topology



Compute the new state variables and deformation using the thermal history and previous state for that topology

New Fluid/Solid Workflow Provides Enhanced Fidelity



Conslusions

Can we understand the properties and performance of LENS components?

- Multiphysics models are being implemented and validated by experiments
- Models can elucidate the conditions that give rise to observed properties

Can we integrate appropriate experimental data to provide model validation?

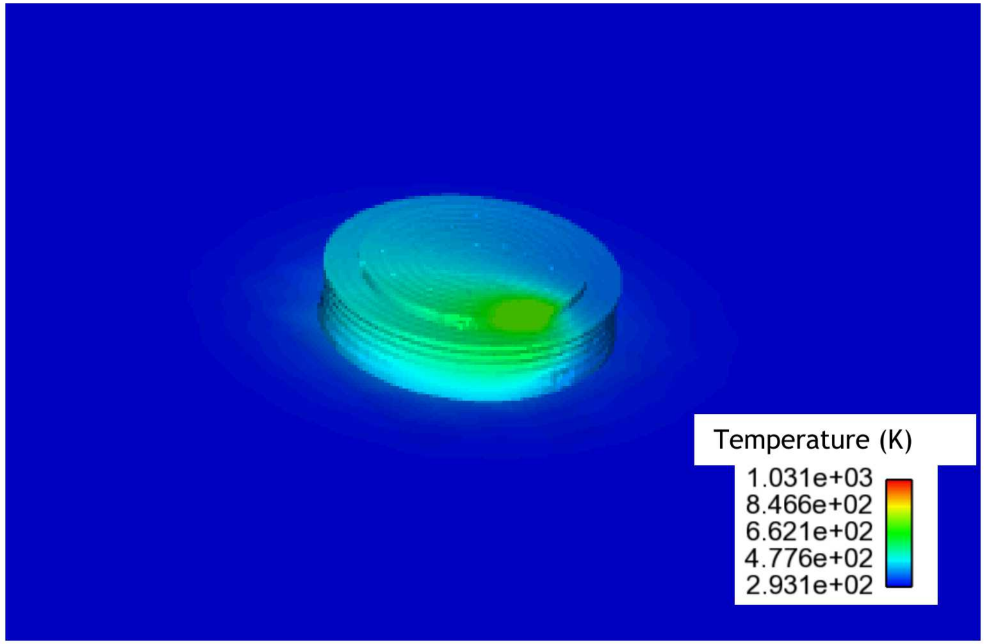
- General agreement observed in temperatures, dislocation density/plastic strain, and residual stress
- Additional validation work will increase confidence in results going forward

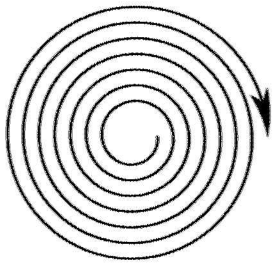
Ultimately, can we certify LENS components for use in critical engineering applications?

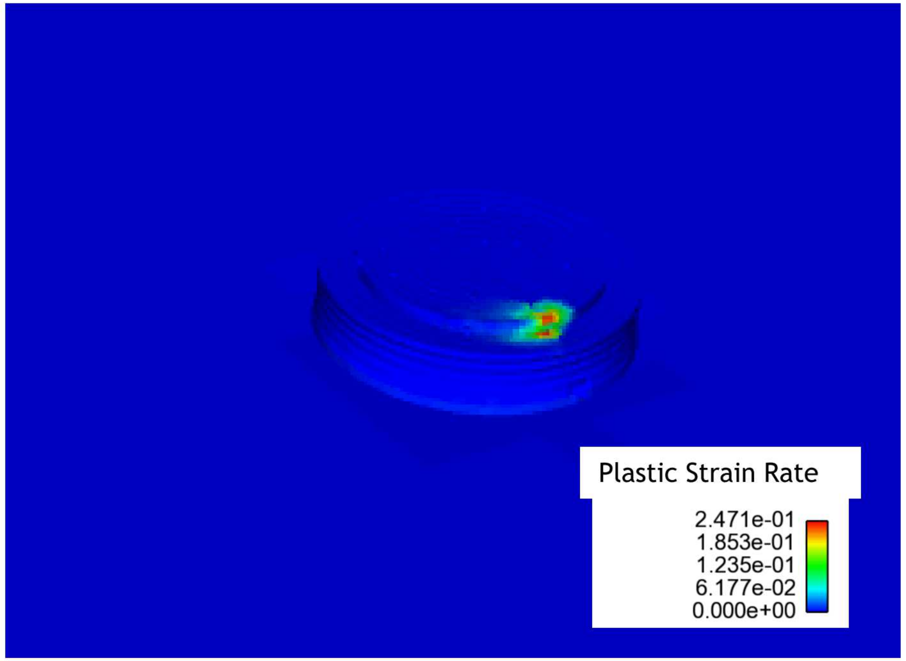
- Traditional manufacturing processes (*e.g*. forging, machining) have relied on large empirical knowledge bases developed over decades
- Integrated computational materials engineering (ICME) can provide a pathway for accelerated science-based certification of AM components

Additional Slides

Thermal Influence on Plastic Strain Rate







Nonzero plastic strain rates are in high temperature regions

Several Fine-Scale Features to Consider in LENS Microstructure