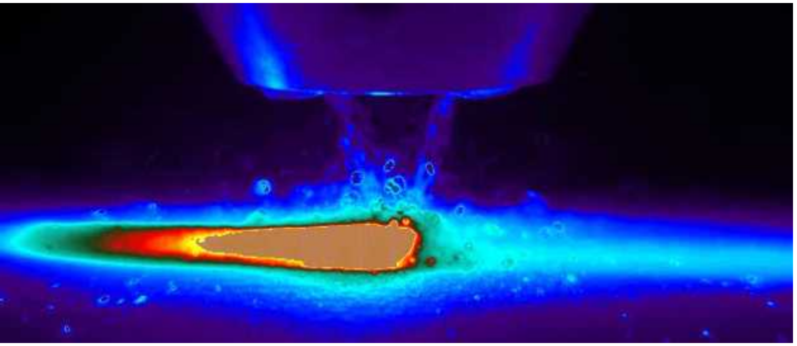
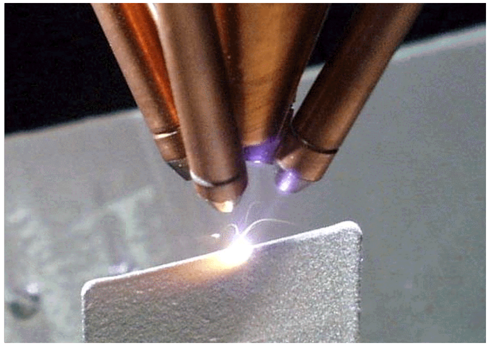
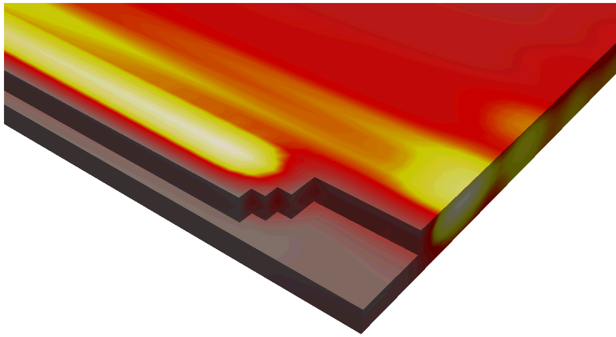
SAND2017-12036C







Predicting Residual Stress and Microstructural Equiaxed-to-Columnar Grain Transition in 304L Stainless Steel LENS Parts

Kyle Johnson, Theron Rodgers, Olivia Underwood, Jonathan Madison, Kurtis Ford, and Joe Bishop

SAND2017-XXXX

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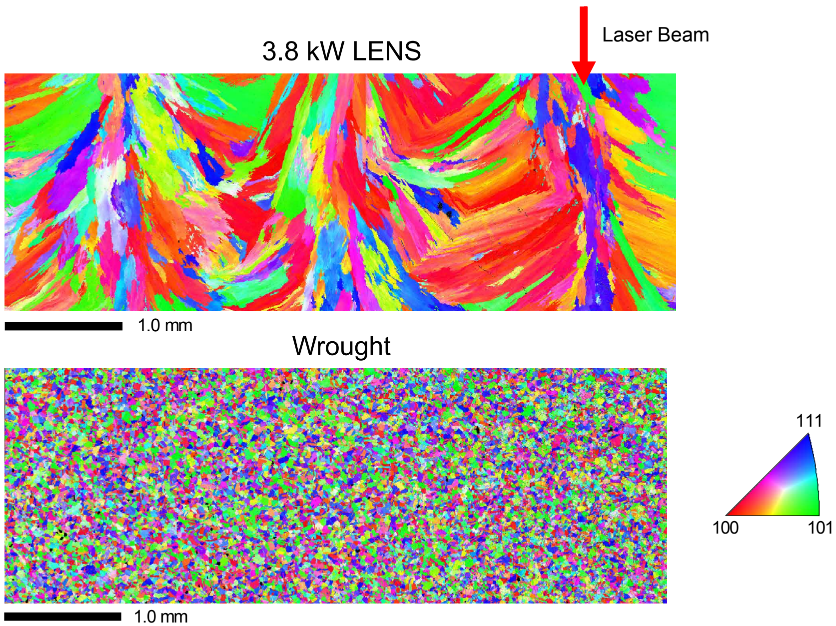
Acknowledgements

- Collaborators
  - Joe Bishop
  - Kurtis Ford
  - Theron Rodgers
  - Sam Subia
  - Daryl Dagel
  - Dave Keicher
  - Shaun Whetten
  - Bradley Jared
  - Jon Madison
  - Olivia Underwood
  - Sierra Code Team

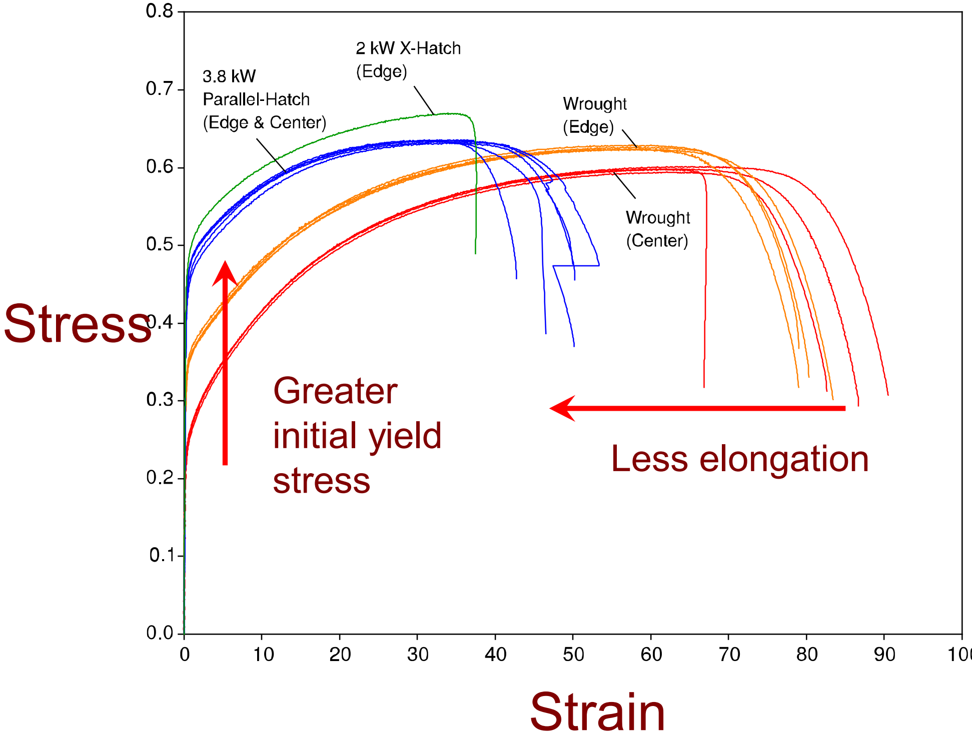
Outline

- Background and Motivation
- Thermal, Solid Mechanics and Microstructure Modeling Methodology
- Single Build Results
- Comparison of Different Inter-layer Delay Time Predictions
- Conclusions and Future Work

AM Can Produce Extreme Properties



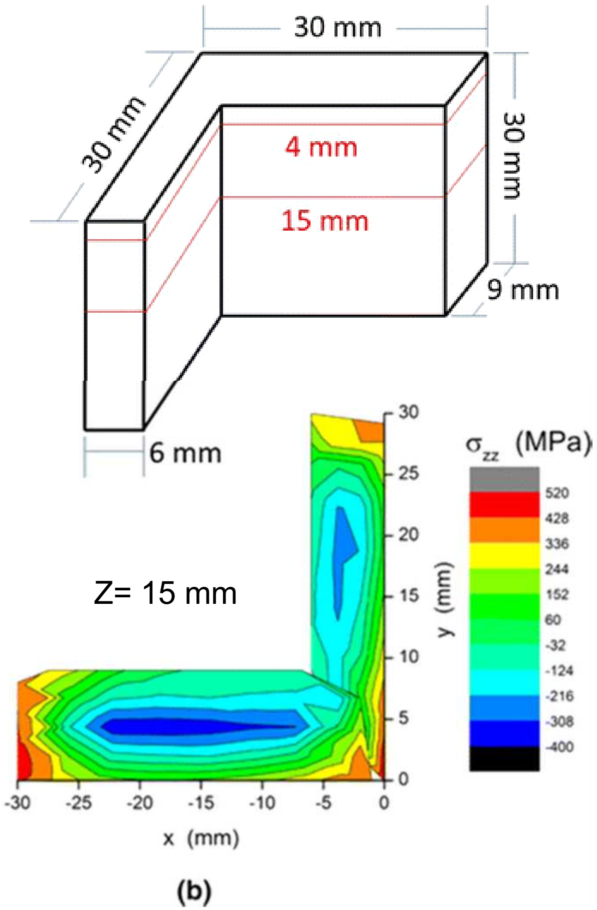
(J. Michael, SNL)



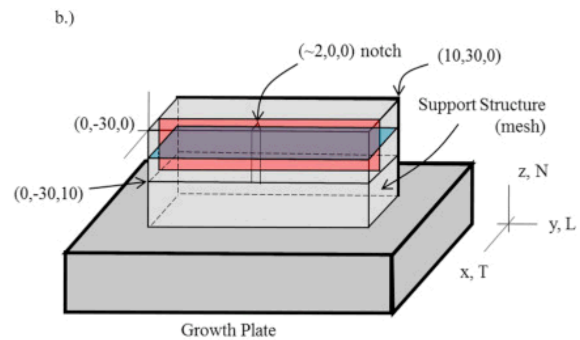
(J. Carroll, SNL)

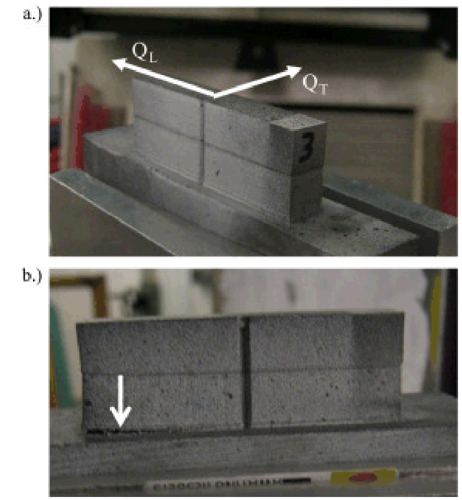
- 304L Stainless Steel

High Thermal Gradients Produce High Residual Stresses

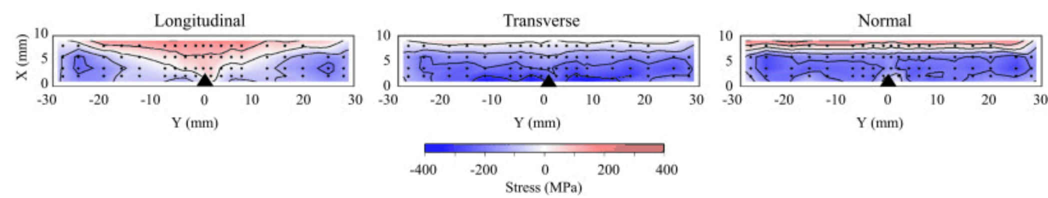


316L Stainless Steel Powder Bed
Wu *et al.* 2014 (LLNL, LANL)



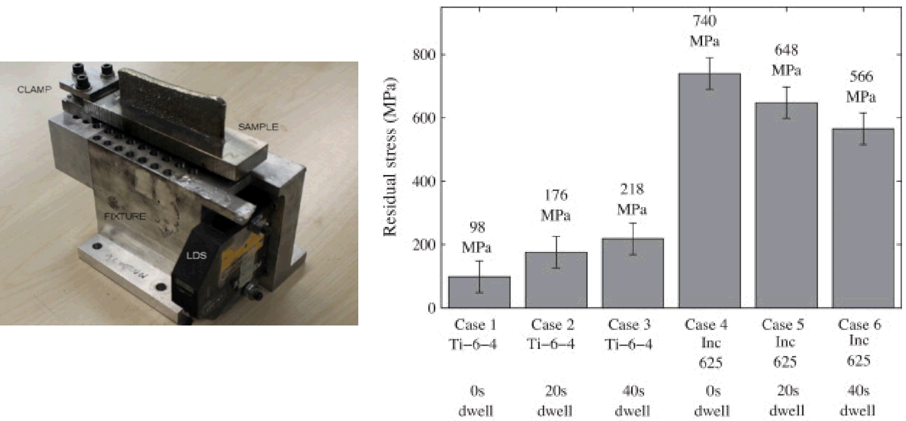


*Stress measured at blue plane

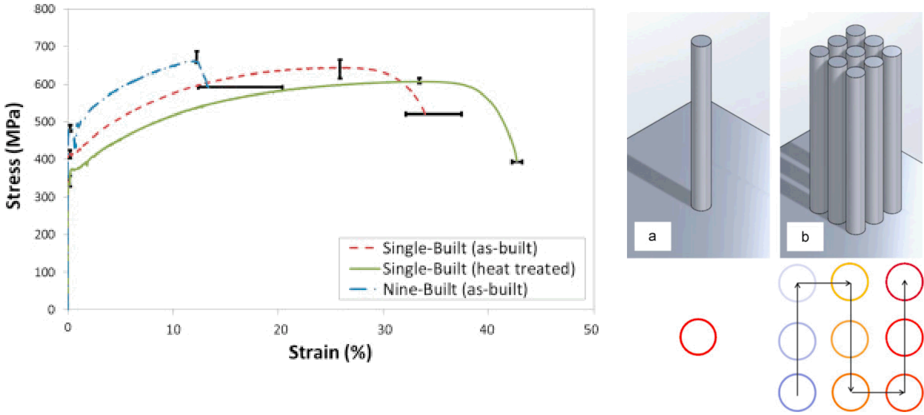


17-4 Stainless Steel Powder Bed
Brown *et al.* 2016 (LANL)

Inter-layer Time Affects Residual Stress and Mechanical Properties



Denlinger et al., J. Mater Process Technol 2015



Yadollahi et al., Mat Sci Eng A 2015

Inter-layer dwell times can change residual stresses

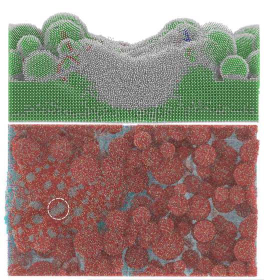
Building multiple parts can change mechanical properties based on different process time intervals

SNL Modeling Work

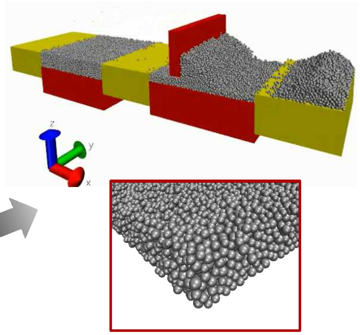
Sandia National Laboratories

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

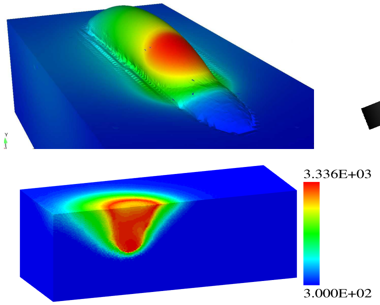
Powder Behavior
Mark Wilson



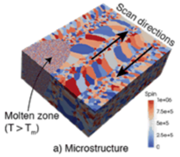
Powder Spreading
Dan Bolintineanu



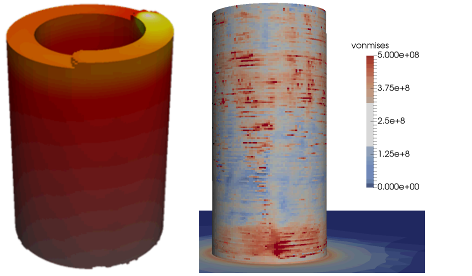
Mesoscale Thermal Behavior
Mario Martinez & Brad Trembacki



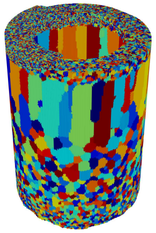
Mesoscale Texture/Solid Mechanics/CX
Judy Brown, Theron Rodgers and Kurtis Ford



Part Scale Thermal & Solid Mechanics
Kyle Johnson, Kurtis Ford & Joe Bishop



Part Scale Microstructure
Theron Rodgers



10^{-6} — 10^{-3} — 1

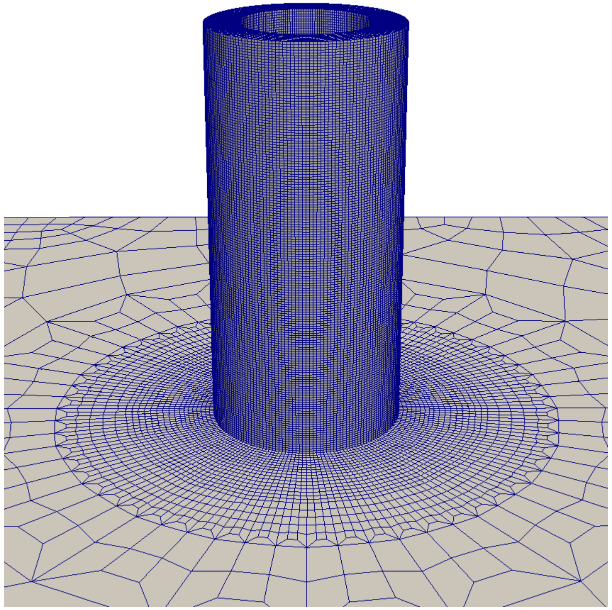
Length Scale (m)

304L Tube Example

Case 1
No inter-layer delay
(continuous build)

Case 2
8 second delay added
between layers
(double build)

Can we capture the difference in microstructure and residual stress due to changing thermal gradients?



- Dimensions: 2” H x 1” W
- LENS process
- Laser diameter = 4 mm
- Laser Speed = 8.46 mm/s
- Layer Thickness = 0.9 mm
- Laser Power = 2000 > 1750 > 1500 > 1250 W

Submitted to: *Computational Mechanics*

Outline

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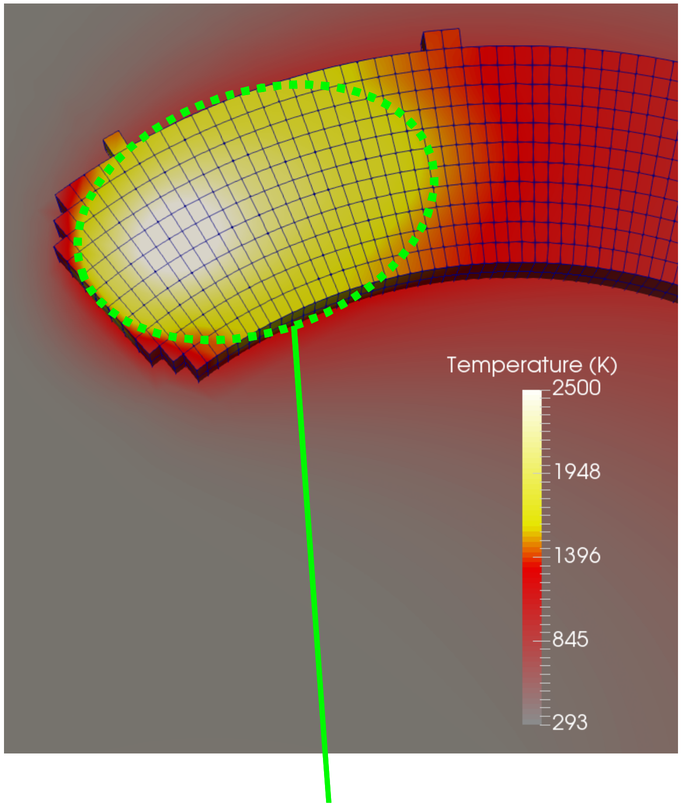
Thermal Approach

Pre-meshed part is initialized with inactive elements. Baseplate elements are active.

Laser heat source is scanned according to input path.

Elements are activated once they reach melt temperature.

Conduction, convection, and radiation are considered.



Approximate Melt Pool

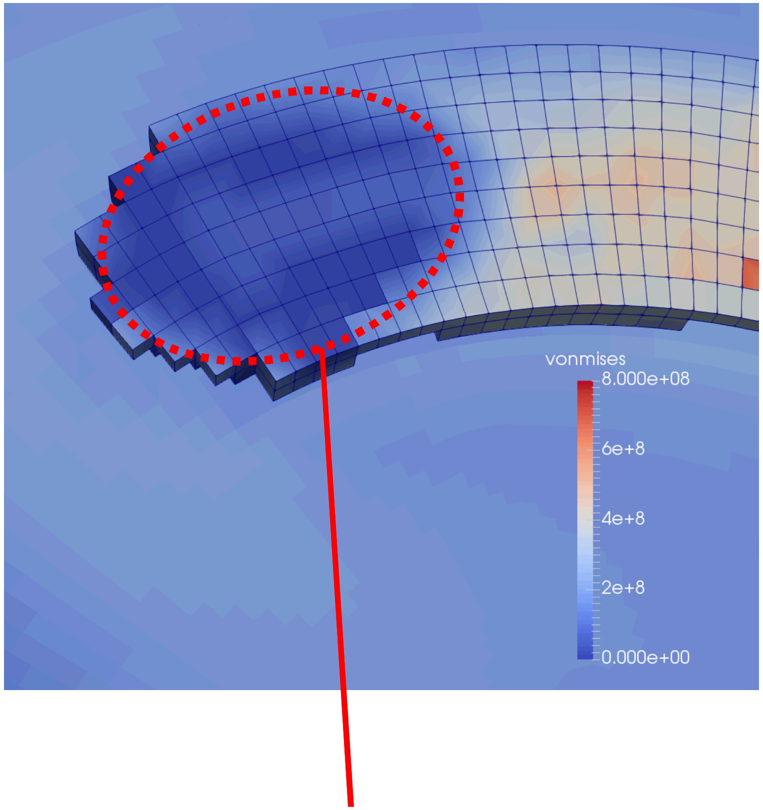
Solid Mechanics Approach

Pre-meshed part is initialized with inactive elements. Baseplate elements are active.

Aria output file is read at every time step to provide temperature fields.

Elements are activated once they reach melt temperature.

Residual stress builds as elements contract upon cooling and build thermal strain.



Approximate Melt Pool (~zero stress)

BCJ Material Model

- Temperature and history-dependent viscoplastic internal state variable model
- Flow rule includes yield stress and hardening internal state variable

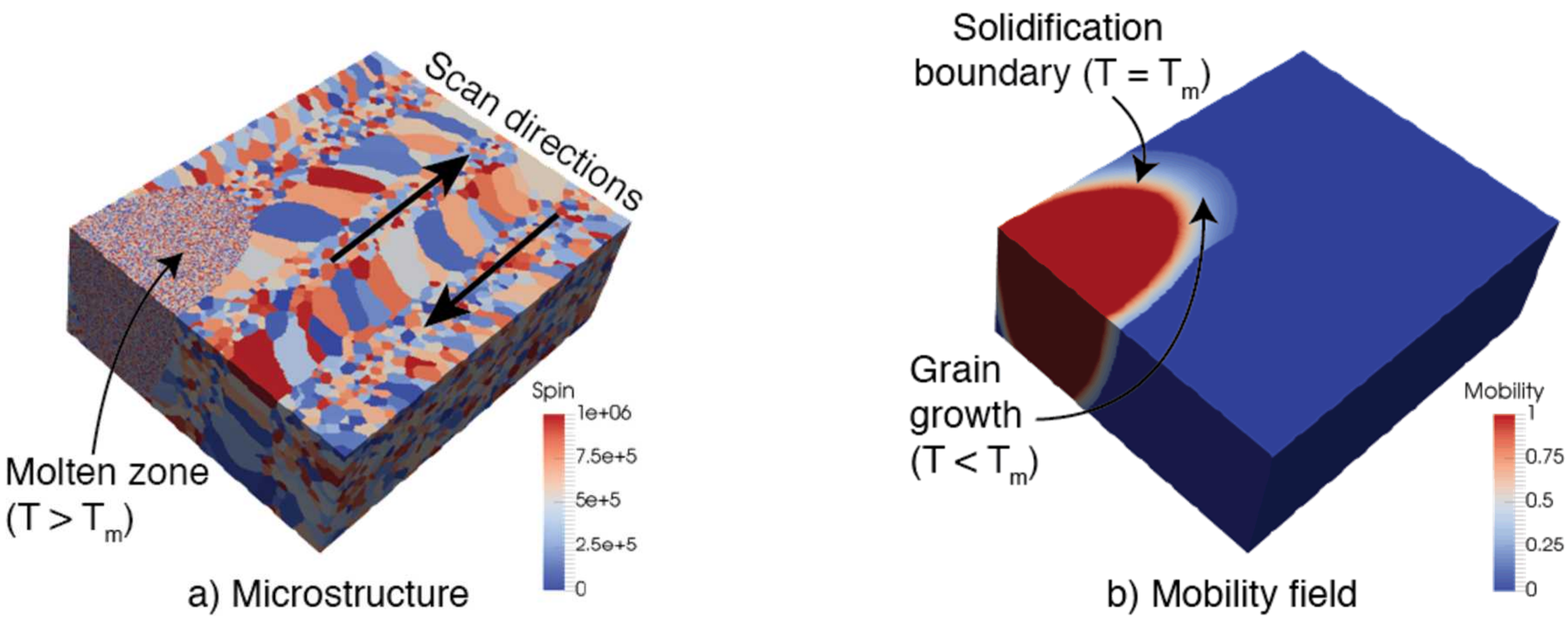
$$\dot{\varepsilon}_p = f\,sinh^n\left(\frac{\frac{\sigma_e}{1-\phi} - \kappa}{Y} - 1\right)$$

- The isotropic hardening variable κ evolves in a hardening minus recovery form.

$$\dot{\kappa} = \kappa\frac{\dot{\mu}}{\mu} + (H(\theta) - R_d(\theta)\kappa)\dot{\varepsilon}_p$$

- Model is calibrated to experimental data over a range of temperatures

Microstructure Prediction in **S**tochastic **P**arallel **PAR**ticle **K**inetic **S**imulator (SPPARKS)

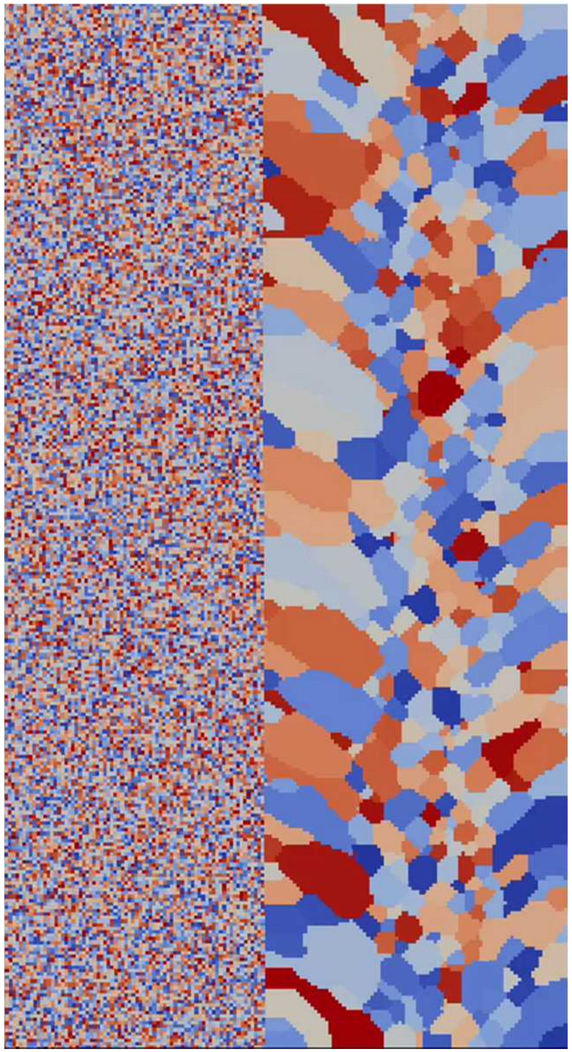


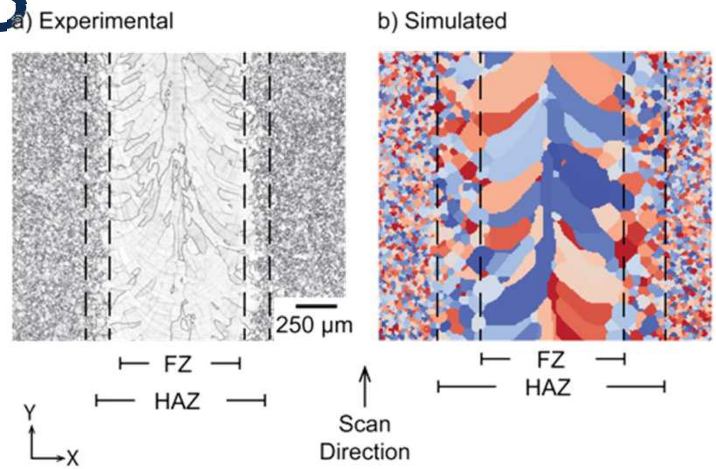
$$M(T) = M_o \exp\left(\frac{-Q}{RT}\right)$$

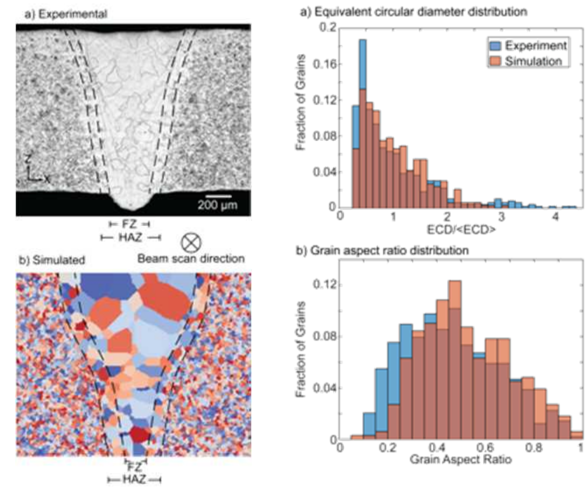
$$P = \begin{cases} M(T)\exp\left(\frac{-\Delta E}{k_B T_s}\right), & if\ \Delta E > 0 \\ M(T), & if\ \Delta E \leq 0 \end{cases}$$

- Aria temperature history is used as material state in SPPARKS
- Captures bulk heating effects on microstructure
- See Rodgers *et al.*, "Simulation of metal additive manufacturing microstructures using kinetic Monte Carlo," *Computational Materials Science*, 2017

3D Microstructure Prediction in SPPARKS







Rodgers et al., JOM 2016, Comp Mat Sci 2017

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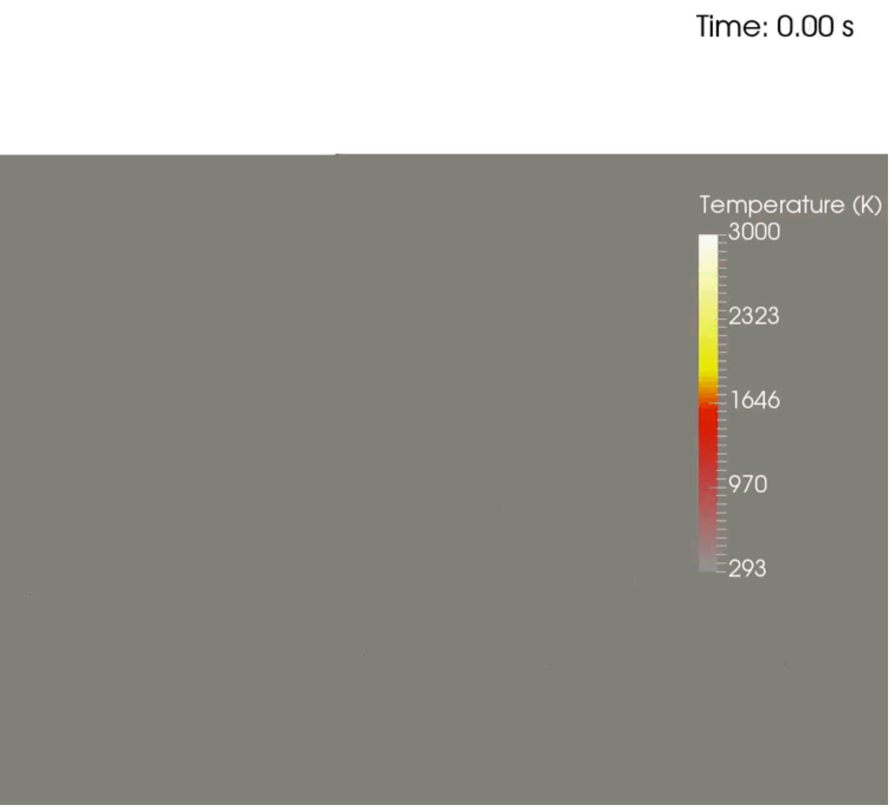
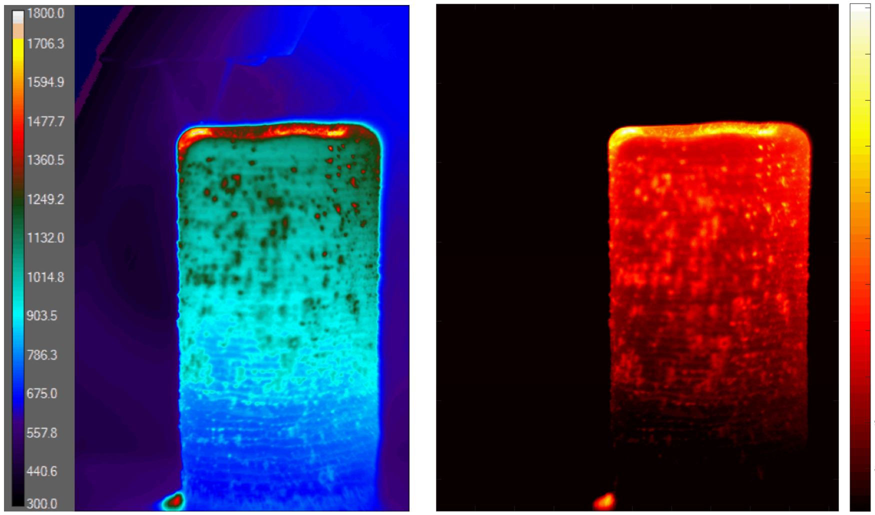
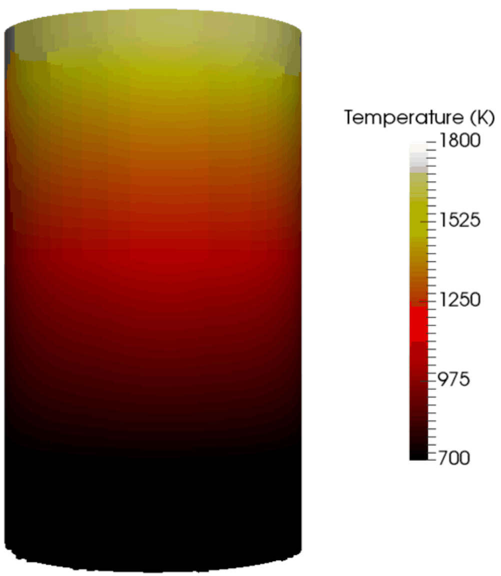
Experimental Comparison - Thermal

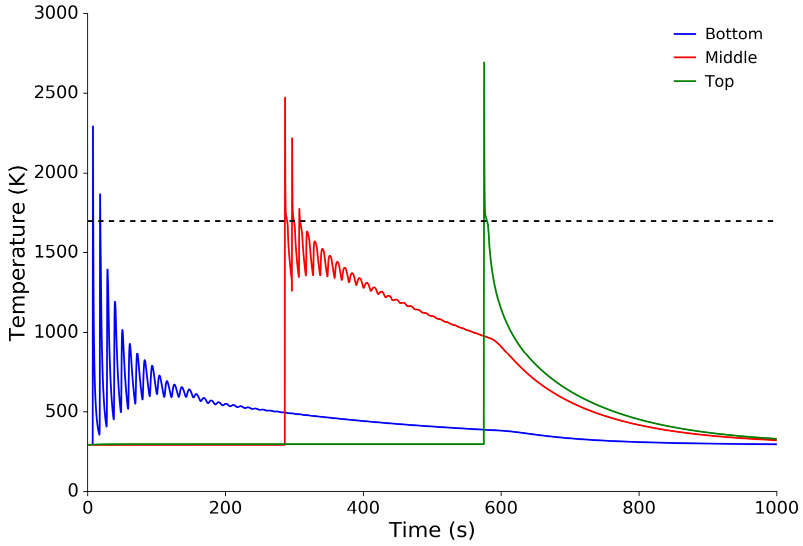




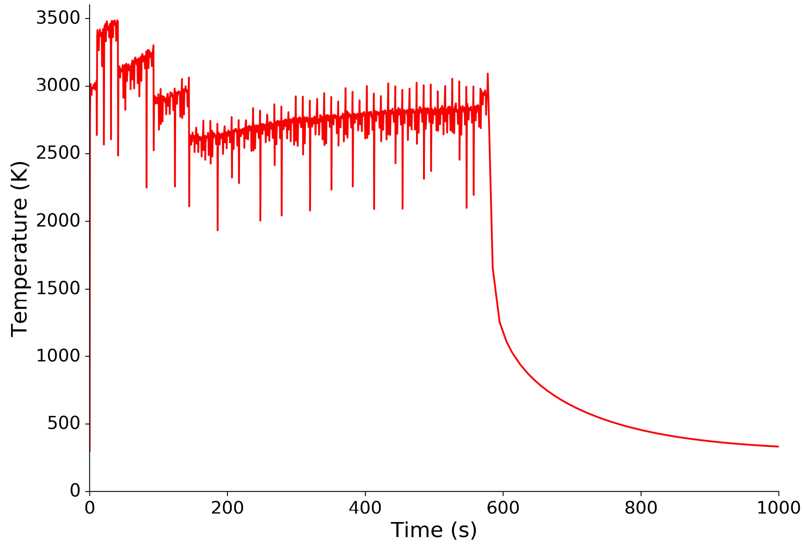


Thermal Histories

Temperature Histories at 3 Different Tube Heights

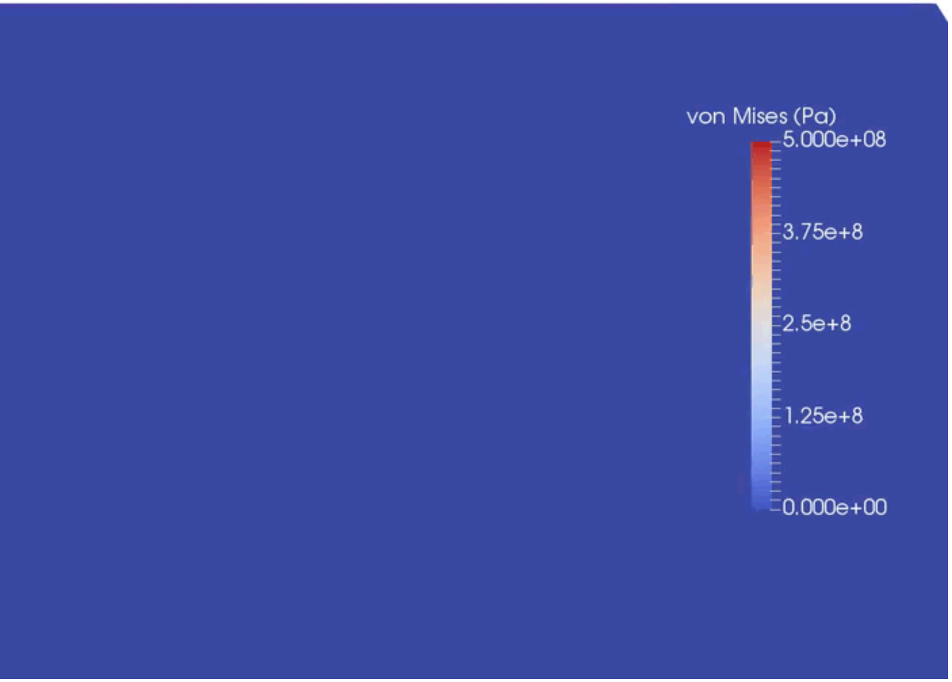


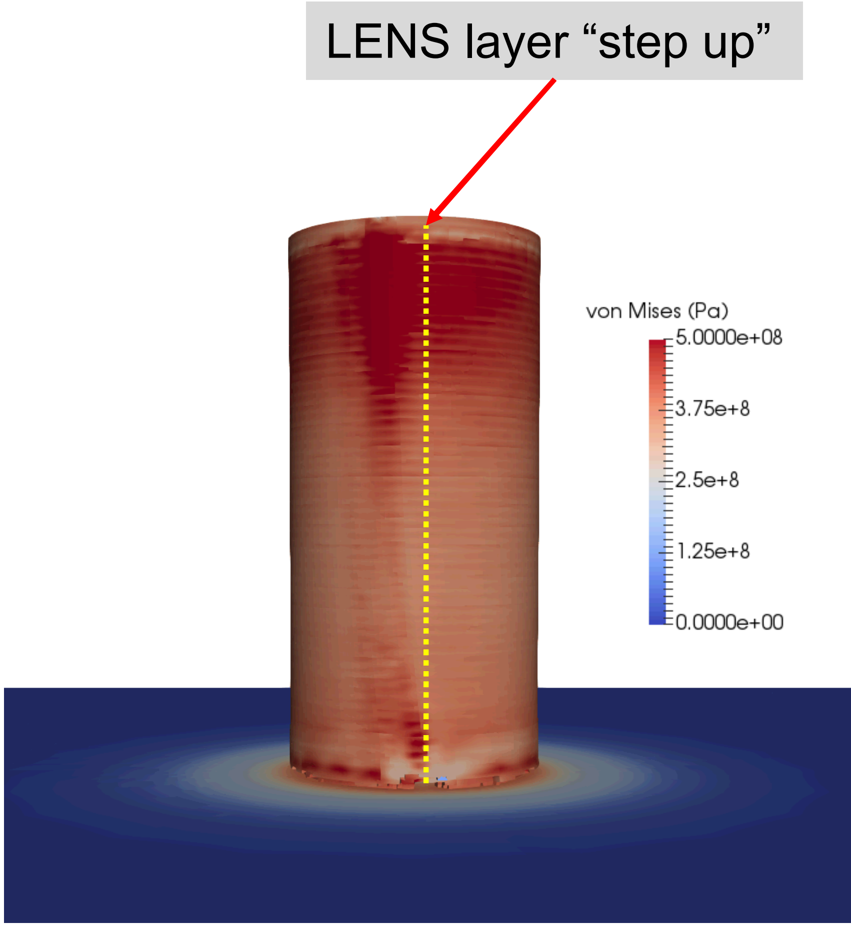
Maximum Temperature Across Entire Part



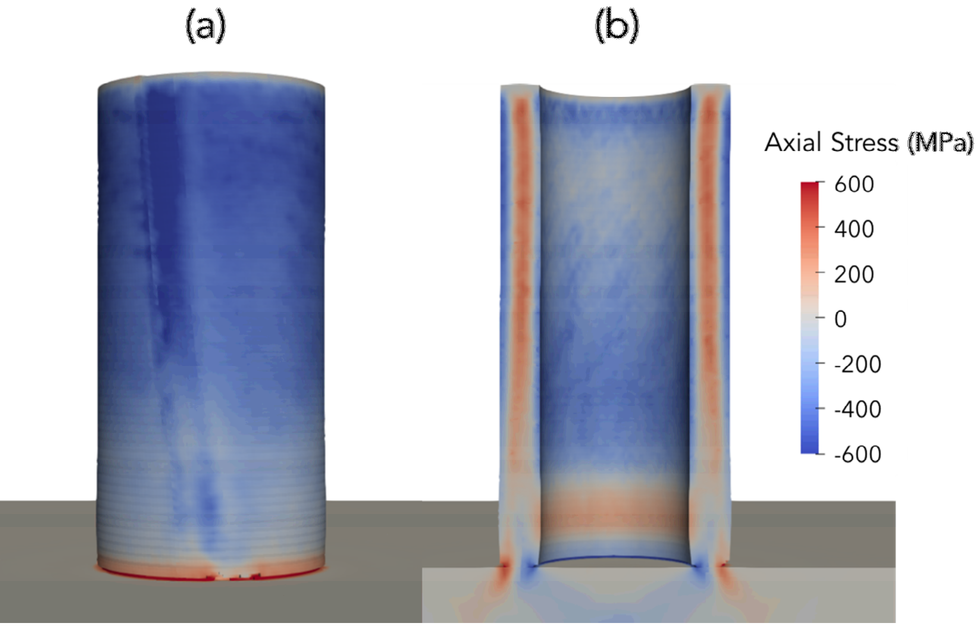
- Different part locations show very different thermal histories
- Middle location goes through 3 melting cycles
- Different thermal gradients throughout cool down
- Drops in maximum temperature demonstrate laser power drops

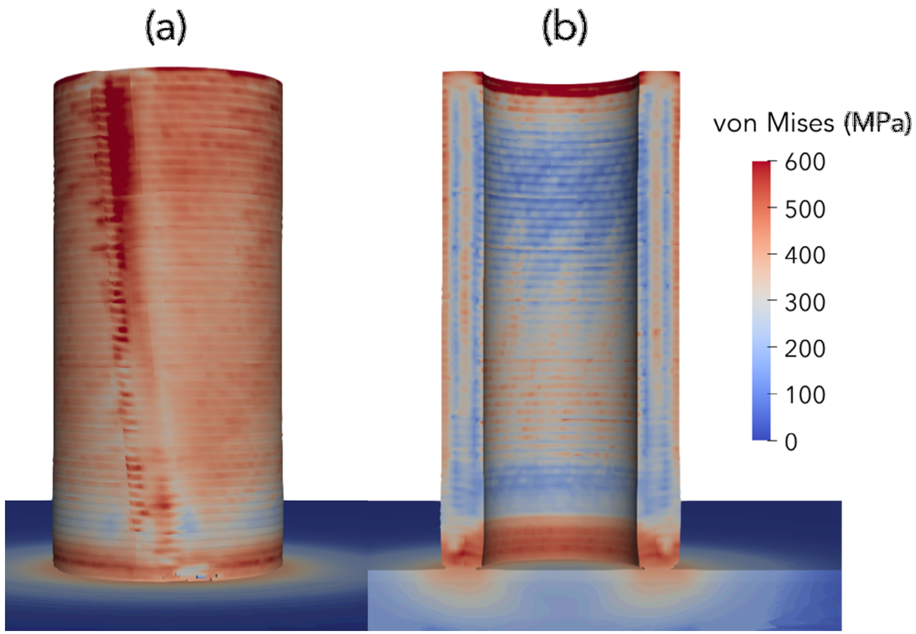
Residual Stress Prediction



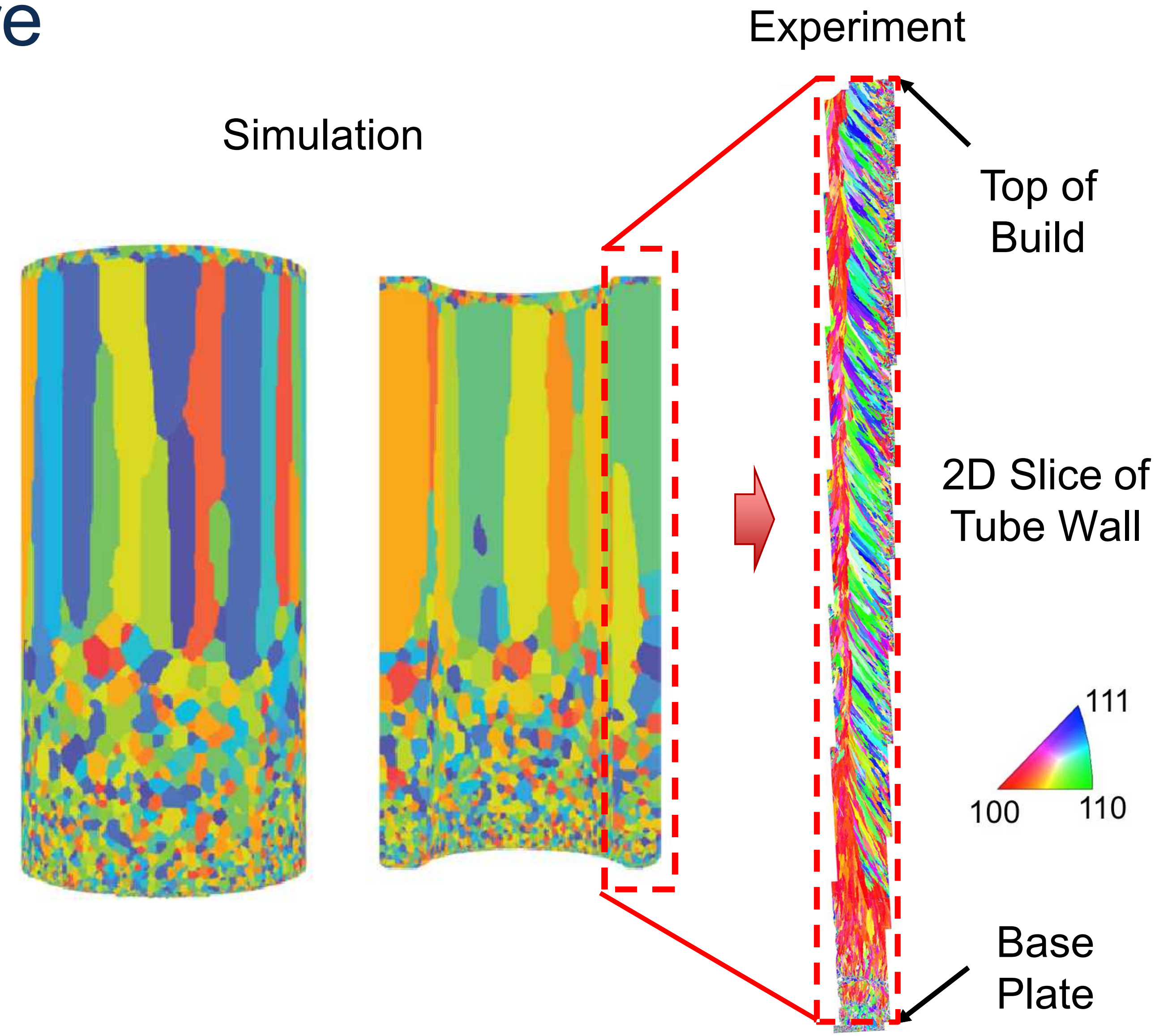


Residual Stress Predictions Show Gradient Through Wall Thickness



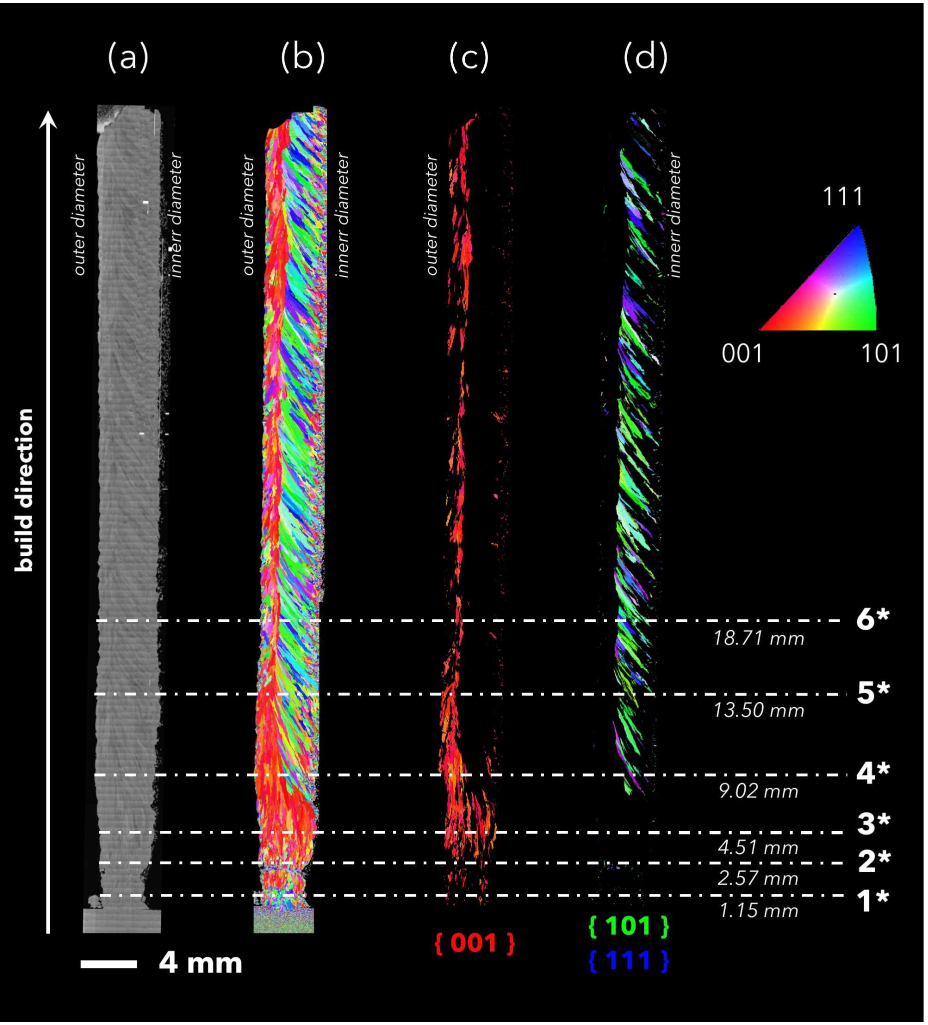


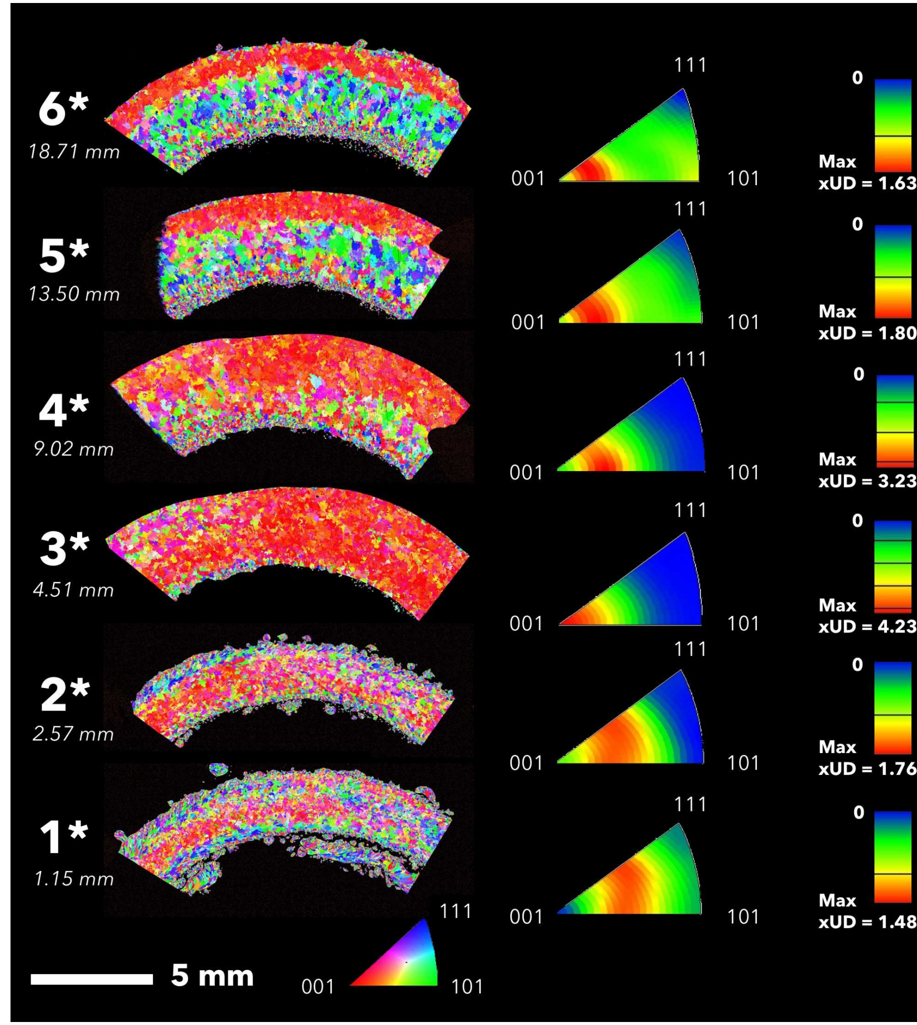
Experimental Comparison - Microstructure



EBSD: O. Underwood, J. Madison, A. Kilgo, J. Michael, S. Dickens

EBSD Shows a Transition Region of (001) Grains With Centerline Offset to O.D. Side





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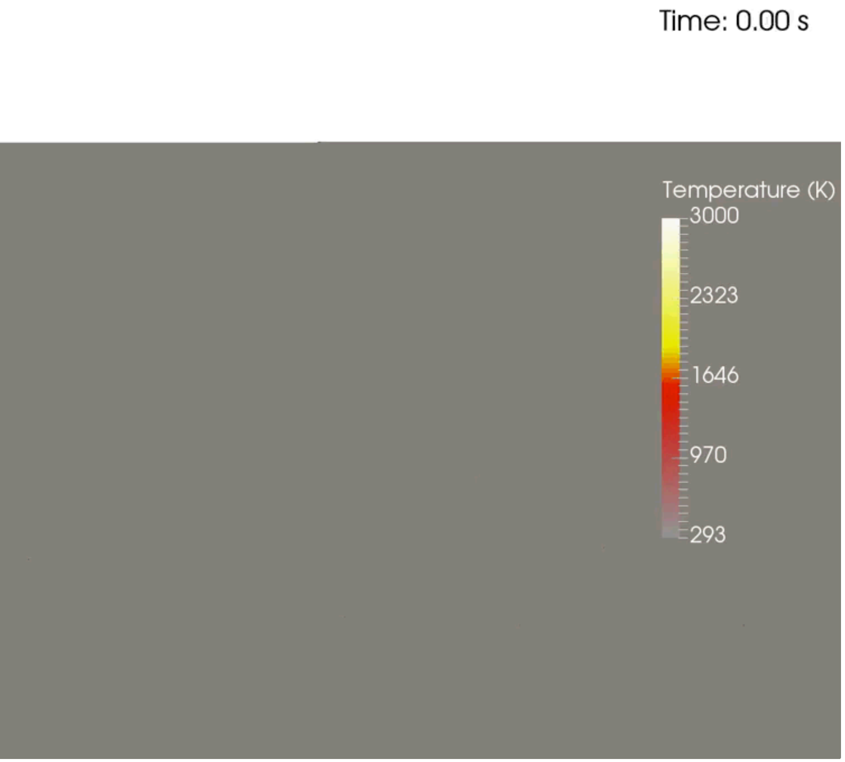
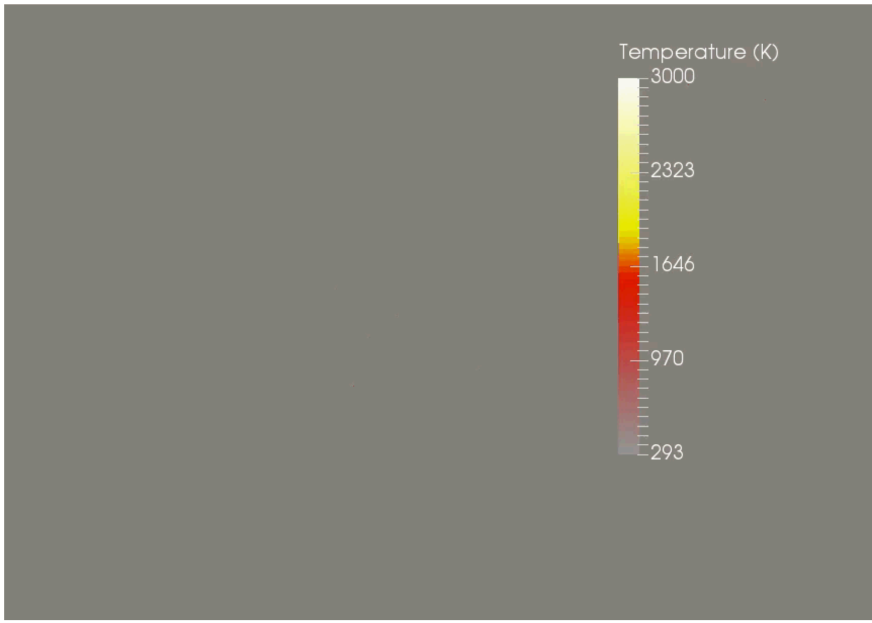
Thermal Comparison

Single Build

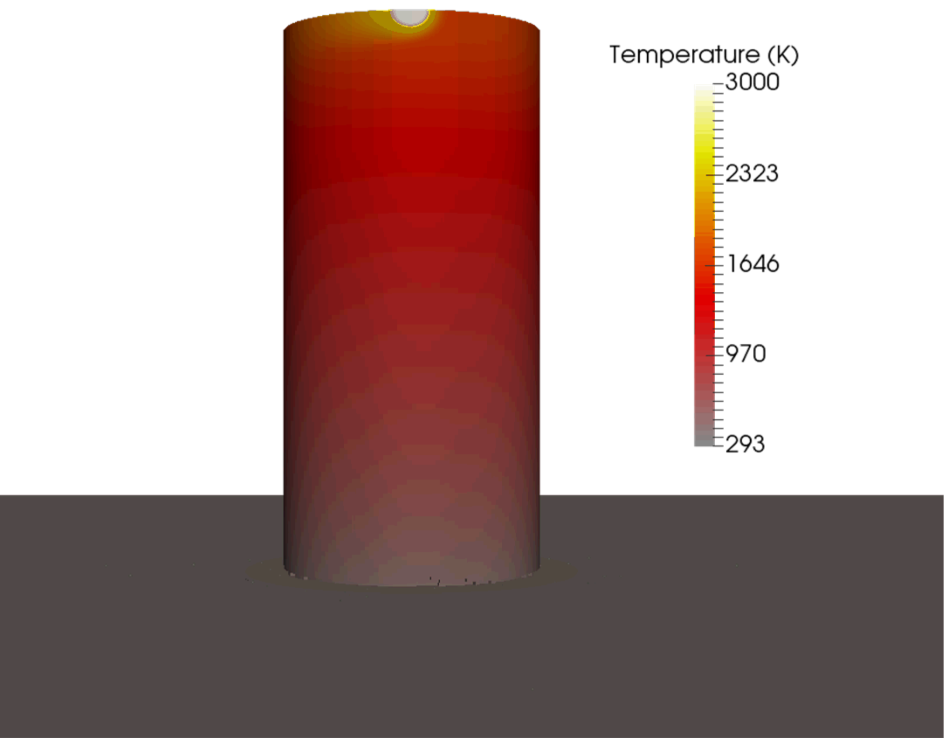


Double Build – 8 Second Inter-layer Delay

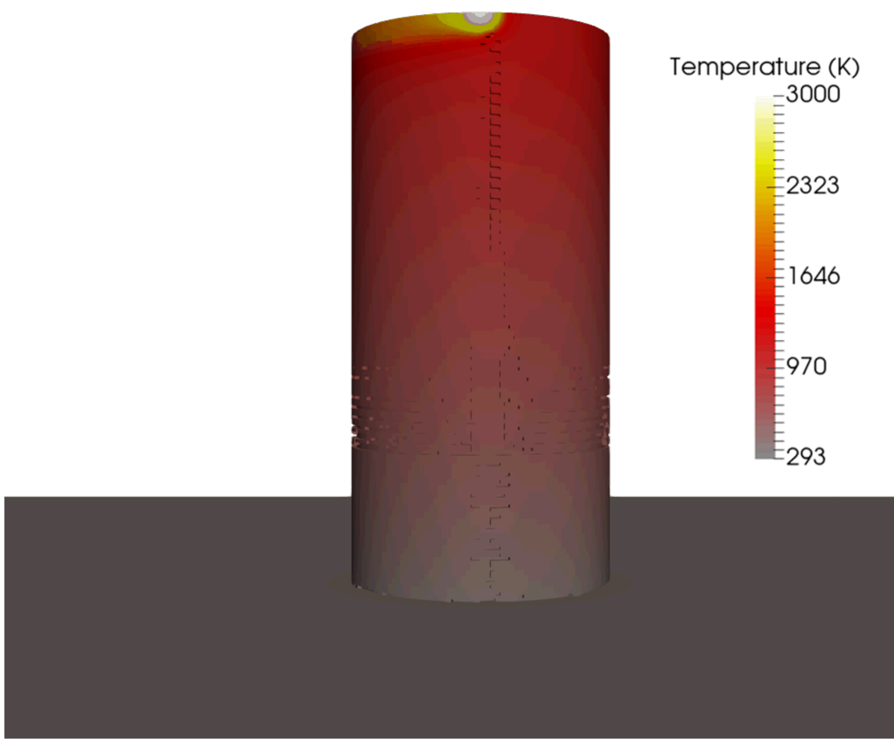


Delay Time Lowers Global Part Temperature

Single Build

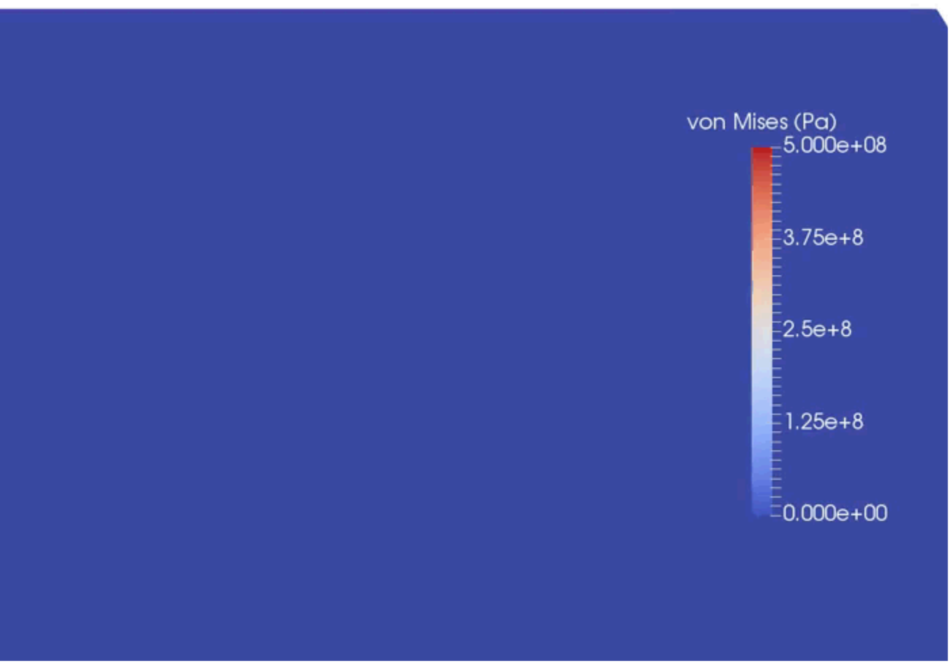


Double Build – 8 Second Inter-layer Delay

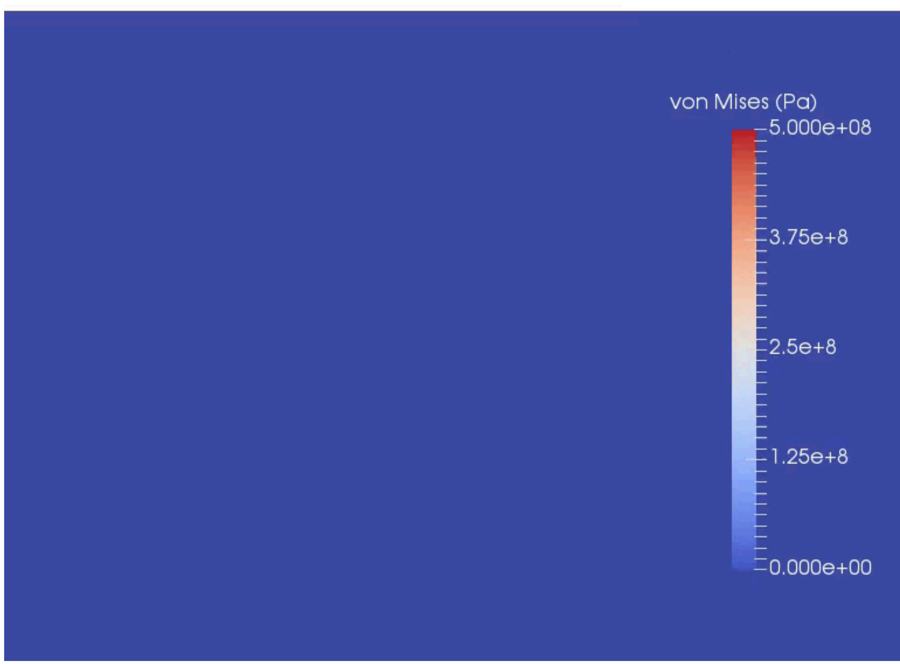


Residual Stress Comparison

Single Build

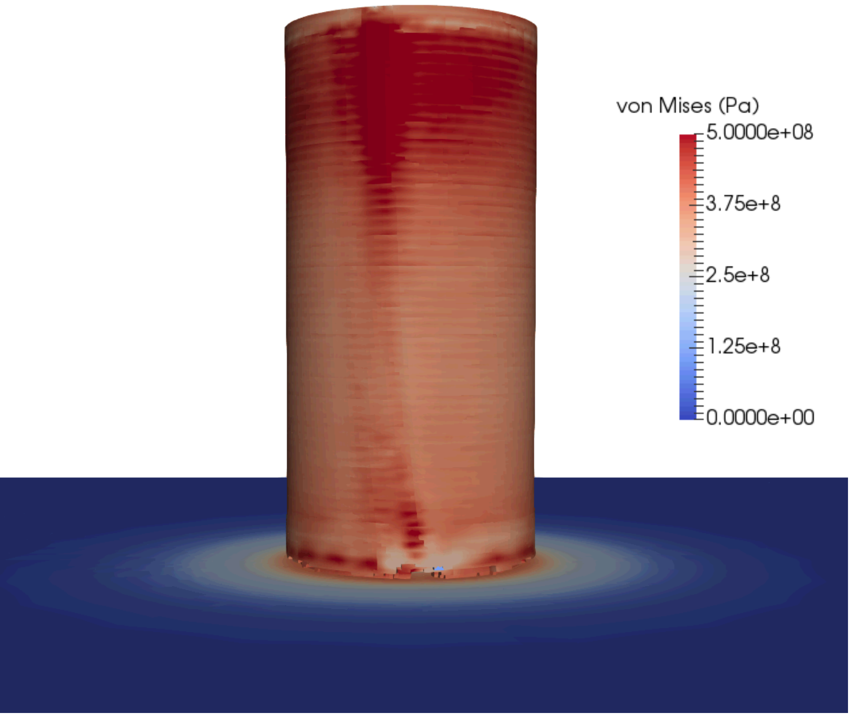


Double Build – 8 Second Inter-layer Delay

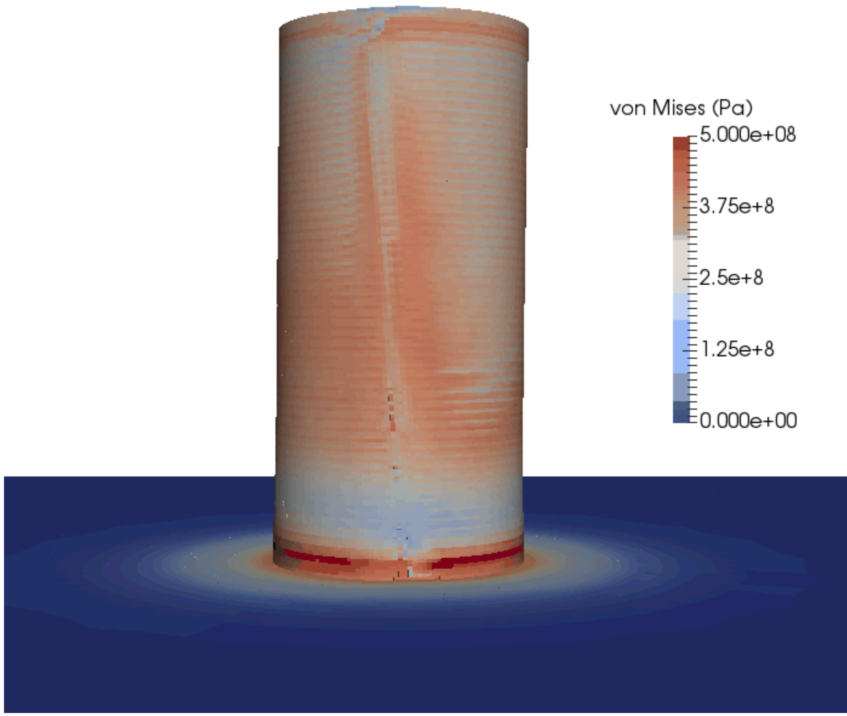


Delay Time Causes Lower Overall von Mises Stress

Single Build

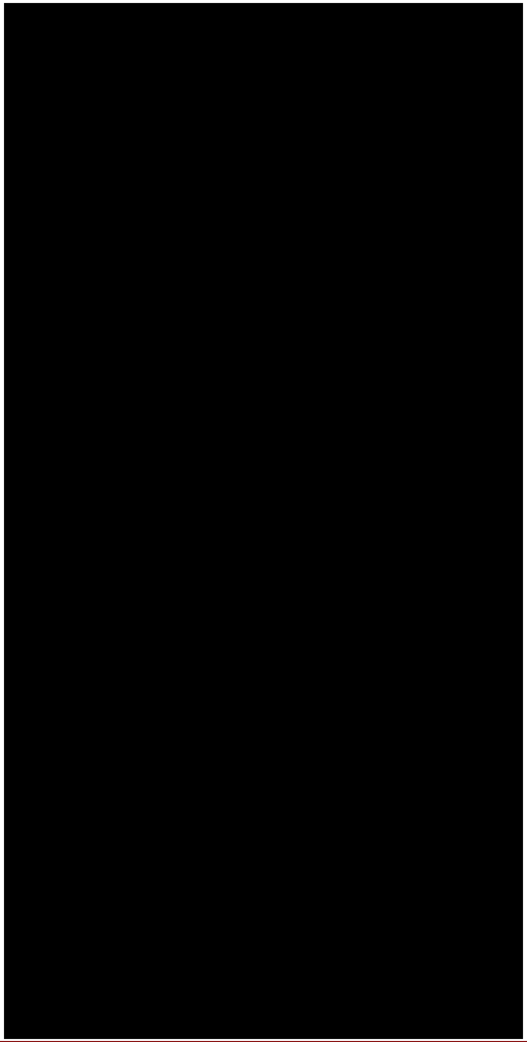


Double Build – 8 Second Inter-layer Delay

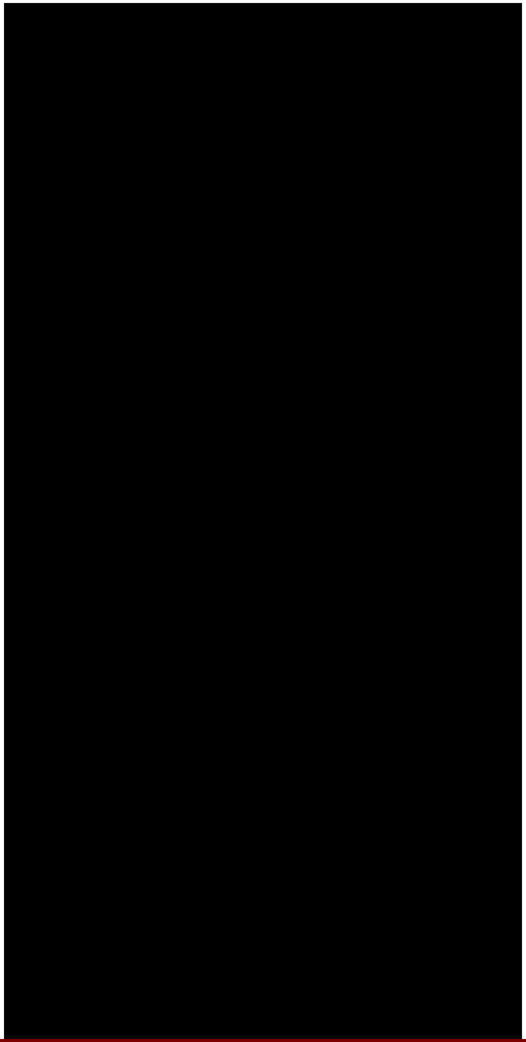


Microstructure Comparison

Single Build

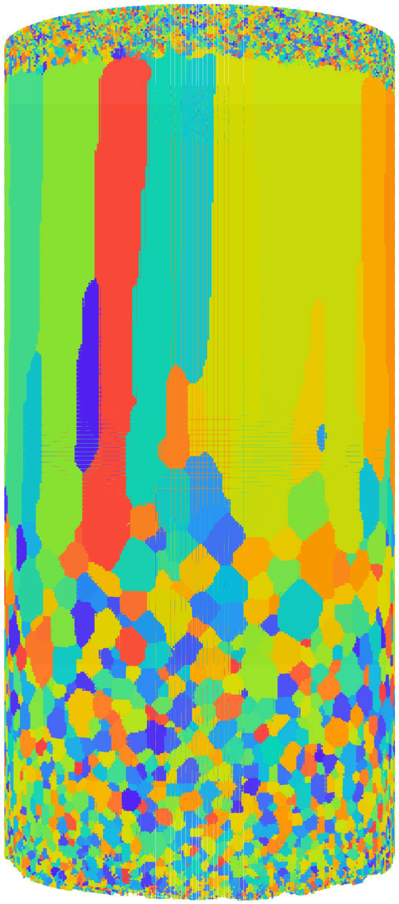


Double Build – 8 Second Inter-layer Delay

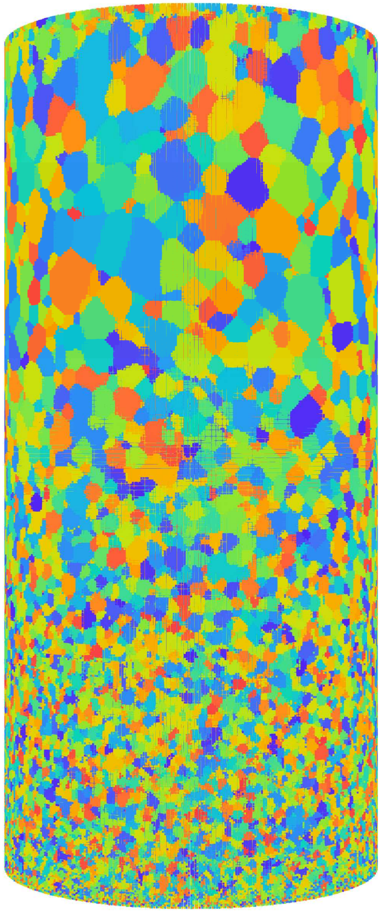


Delay Time Inhibits Equiaxed-to-Columnar Transition

Single Build



Double Build – 8 Second Inter-layer Delay



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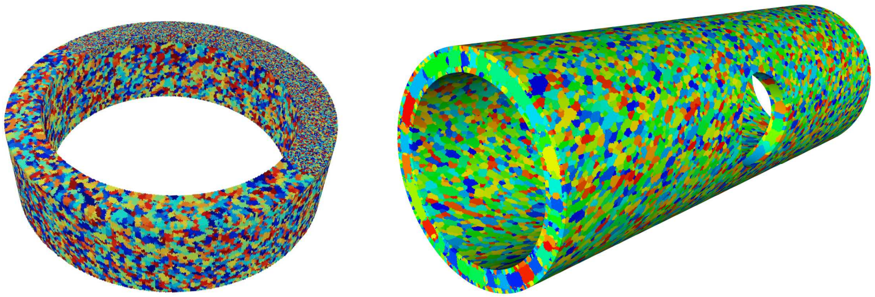
Conclusions and Future Work

- Thermal, residual stress, and microstructures have been predicted and compared to experiments
- Residual stress decreases with short inter-layer dwell time relative to continuous build
  - Likely specific to to this build and process settings
- Inter-layer delay time inhibits equiaxed to columnar transition for selected process settings
- Work ongoing to predict grain orientation
- Currently comparing effects of part-scale thermal model to combined thermal fluid model on residual stress

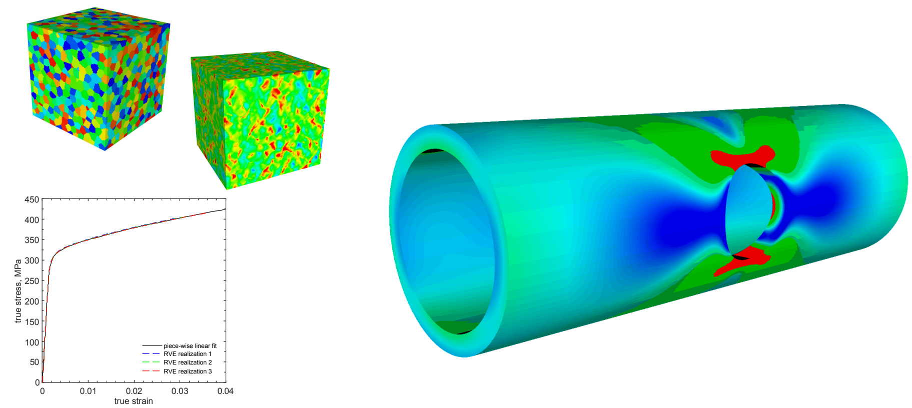
Quantifying material variability using multiscale *a posteriori* error-estimation techniques

Sandia National Laboratories

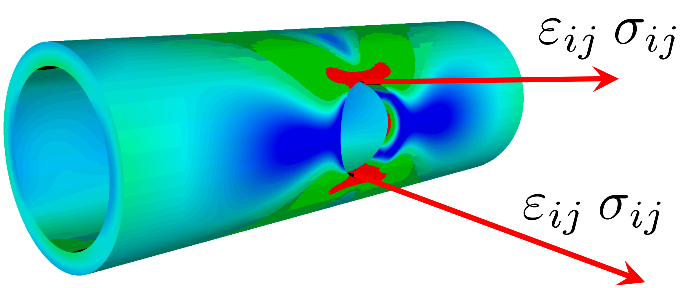
1. Generate Microstructures Using Kinetic Monte Carlo (KMC)

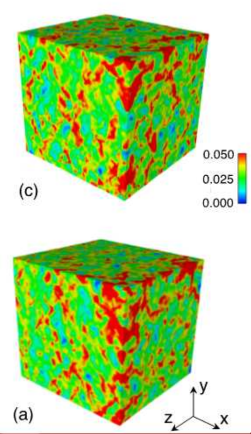


2. Run Homogenous Simulation With Isotropic Material Model



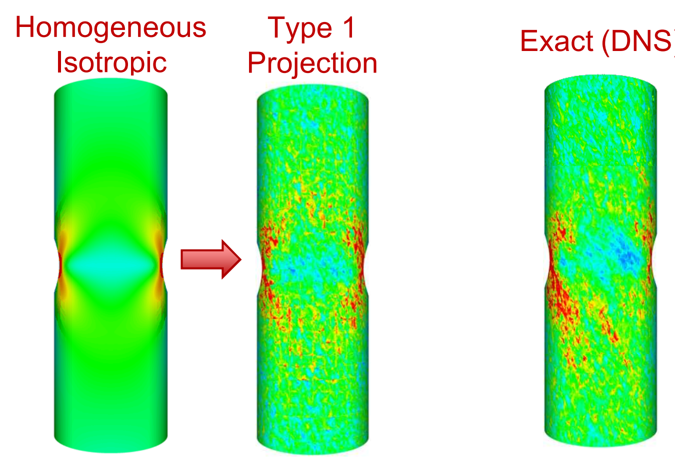
3. Recover Localized Stresses Using *a posteriori* Error Methods



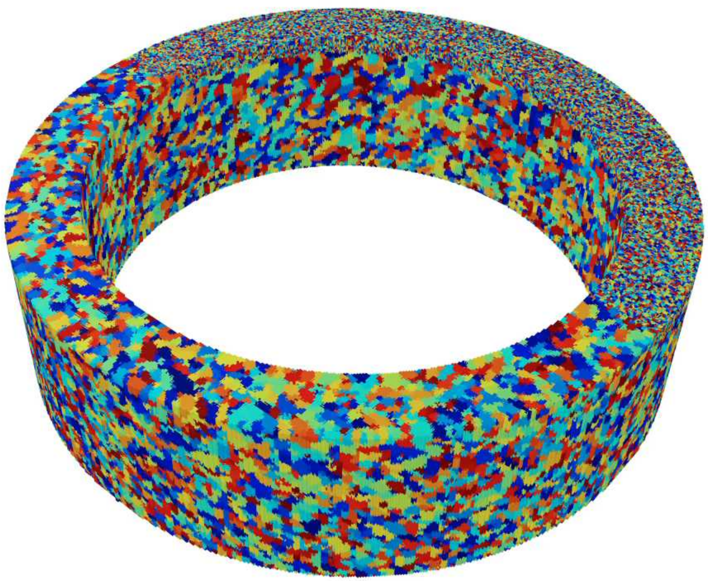


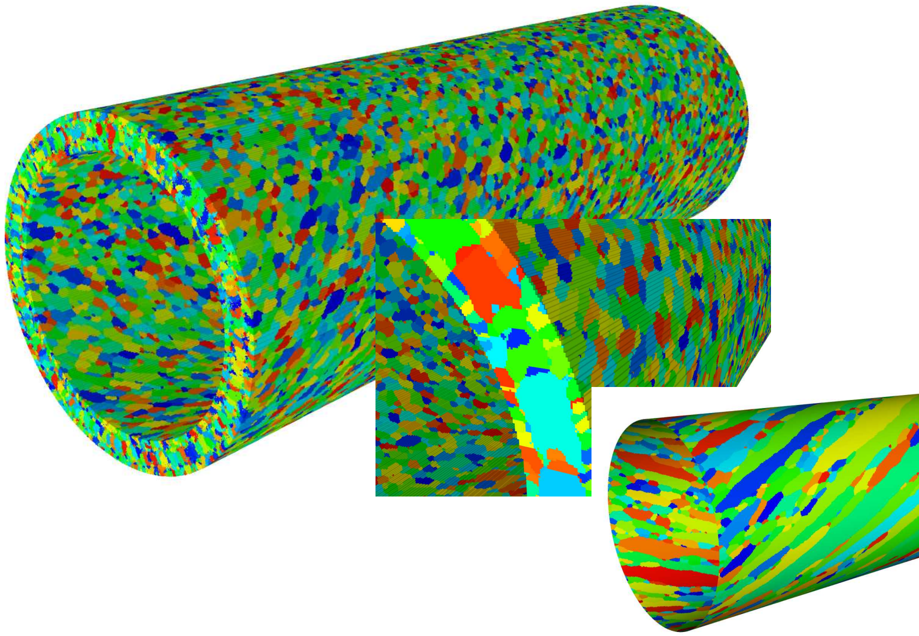
$$||\mathbf{u}-\mathbf{u}^0||_E^2 \leq \int_\Omega (\boldsymbol{\varepsilon}^0 - \bar{\boldsymbol{\varepsilon}}) : (\bar{\boldsymbol{\sigma}} - \boldsymbol{\sigma}^0)\, d\Omega$$

4. Compare to Direct Numerical Simulations of Full KMC Microstructure



Synthetic additive microstructure using KMC

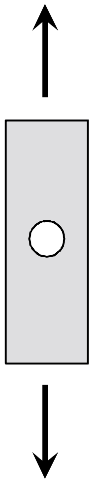


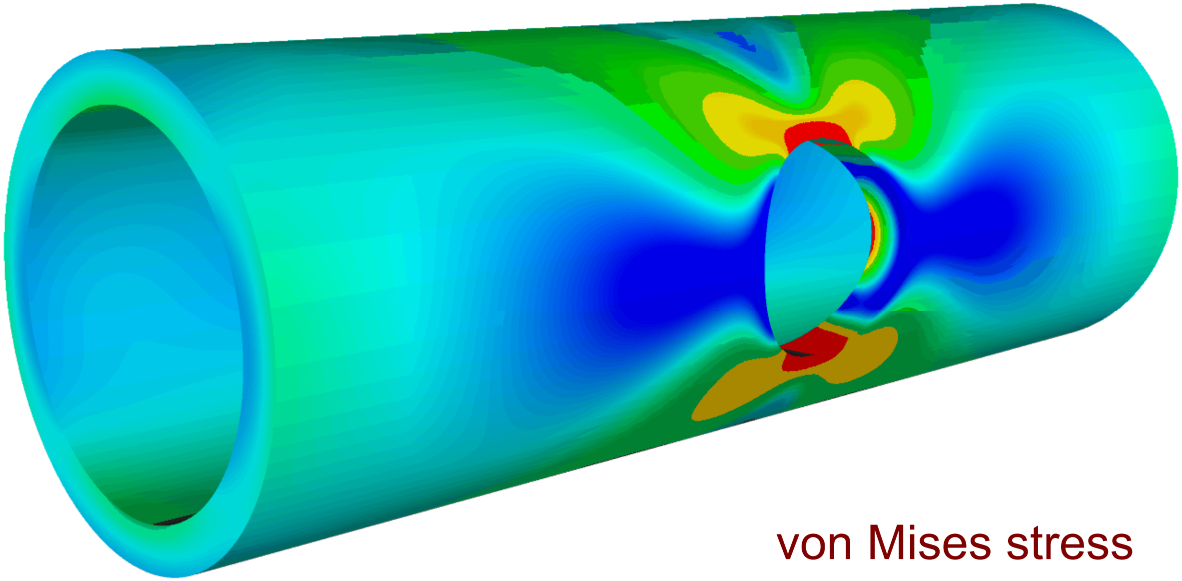


- KMC (SPPARKS) voxelated geometry
    - 55M voxels
- Two laser passes per layer (difference between surface and interior microstructure)
- Map to conformal finite-element mesh
    - 30M elements

Homogeneous analysis results

- Using homogenized material properties for wrought 304L
- Isotropic (no texture)

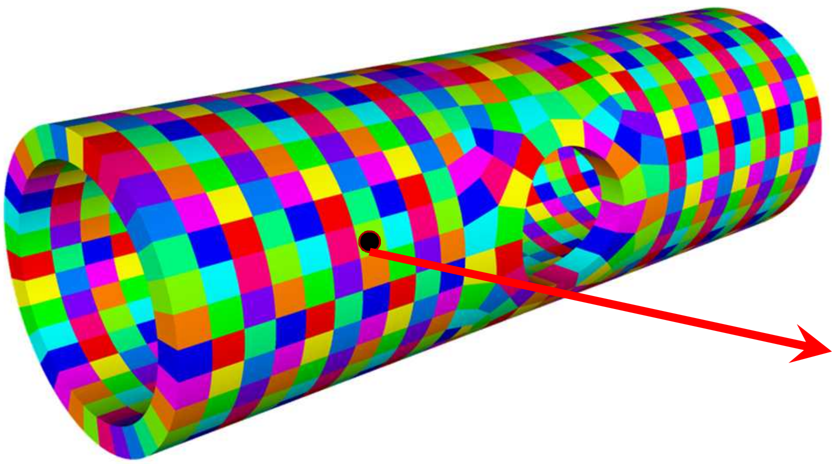


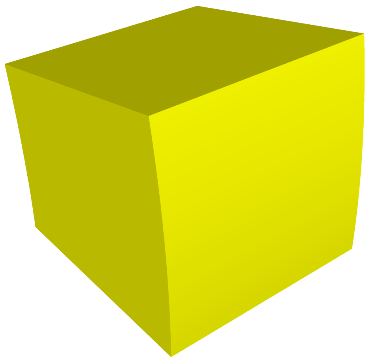


von Mises stress field

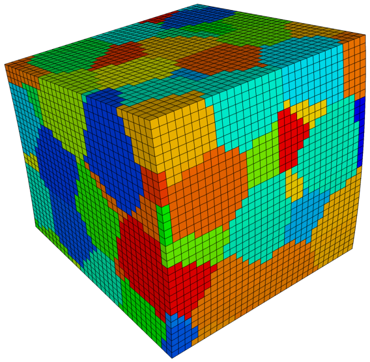
Sandia National Laboratories

Type 1 localization

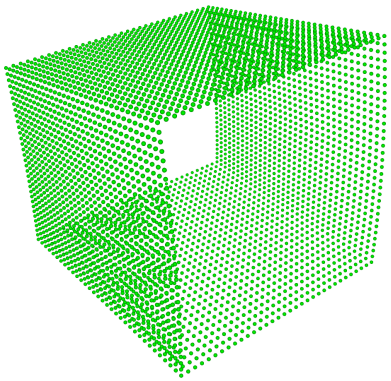




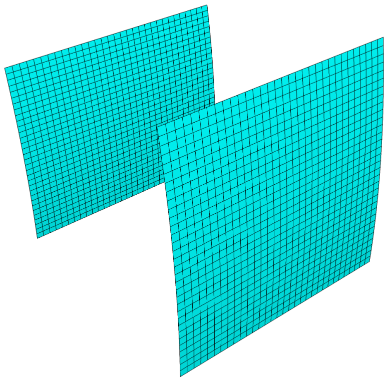
33K Hex Elements



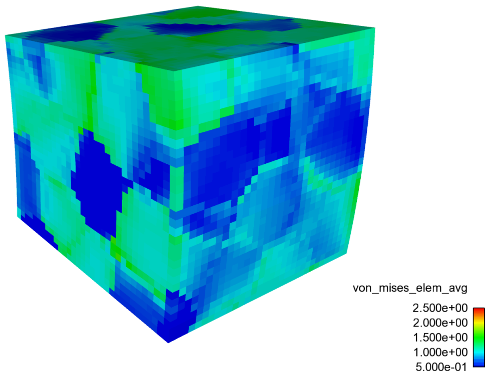
Displacement B.C.s



Traction B.C.s

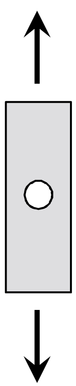


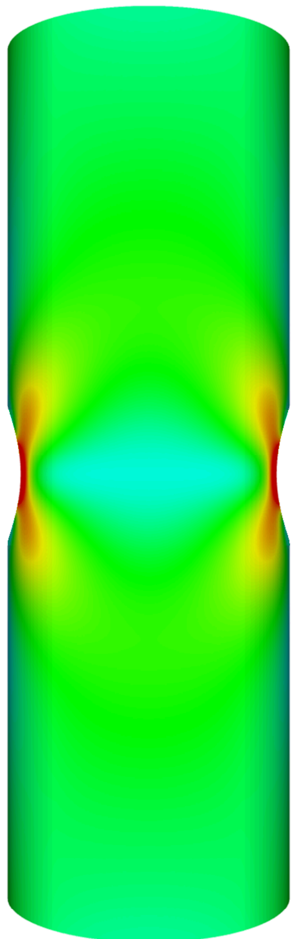
Local Stress Field



Localization results (AM)

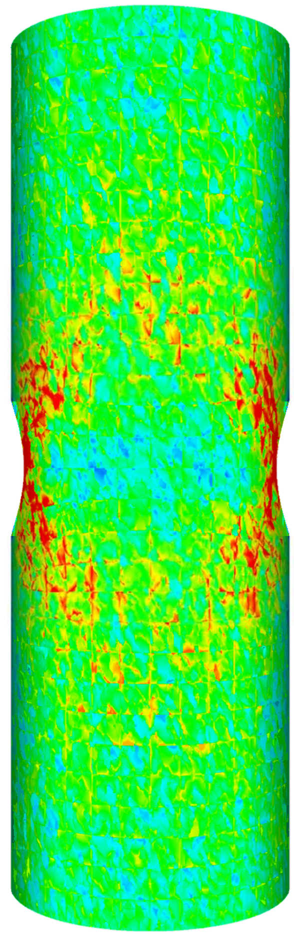
Homogeneous Isotropic



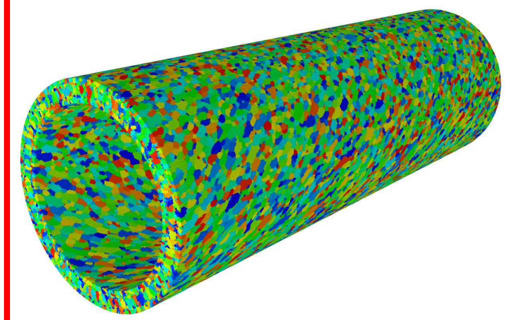


Dirichlet projection (submodeling)

Type 1 Projection

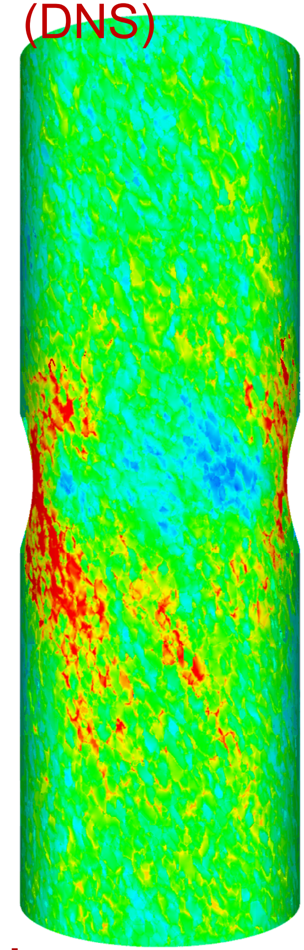


Minutes



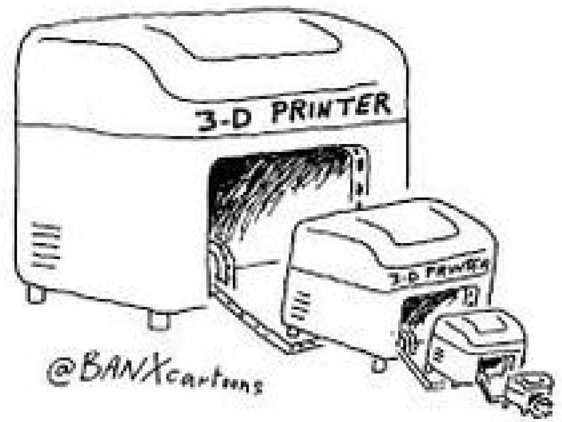
- Direct Numerical Simulations (DNS)
- Run using crystal plasticity model with individually resolved grains
- ~30 M elements

Exact (DNS)



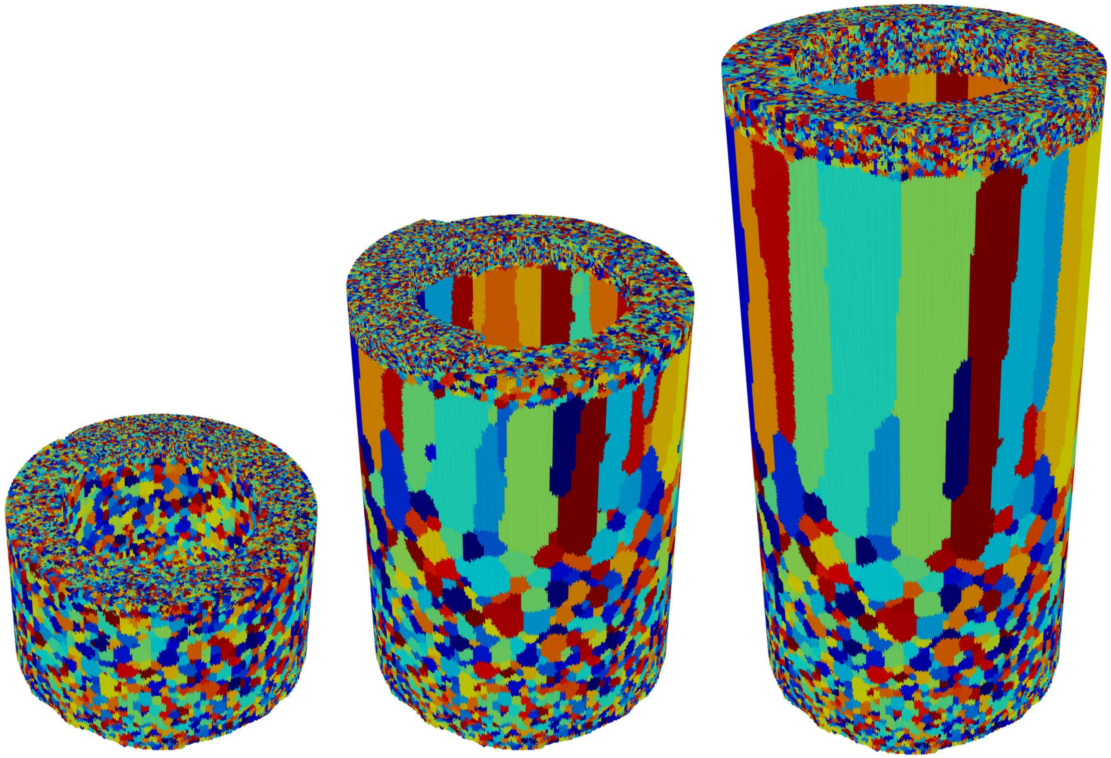
~4 days on 2048 cpus

Questions?

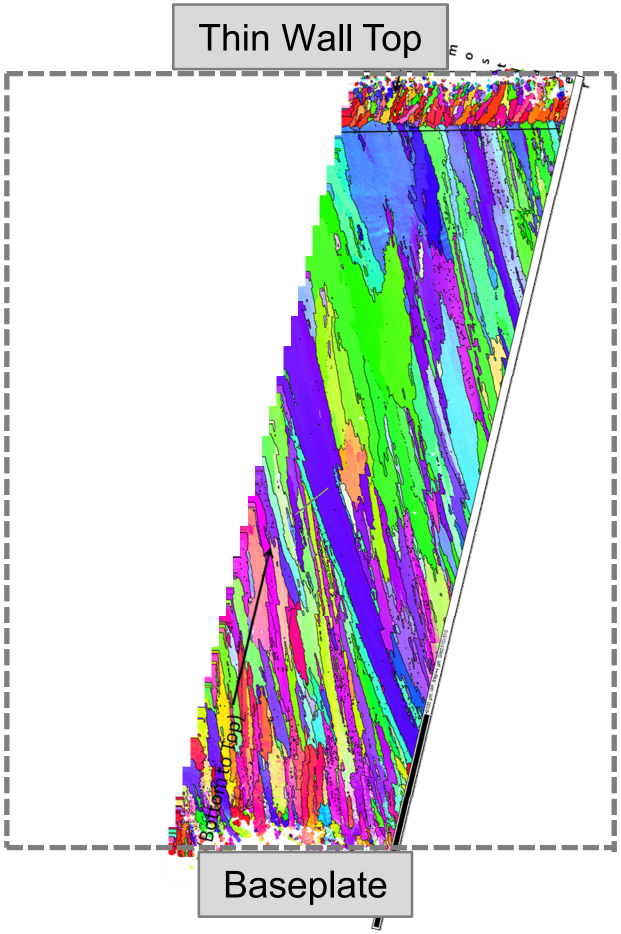


Backup Slides

Equiaxed to Columnar Transition Observed in Literature

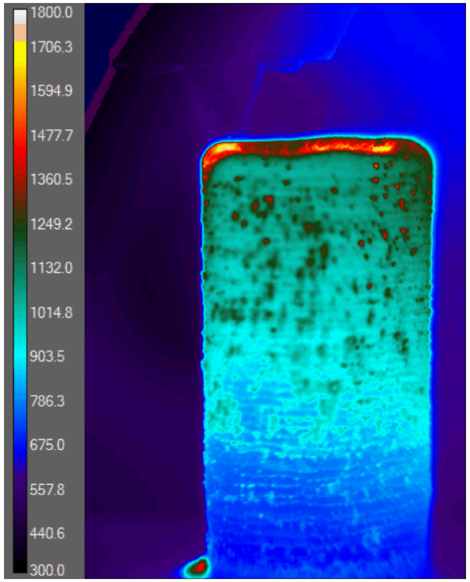


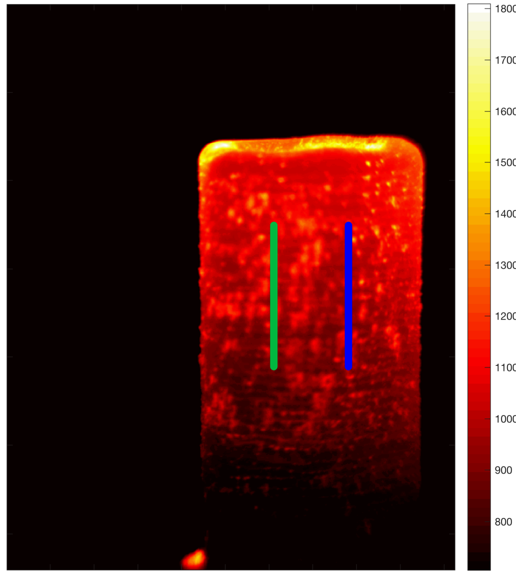
T=137 s T=273 s T=410 s

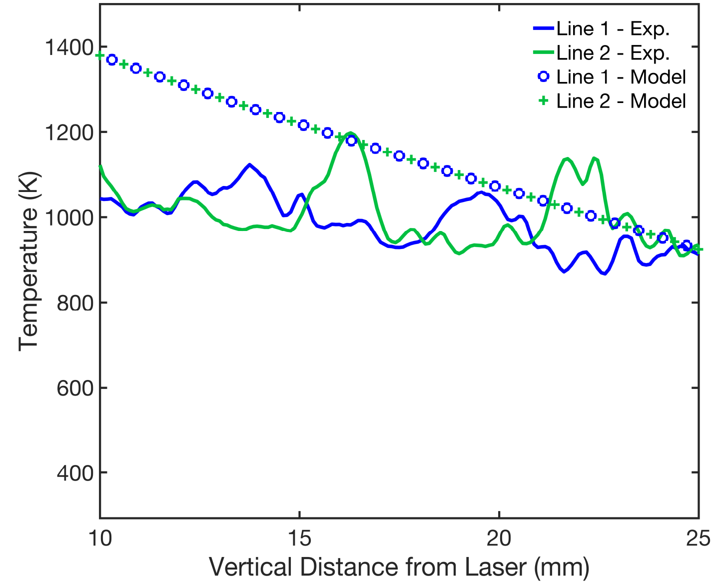


Thin wall IN718 LENS build at 900 W
Parimi *et al.* 2013

Comparison to IR Imaging

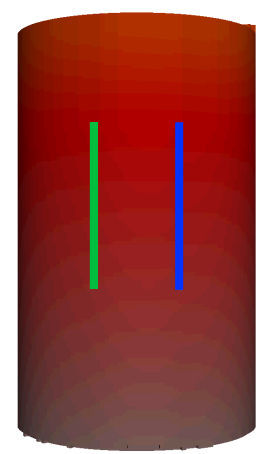




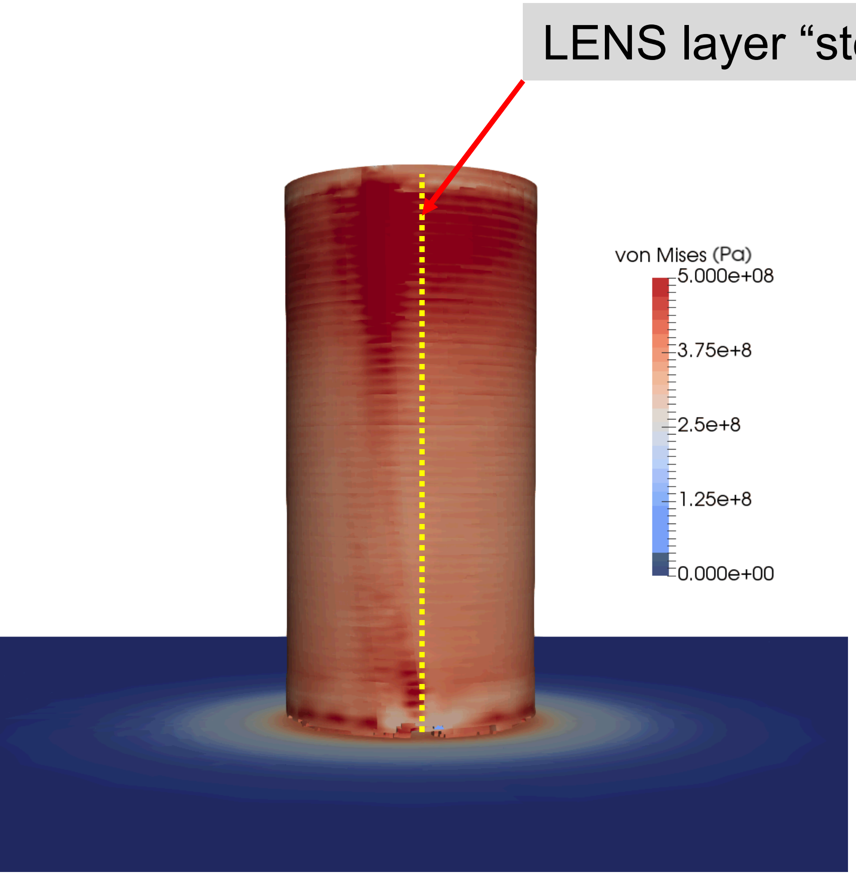


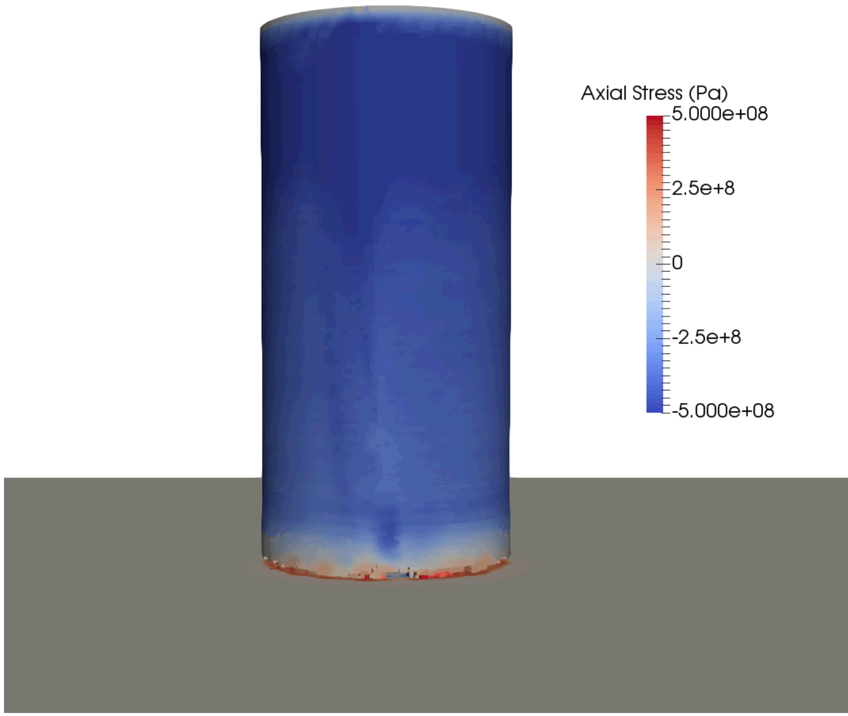
- IR camera mounted on LENS machine
- Assumes constant emissivity
- Compared to simulation

Simulation Results



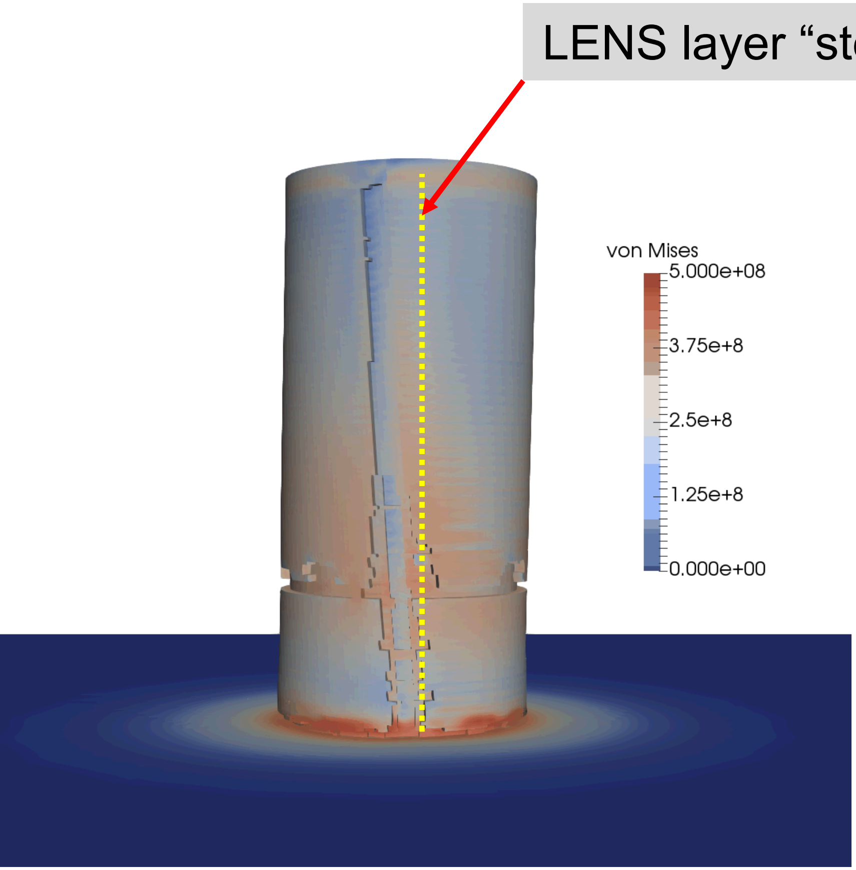
Final Von Mises and Axial Stress

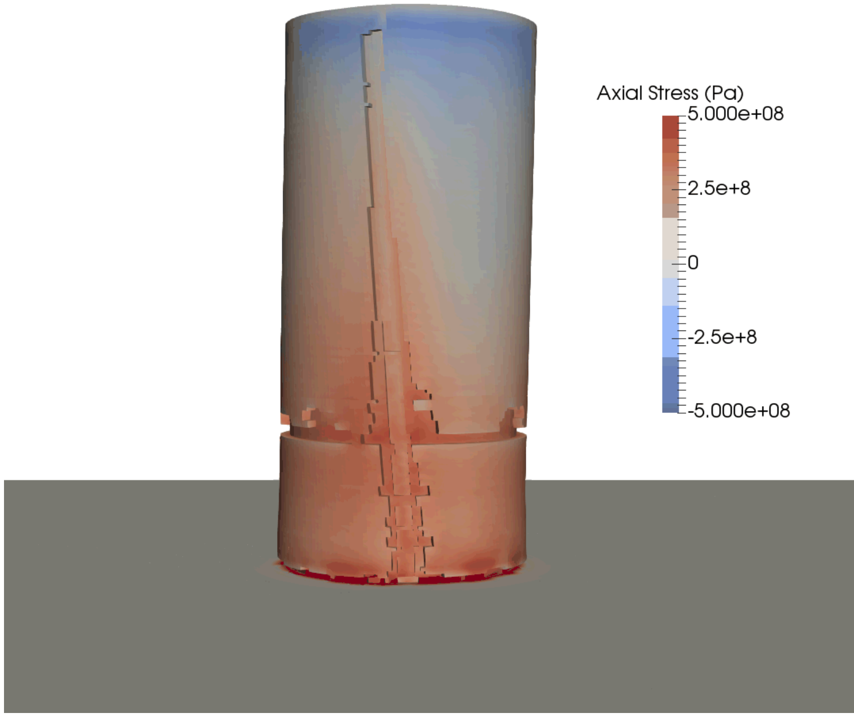




- Images taken after cool-down

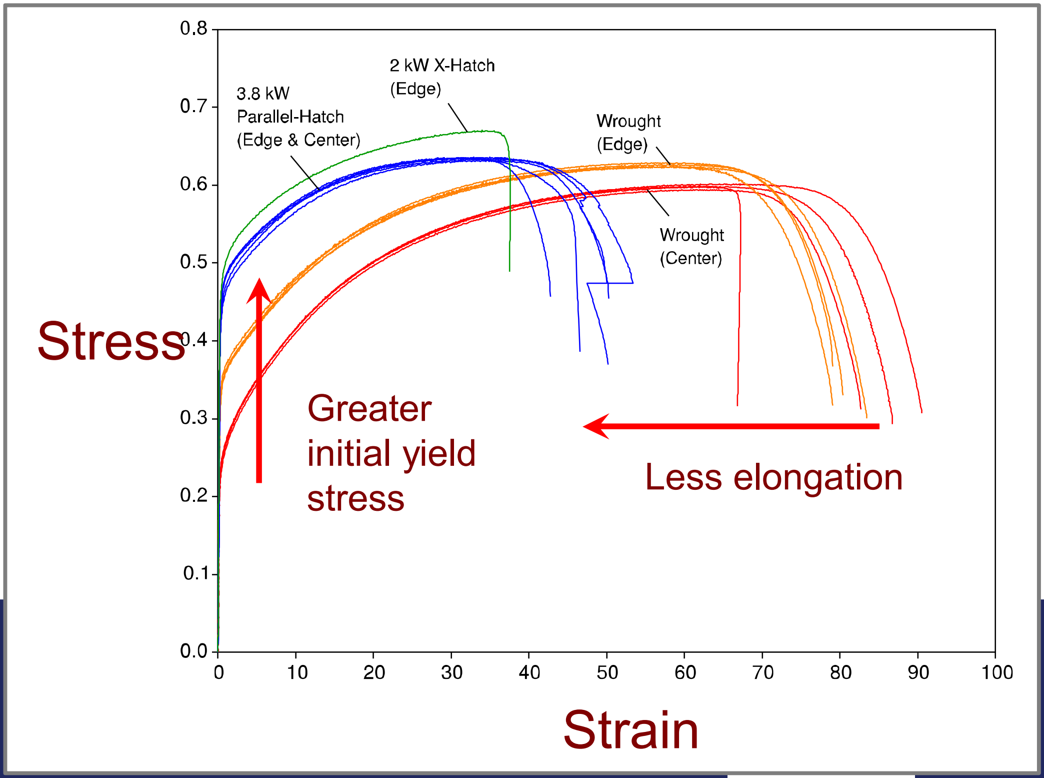
Final Von Mises and Axial Stress

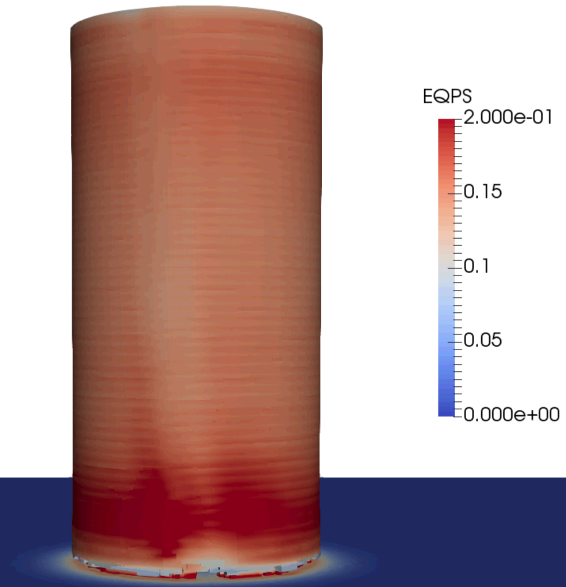




- Delay time causes lower overall von Mises stress and altered axial stress state

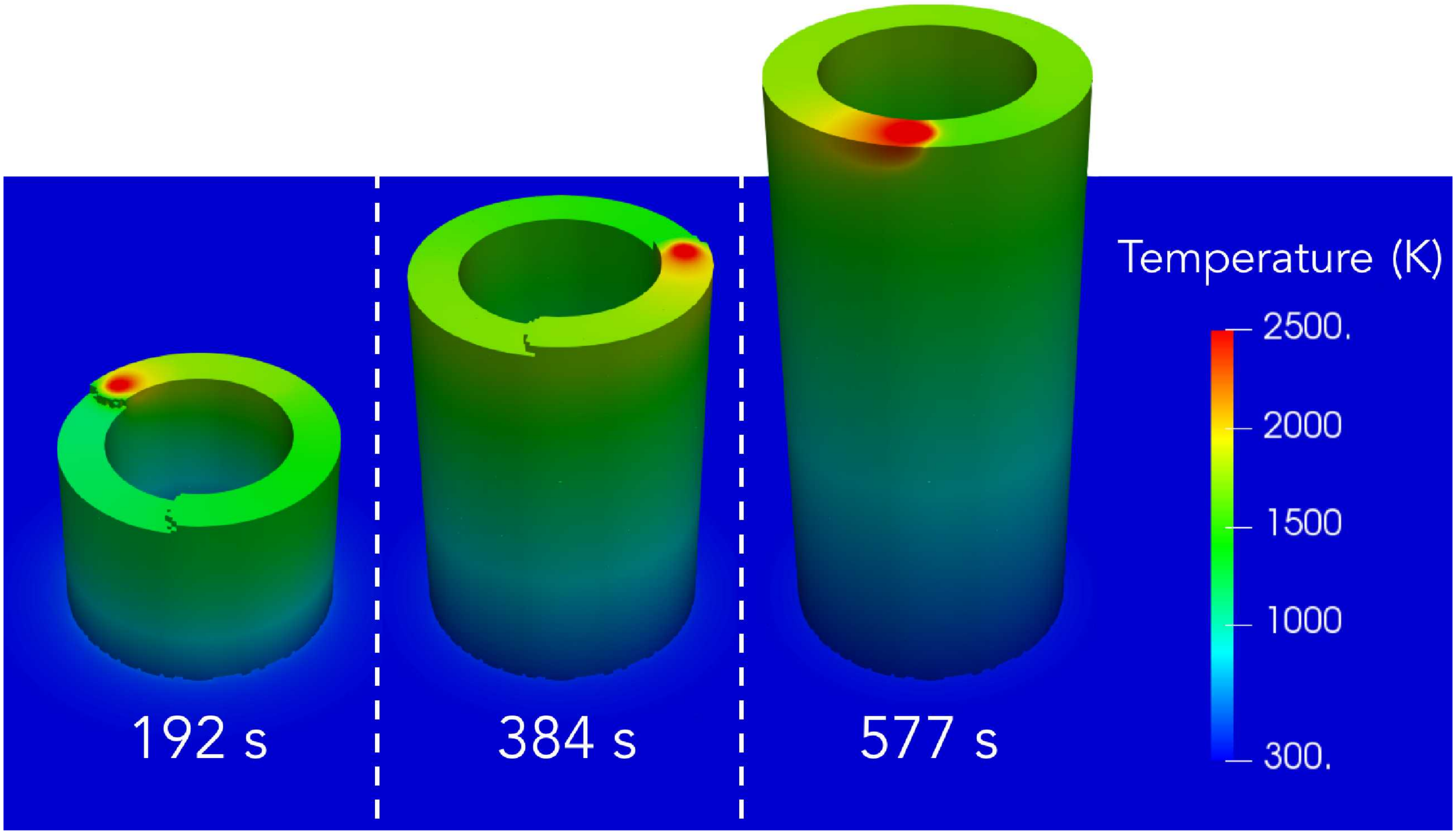
Final Displacement and EQPS



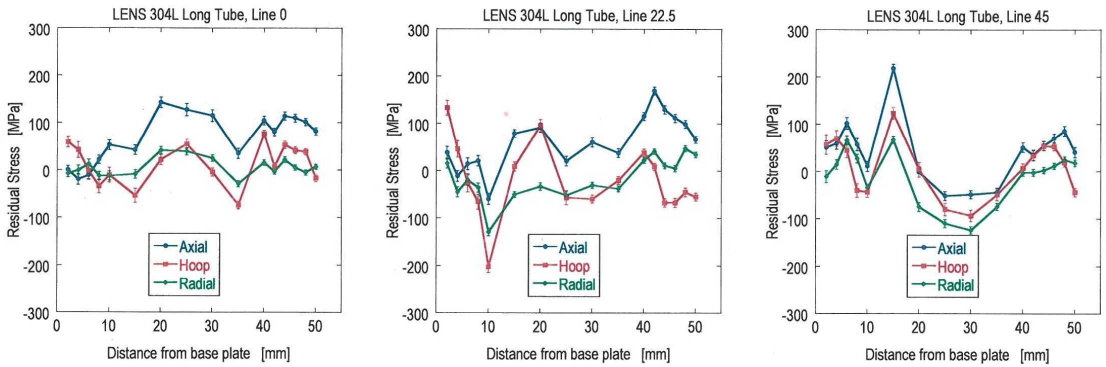


- High EQPS at baseplate indicative of plate warpage observed experimentally

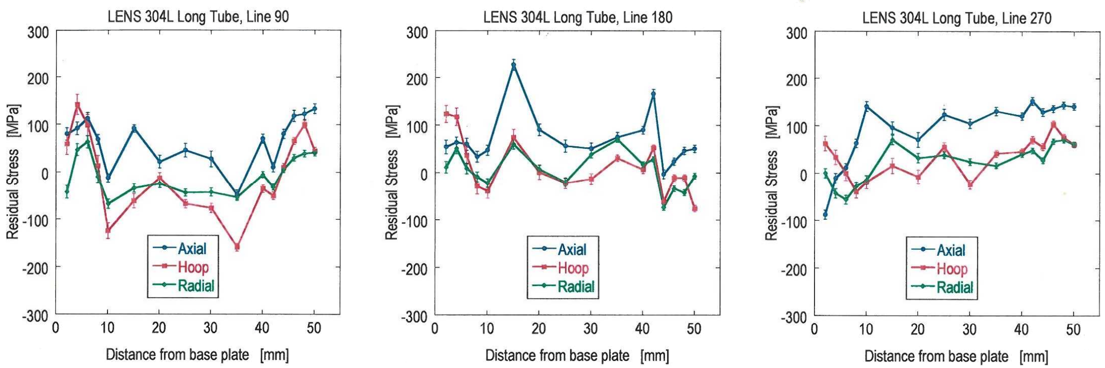
Thermal Profile at 3 Different Times

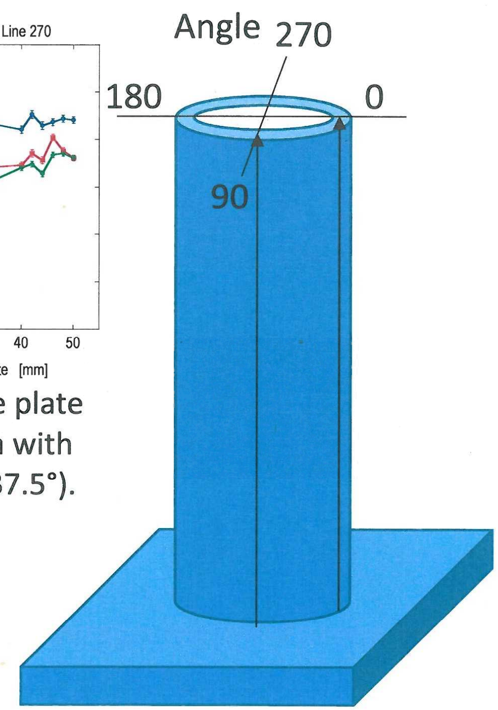


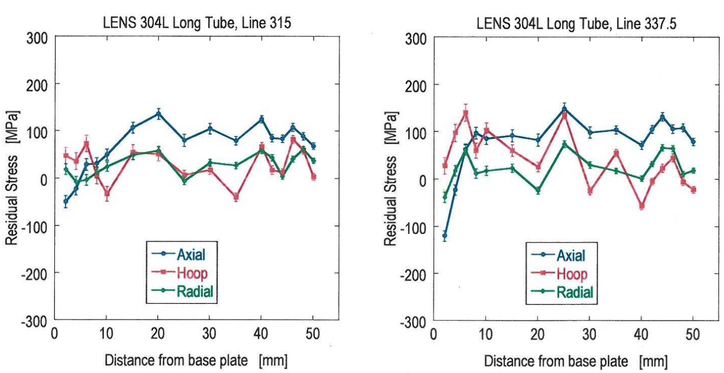
Experimental Comparison - Residual Stress



8 lines along axial direction. Transverse hole will be cut at mid length at 0 degrees.







Axial stress at base plate varies +/- 100 MPa with angle (270° and 337.5°).

OD = 24 mm
ID = 16 mm
Length = 52 mm
Base plate is ¼” thick and 3”x3”

Experiments by Don Brown and Bjorn Clausen (LANL)