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Additive Manufacturing Process Modeling – Progress Towards Science-Based Certification

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Sandia – UC Davis Research Partnership Symposium

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U.S. DEPARTMENT OF ENERGY

NNSA

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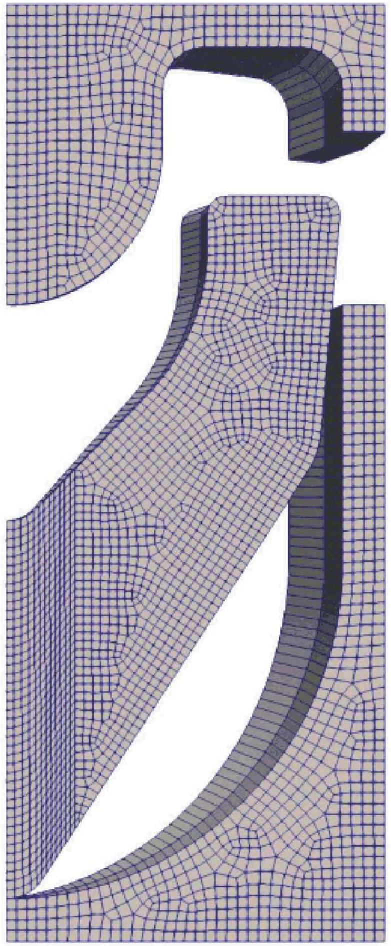
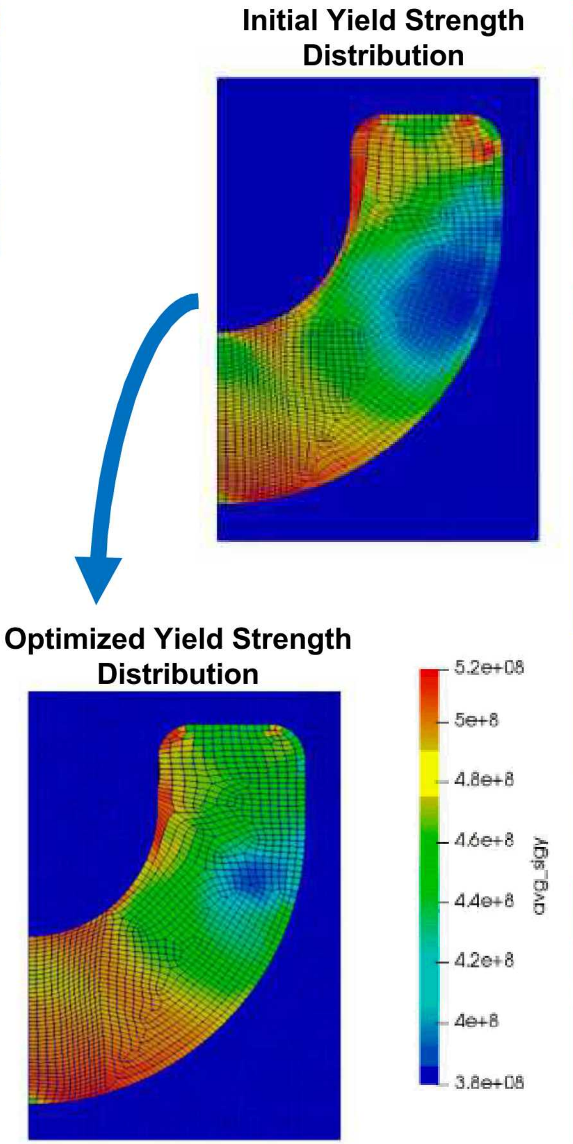
Additive manufacturing – integrated computational materials engineering to accelerate development

- Historically, traditional manufacturing methods have been developed over long periods of time
  - Large empirical data sets, trial and error, etc.
- At Sandia, computational engineering has been employed to optimize traditional manufacturing processes (e.g. forgings)
- Additive manufacturing presents many advantages, yet requires an accelerated development timeline
  - Computational simulation should be applied to accelerate development and enhance understanding for additive manufacturing to improve outcomes
  - Certification of properties and performance for AM parts requires additional research and development activities



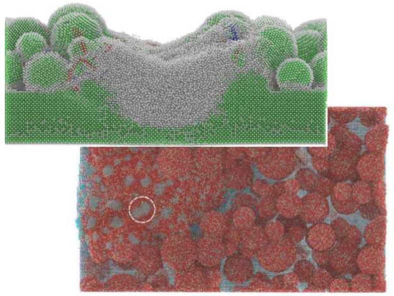


*forging simulations from L. Beghini, et al.

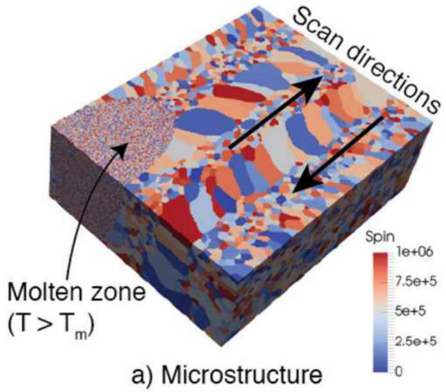
A variety of modeling tools for additive manufacturing have been developed by Sandia National Laboratories

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

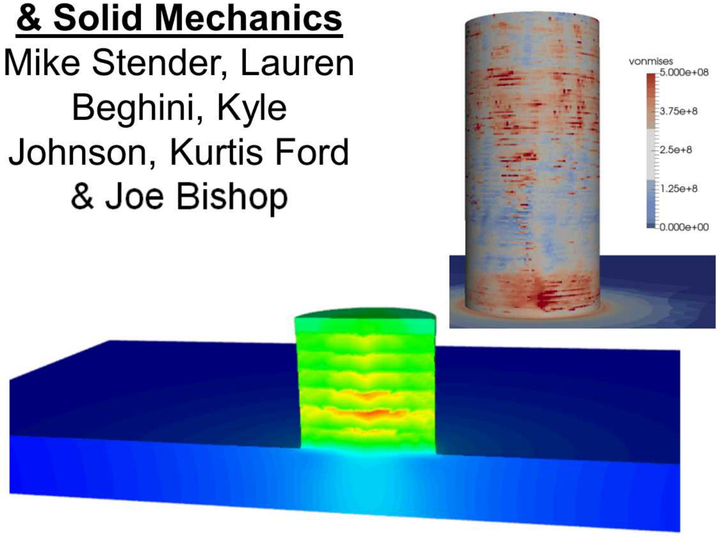
Powder Behavior
Mark Wilson



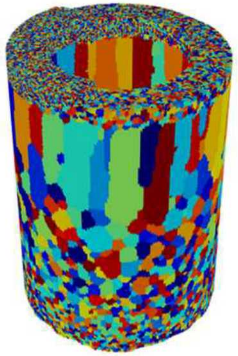
Mesoscale Texture/Solid Mechanics/CX
Judy Brown, Theron Rodgers and Kurtis Ford



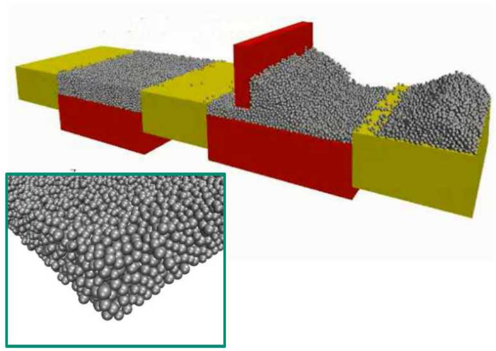
Part-Scale Thermal & Solid Mechanics
Mike Stender, Lauren Beghini, Kyle Johnson, Kurtis Ford & Joe Bishop



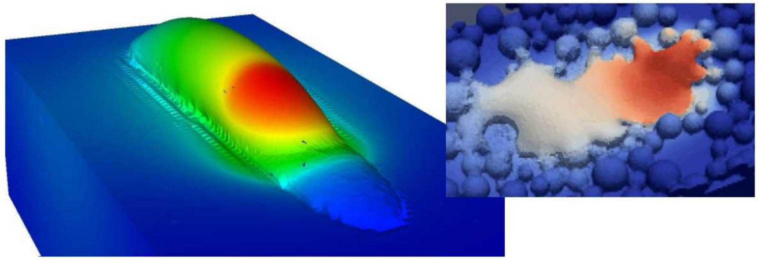
Part-Scale Microstructure
Theron Rodgers



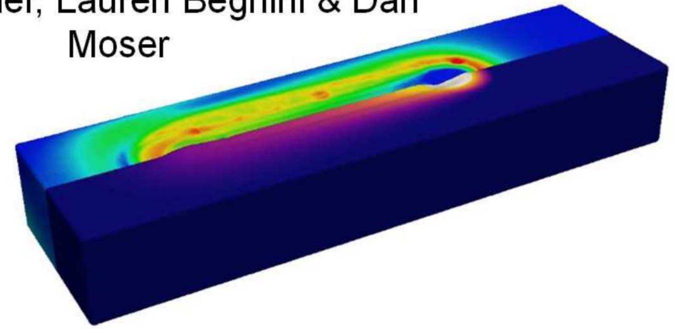
Powder Spreading
Dan Bolintineanu



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

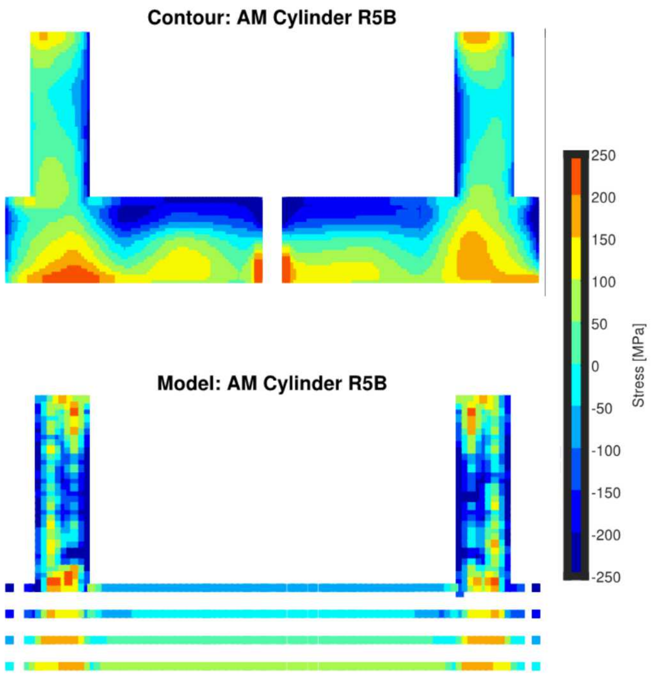


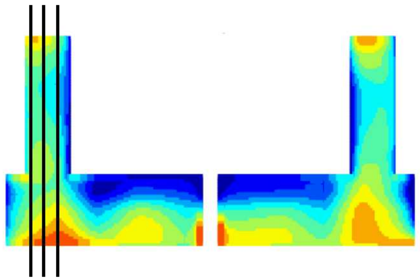
Mesoscale Coupled Solid/Fluid Behavior
Mike Stender, Lauren Beghini & Dan Moser



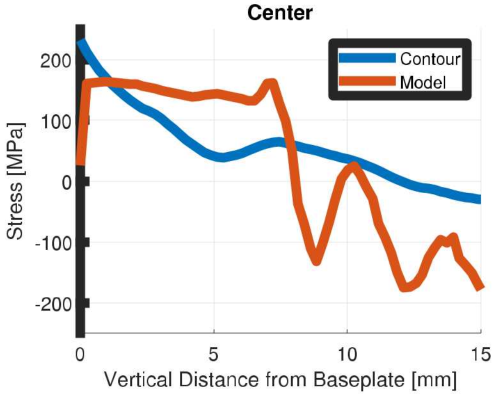
Work completed in Partnership with UC Davis has provided valuable validation information

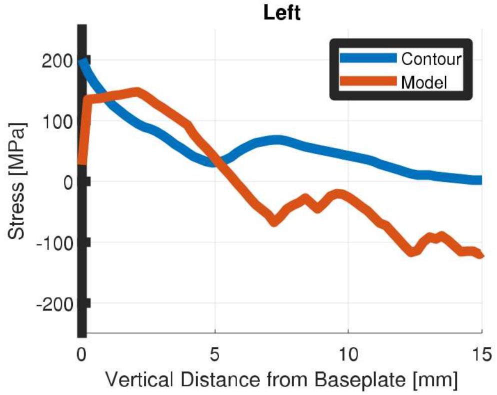
- Campus Executive LDRD projects have supported initial process model validation activities in FY19
  - Prof. Mike Hill, Chris D'Elia, Nick Bachus – residual stress measurement in additive manufactured parts
  - Prof. Mark Rashid, Madison Richey – efficient simulation for additive manufacturing
- Measurements from Mike Hill and Chris D'Elia shown here have provided essential residual stress data for model validation

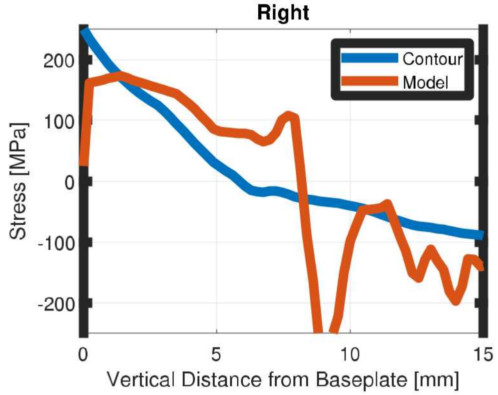




*~1.3mm line spacing from center line







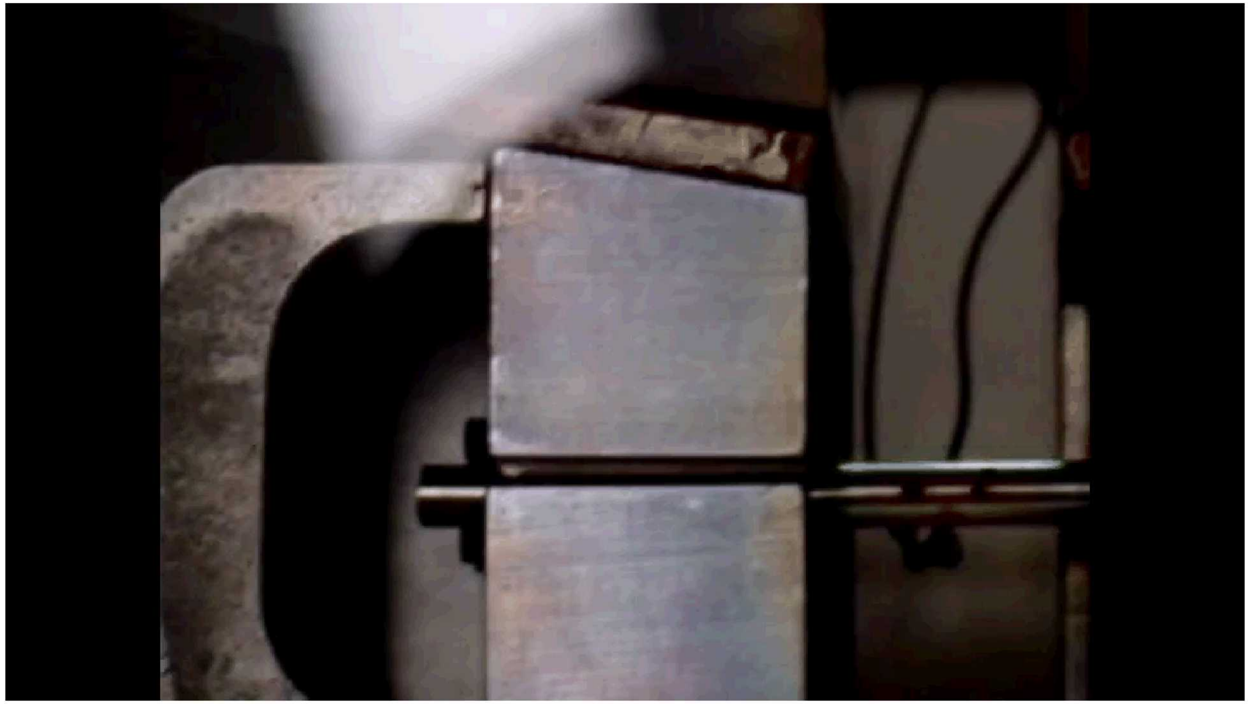
Tractable challenges for additive manufacturing simulation

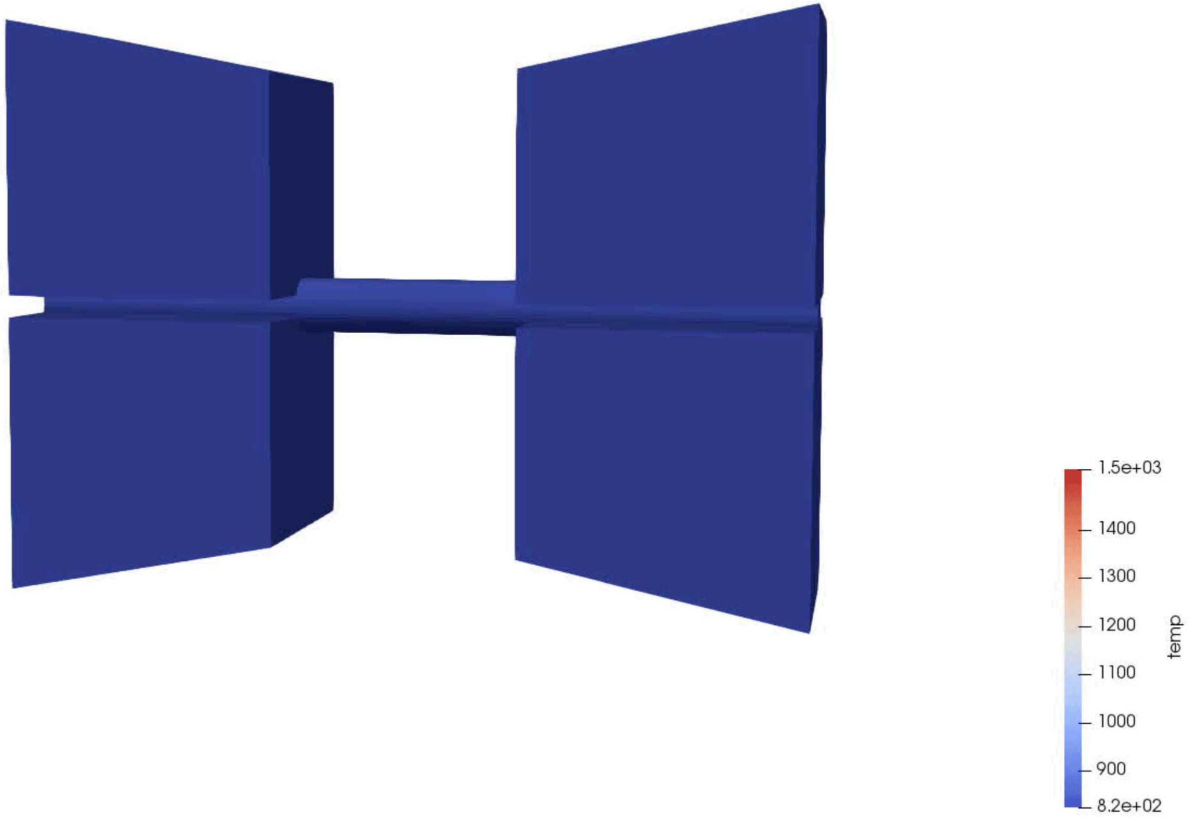
- Many opportunities exist to improve outcomes for additively manufactured components
- Process improvements and additive manufacturing specific opportunities
  - Laser optimization – scan path, active power control, thermal mechanical history control
  - Residual stress engineering
  - Engineering of material properties to optimize performance
  - Hybrid and functionally graded materials
- Continued validation of initial model predictions is essential
  - It is critical to compare across measurement techniques (e.g. contour method, neutron diffraction, slitting) whenever possible
  - Similarly, different modeling strategies (e.g. solid-fluid coupled, part-scale) should be compared and assessed against each other
- Perfect validation is unlikely, understanding differences and quantifying uncertainties in models and experiments is critical

Backup Slides

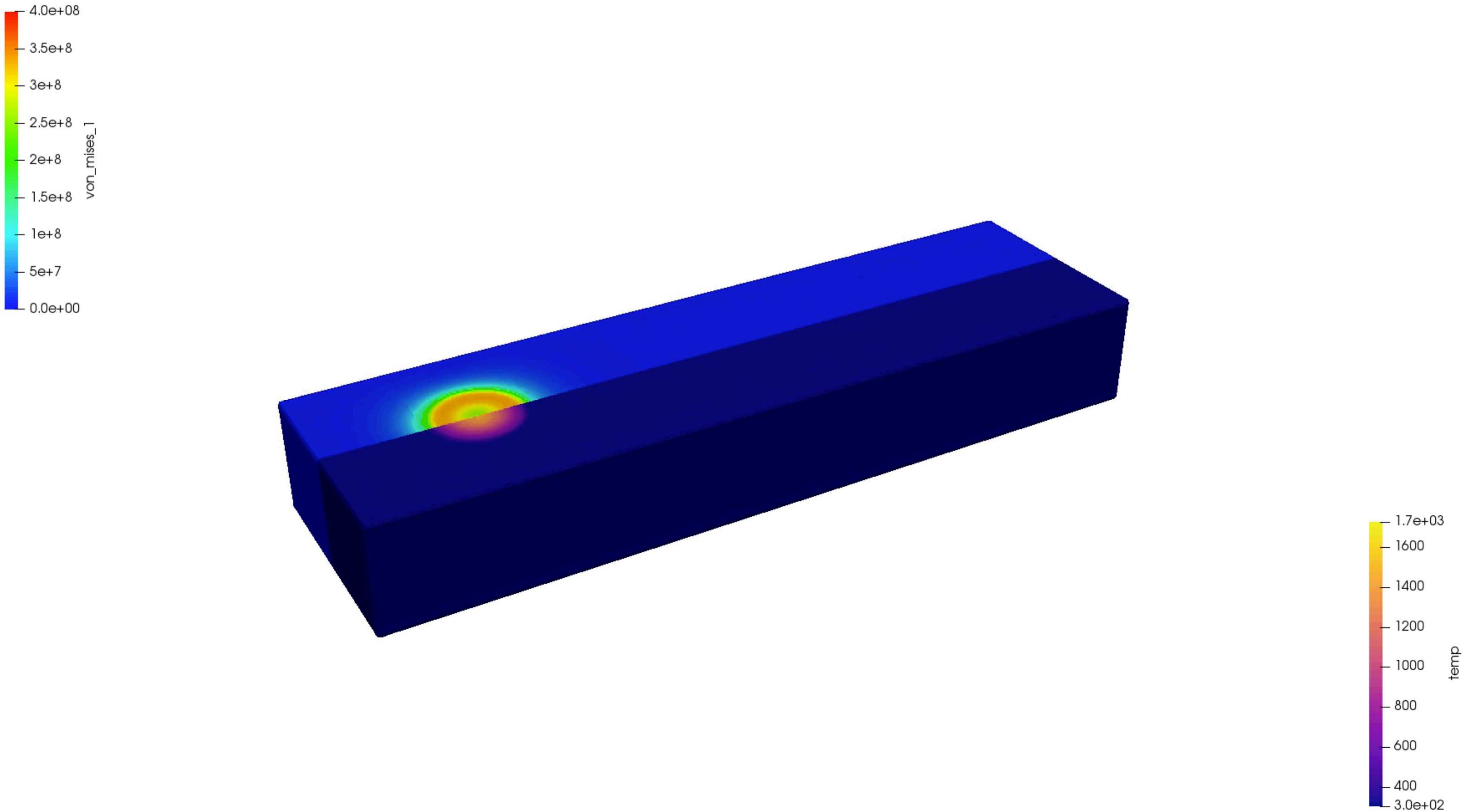
Constitutive model calibration is leveraging Gleeble tests

- Gleeble tests are underway to calibrate high temperature material parameters





High-fidelity model shows improvements in residuals stress calculations



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,

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