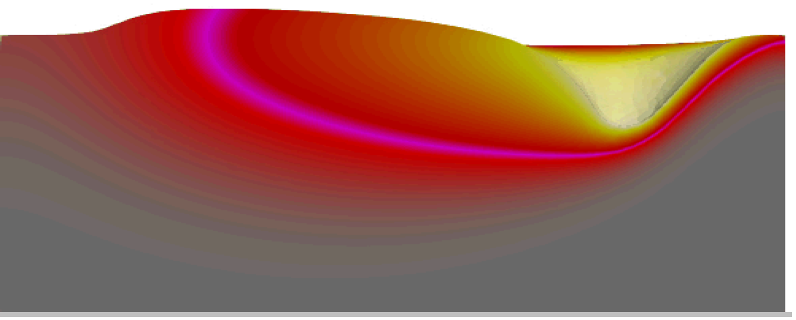
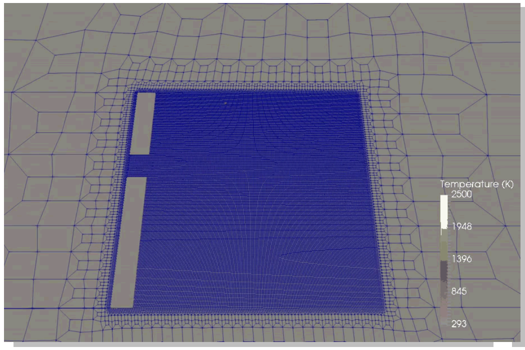
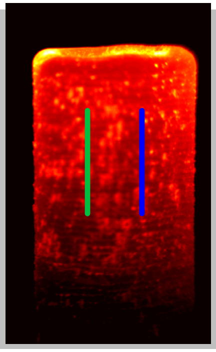
SAND2018-2660C







Multi Scale Solid Mechanics Models of Additive Manufacturing

Kurtis Ford, Lauren Beghini, Theron Rodgers, Joe Bishop, Kyle Johnson, Brad Trembacki

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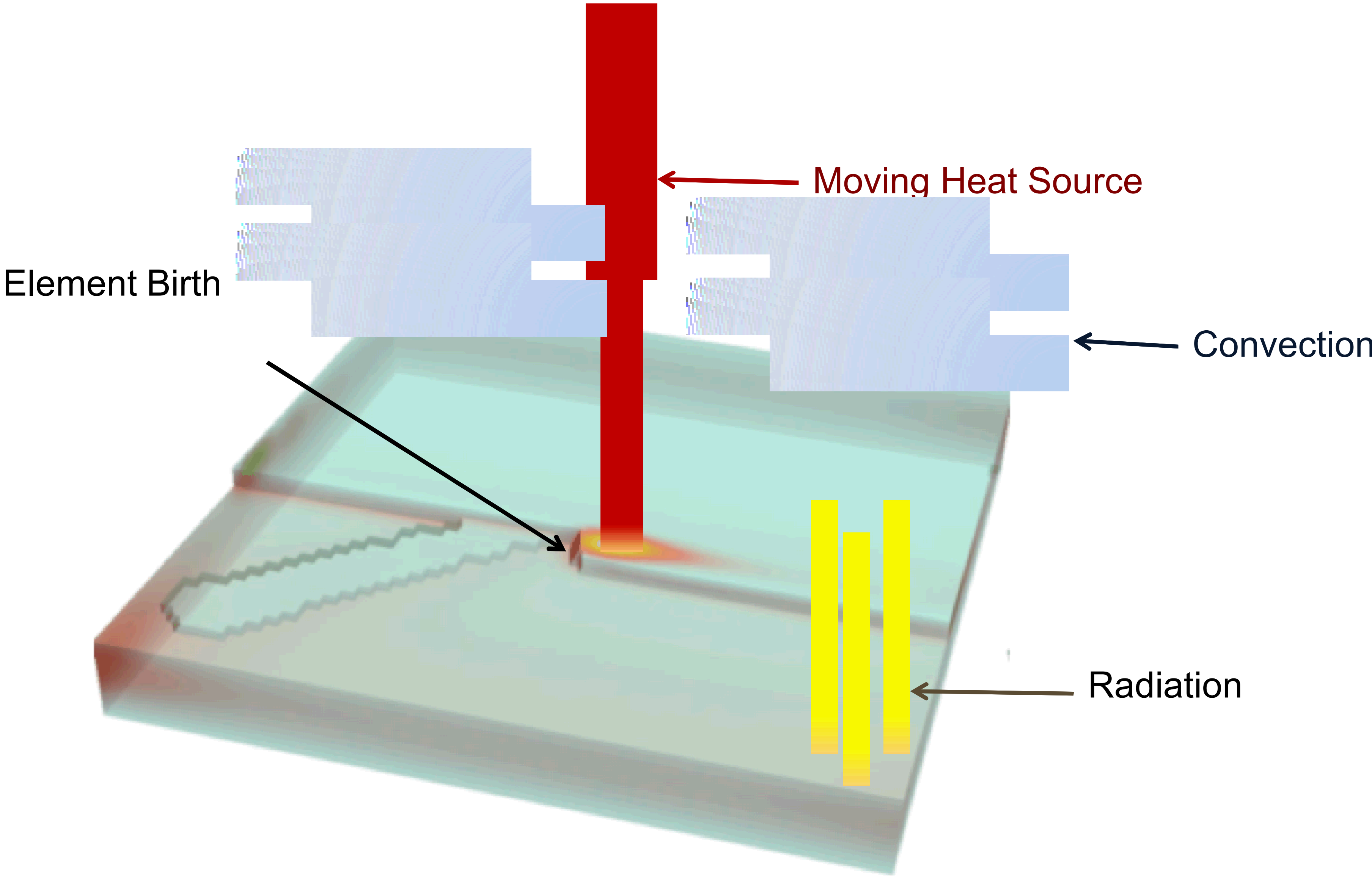
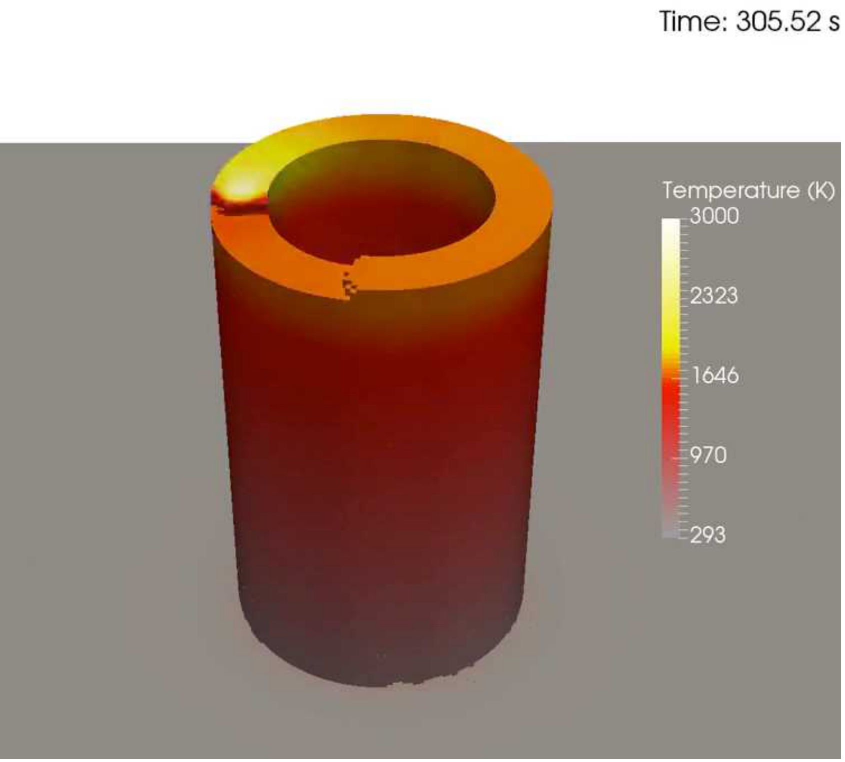
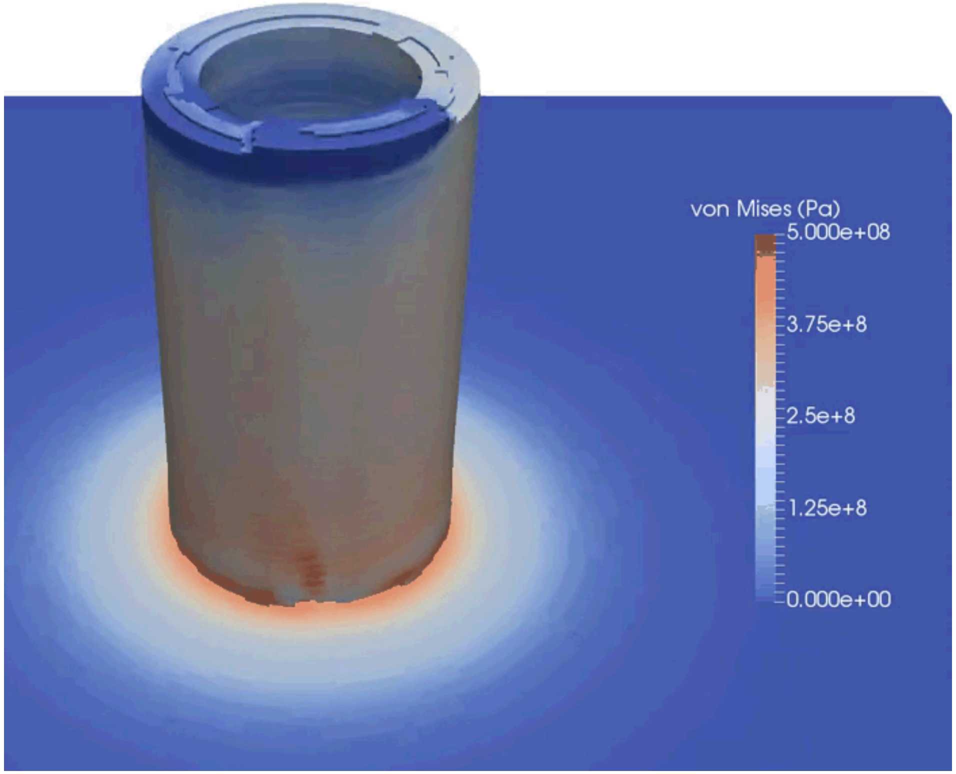
Additive Process Model at Sandia

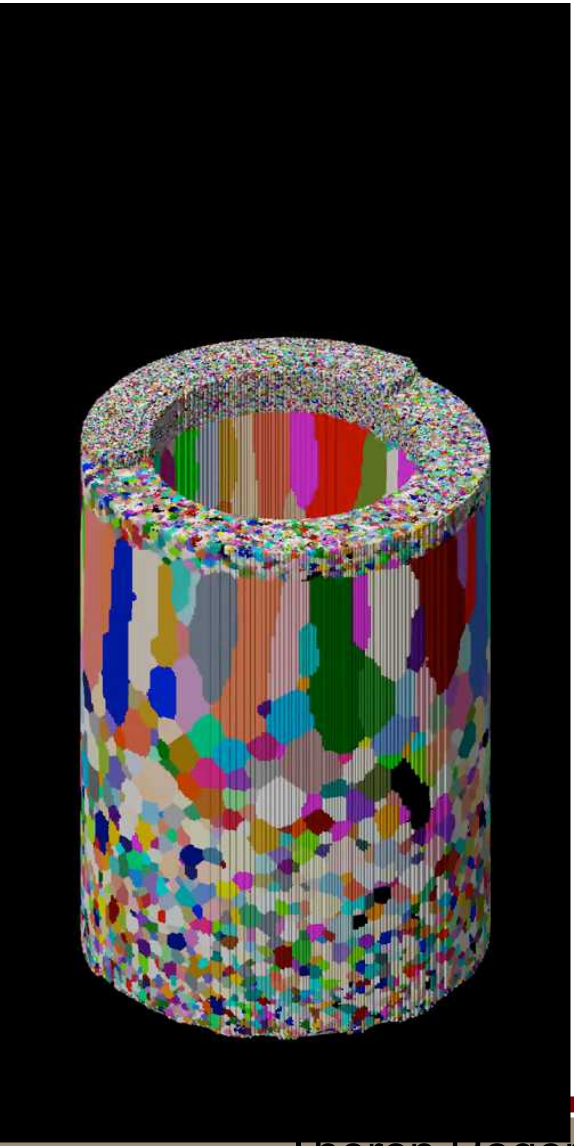


Hot Spot to Approximate Melt Pool

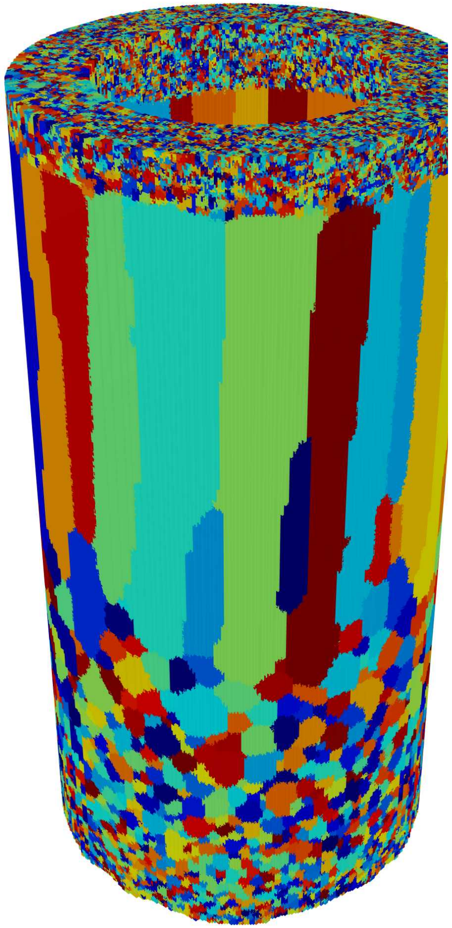




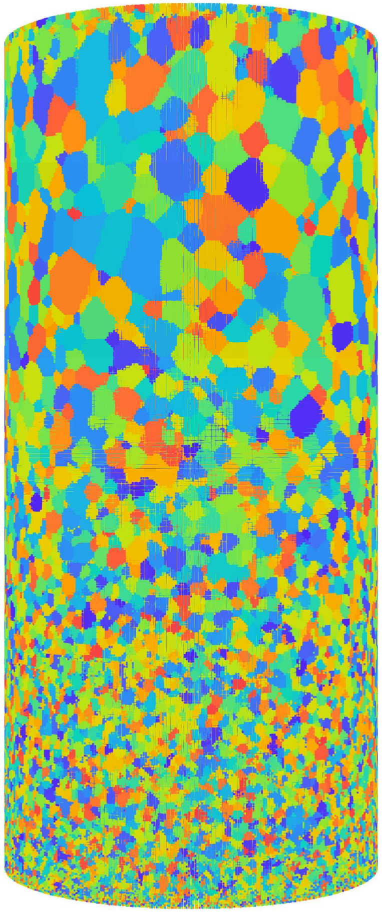
Grain Growth Predicted by Thermal History



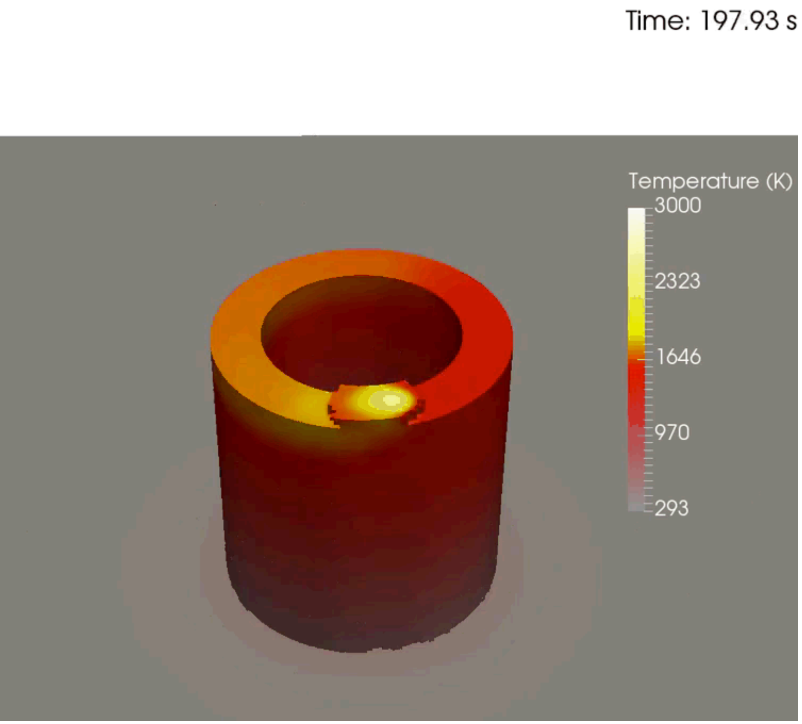
Single Build

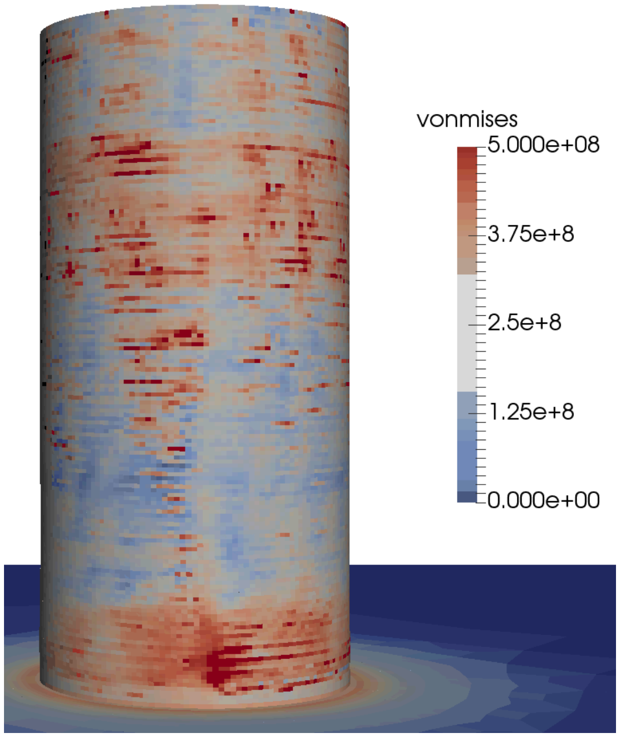


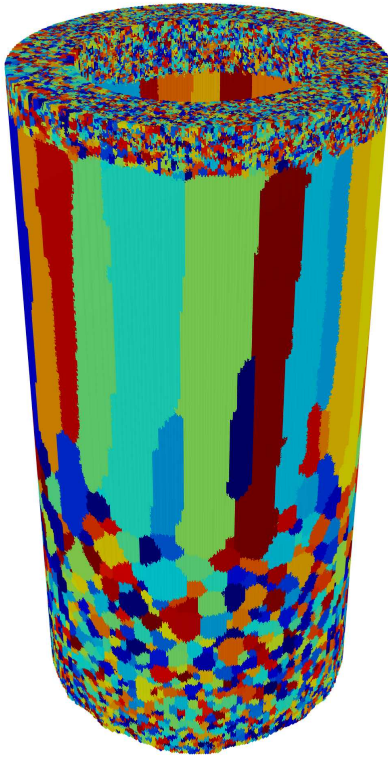
Double Build – 8 Second Inter-layer Delay



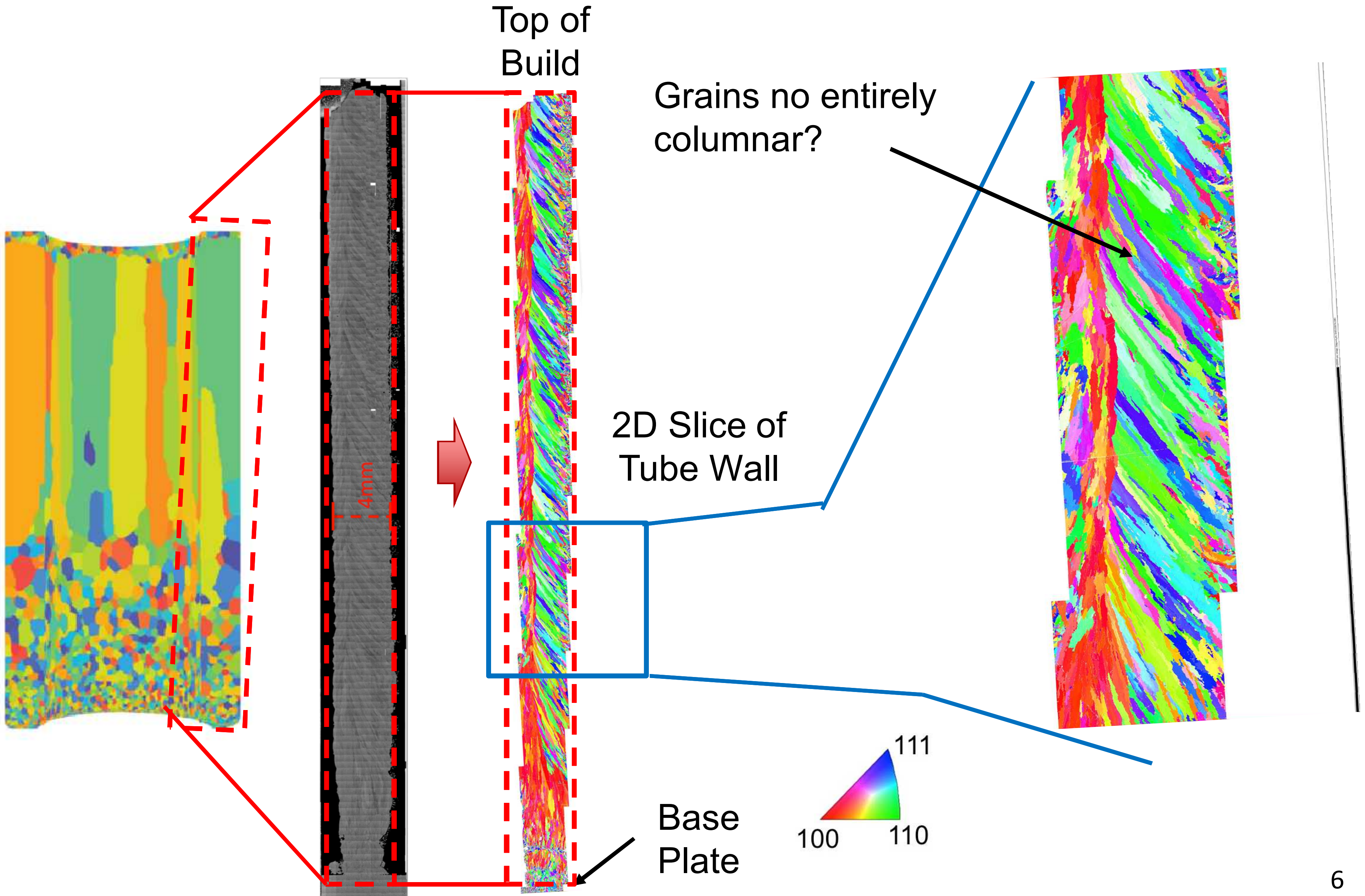
Scalable Part Scale Model





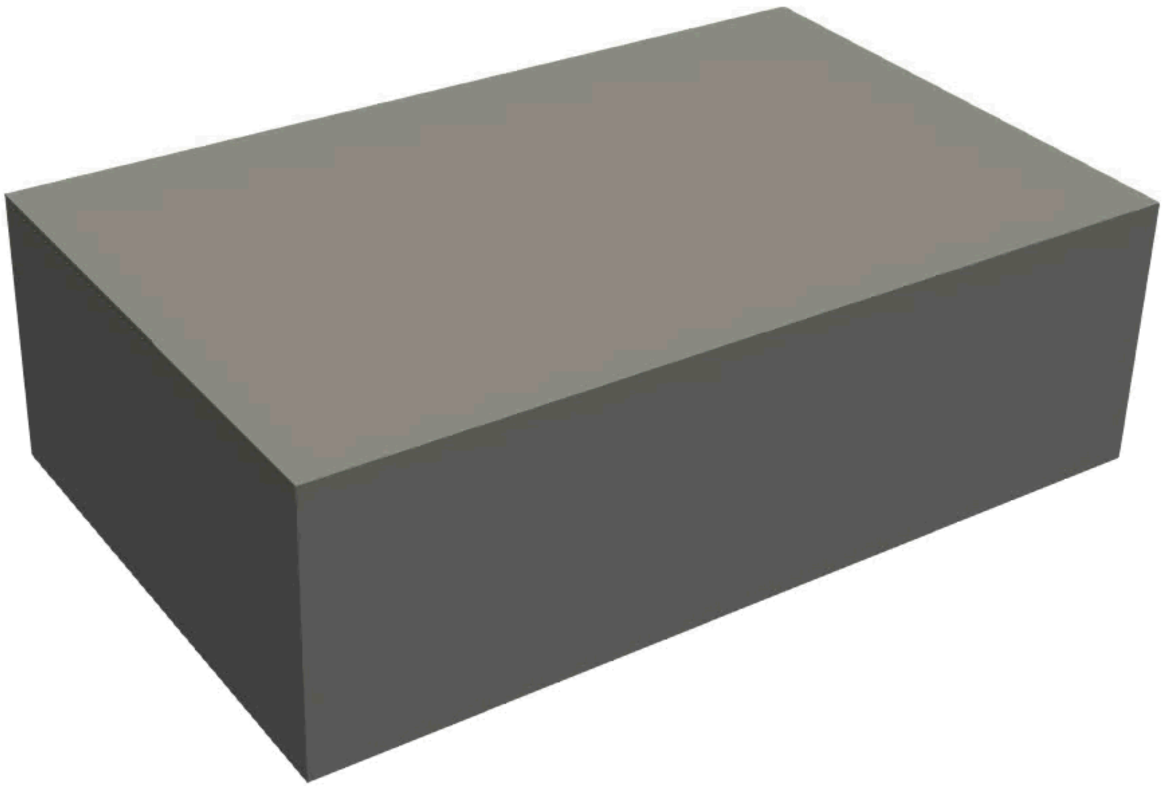


Experimental Comparison - Microstructure

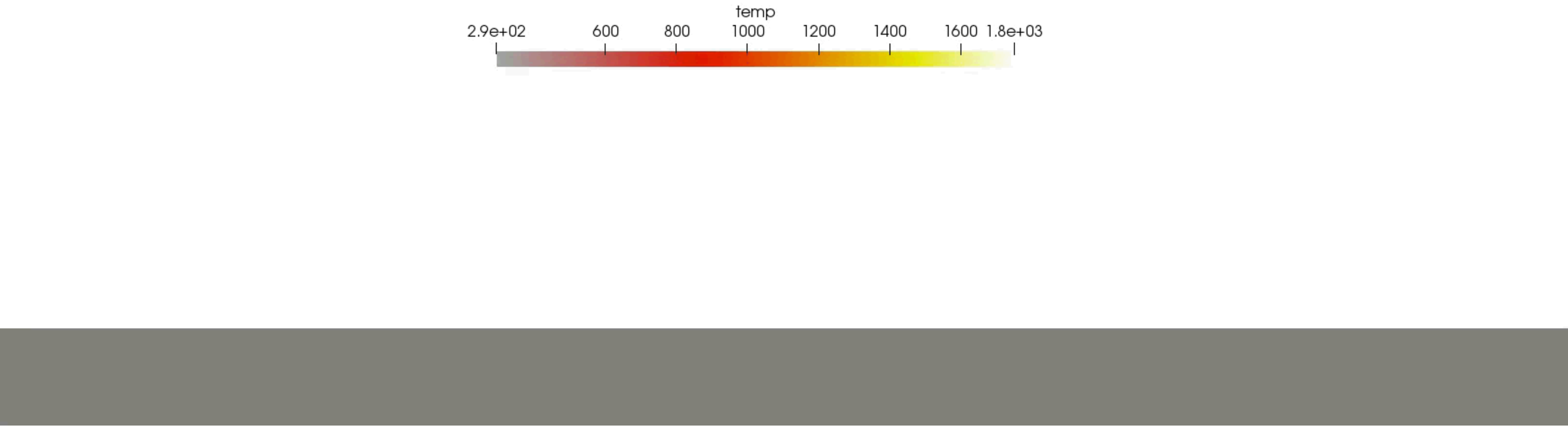


EBSD: O. Underwood, J. Madison, A. Kilgore, J. Michael, S. Dickens

Part Scale Model of Wall



Part Scale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800
1000
1200
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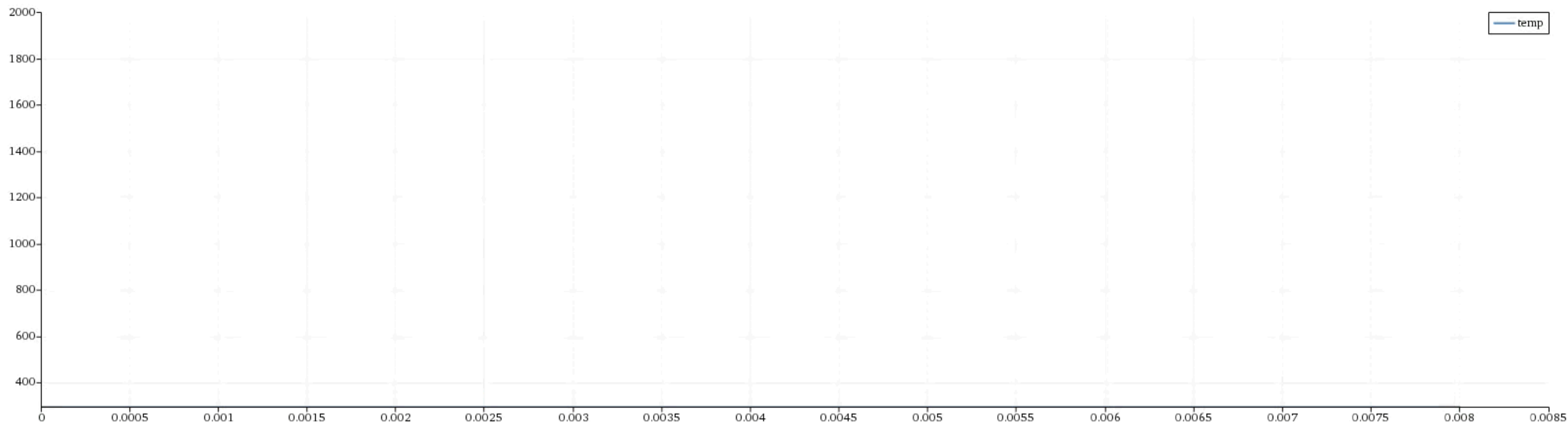
1600
1.8e+03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0.003
0.0035
0.004
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0.0055
0.006
0.0065
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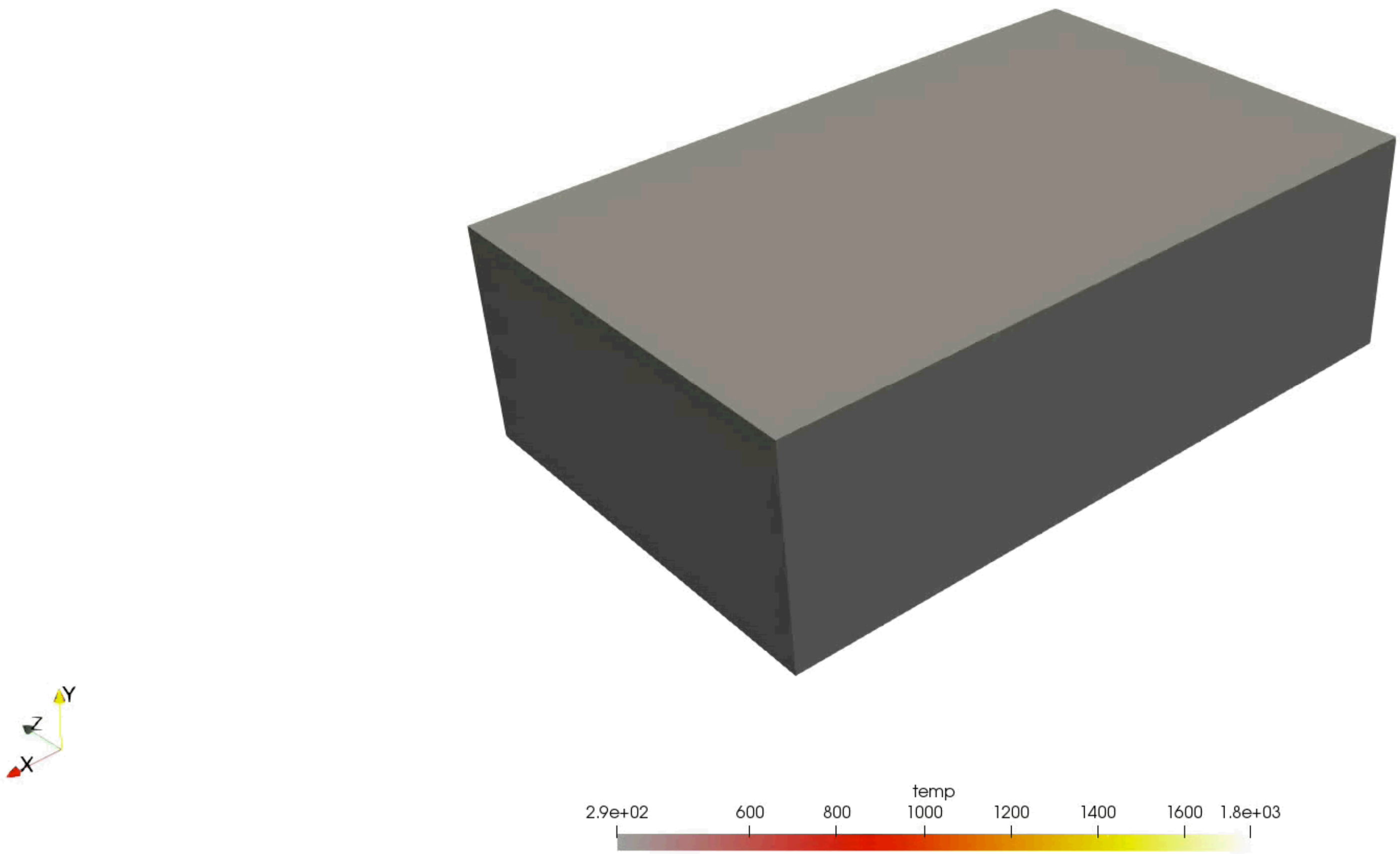
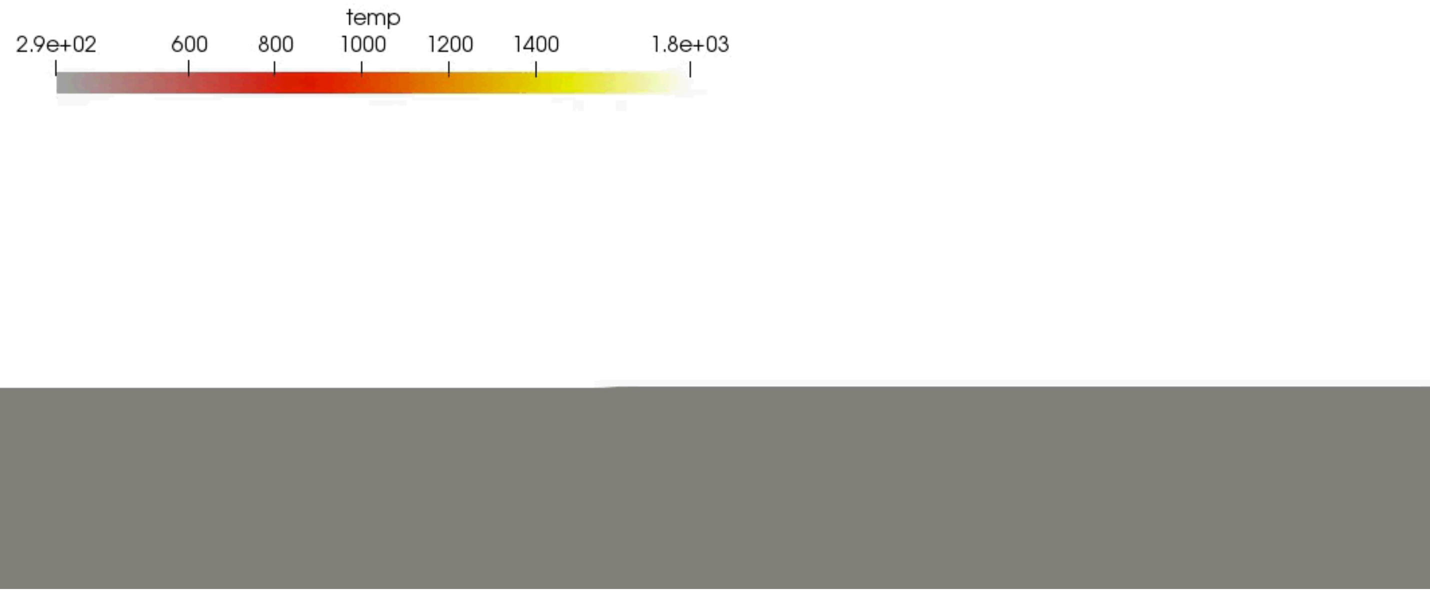
0.0075
0.008
0.0085

Fluid Model of Wall

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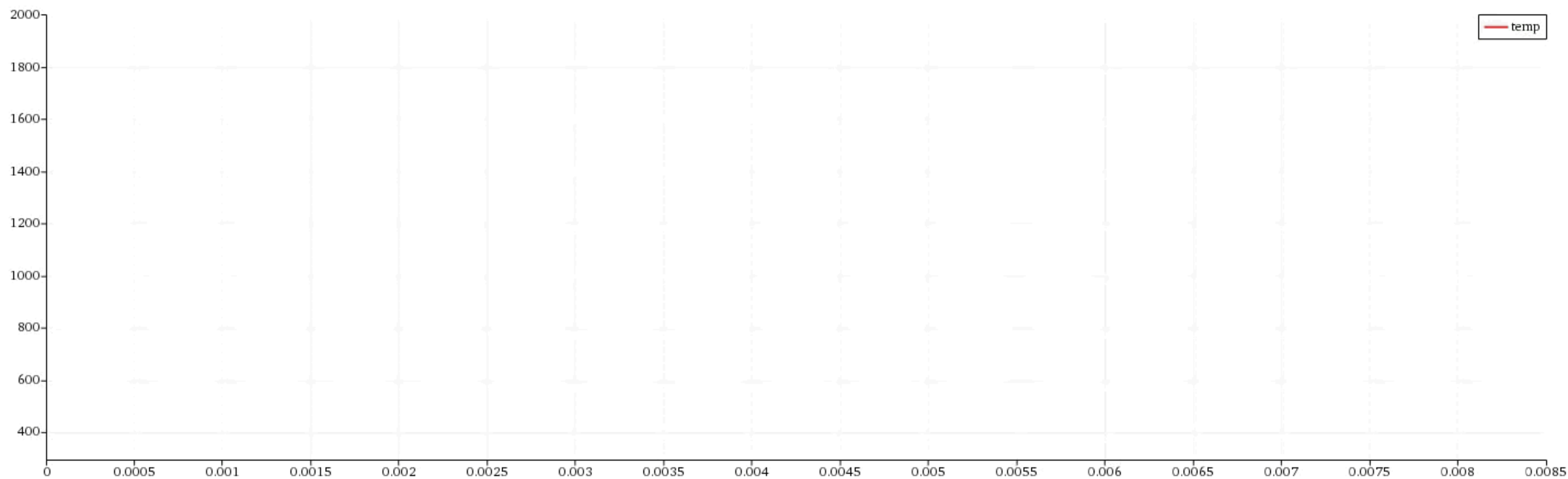
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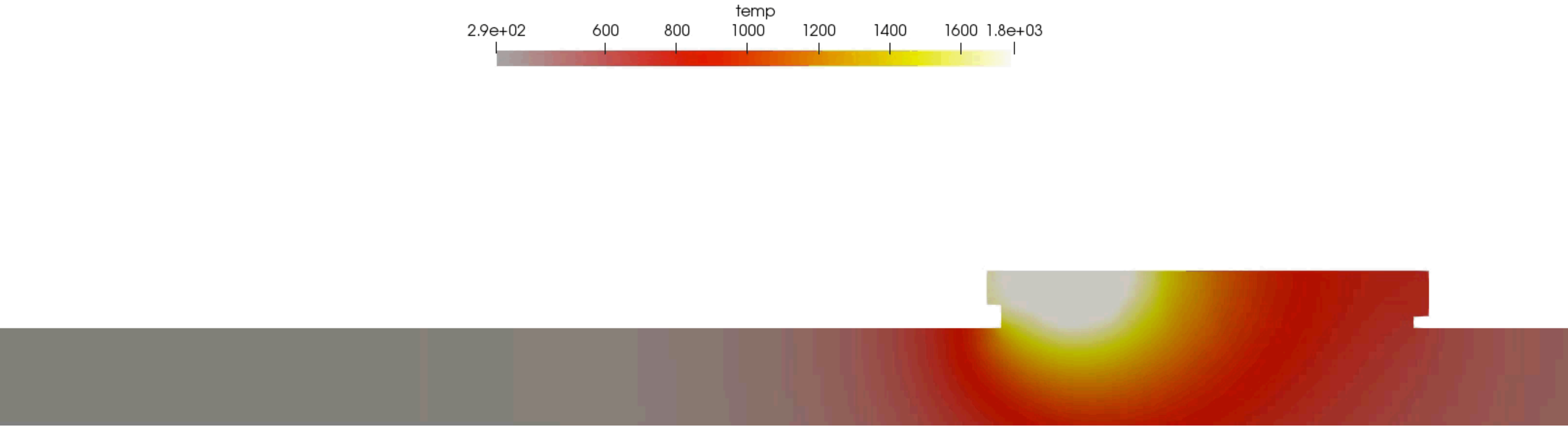
Comparison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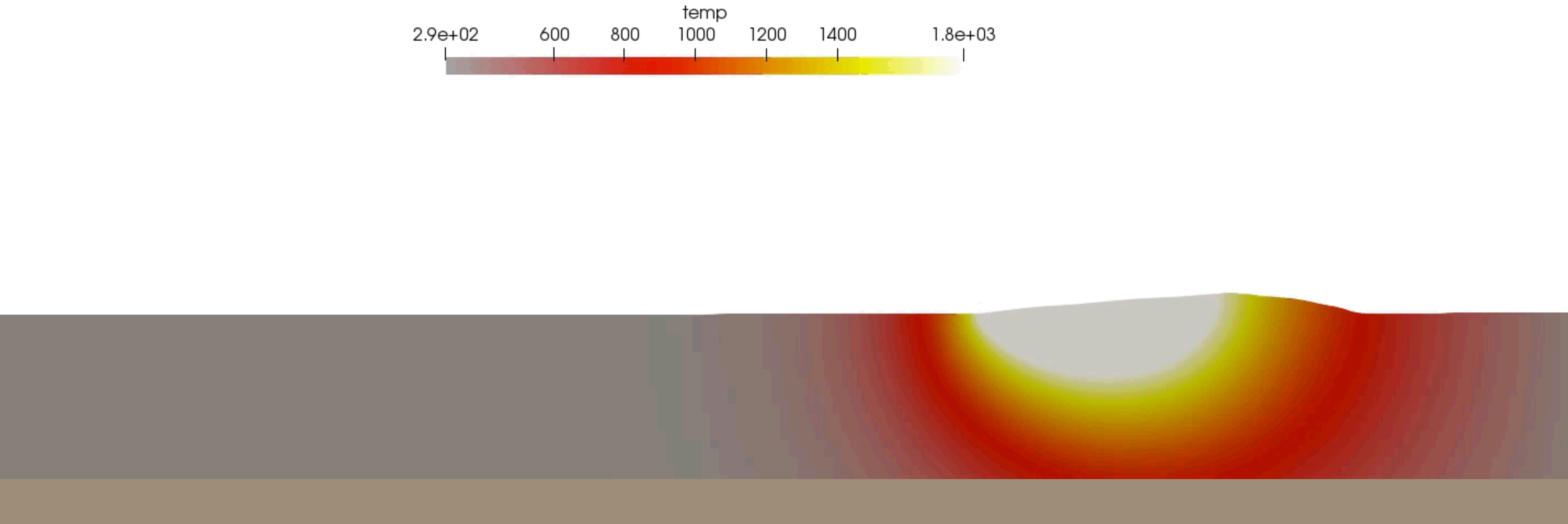
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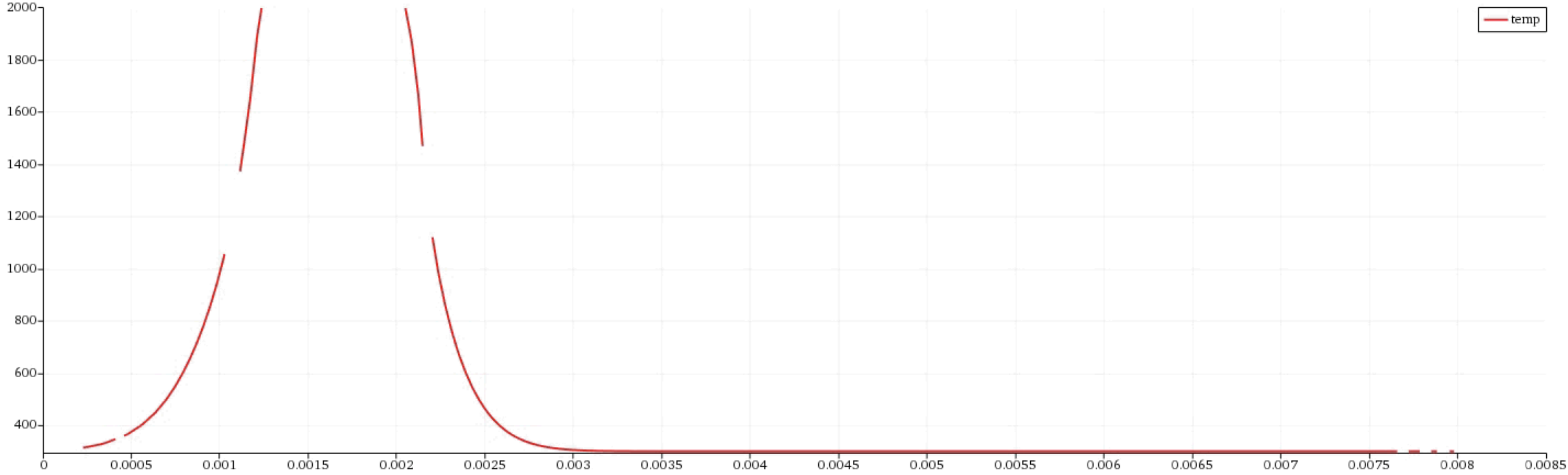
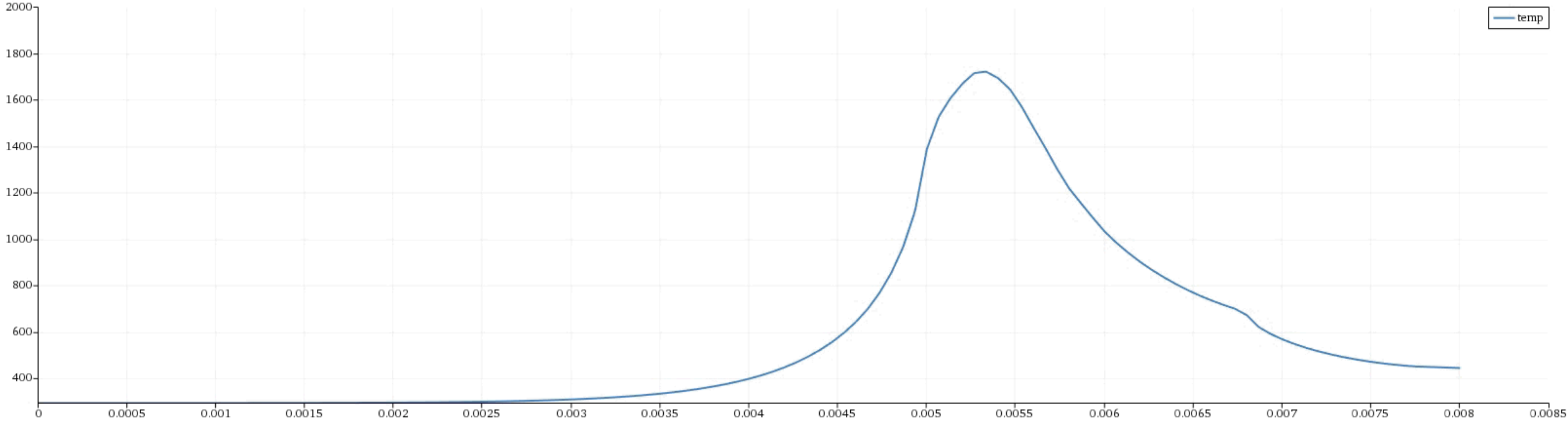
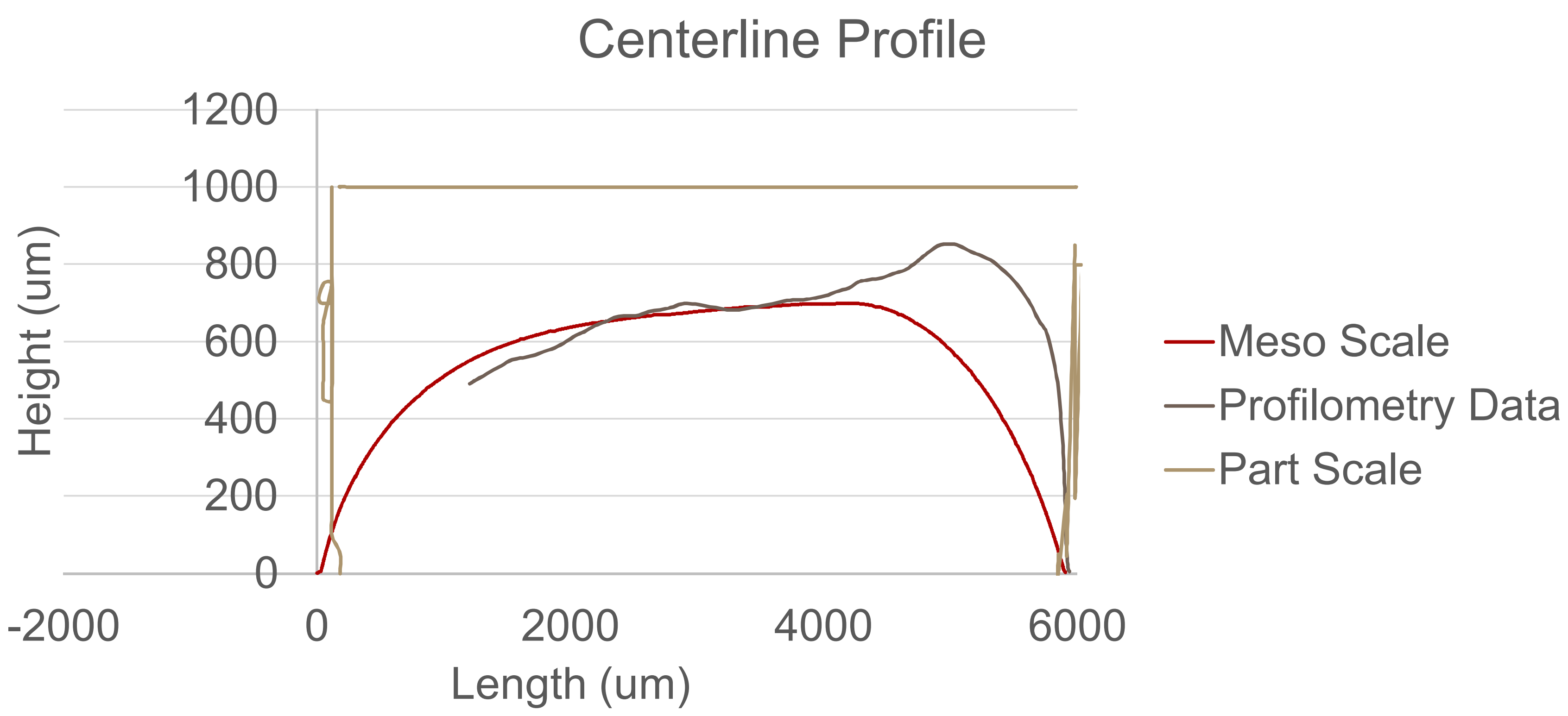
Comparison Continued

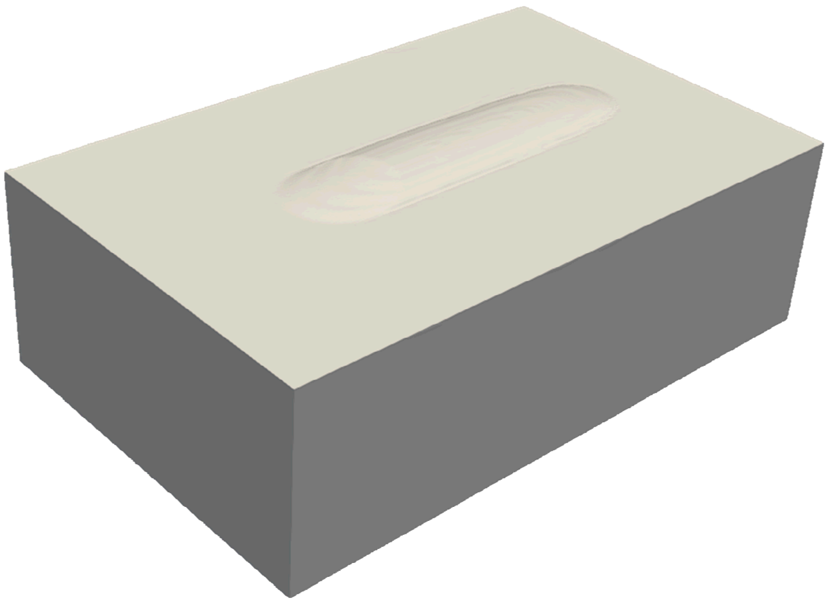


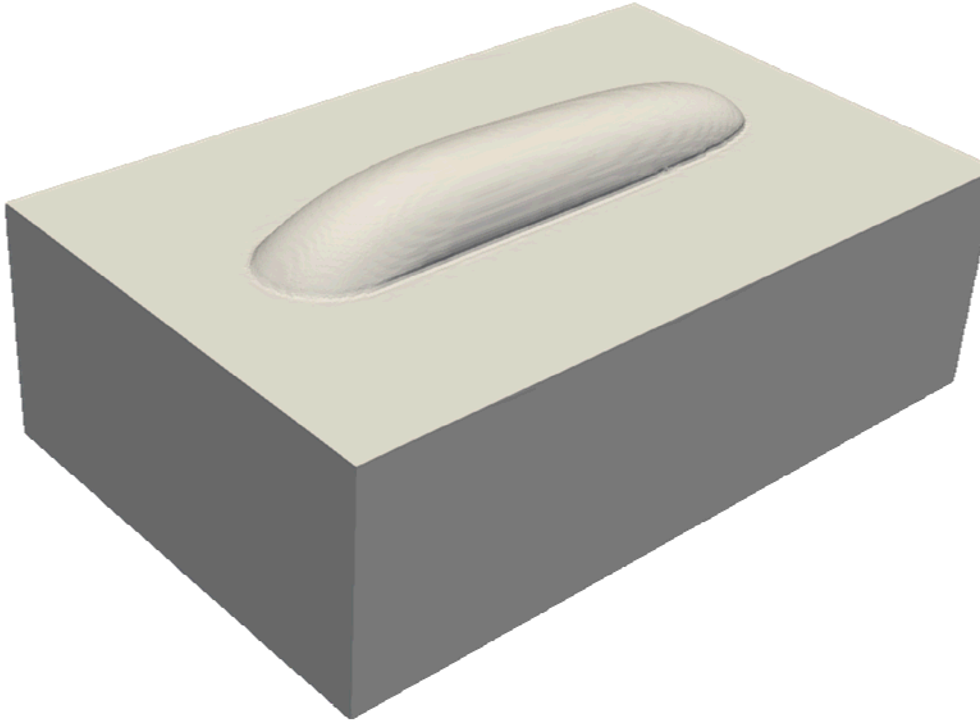


Multi Scale Model Comparsion

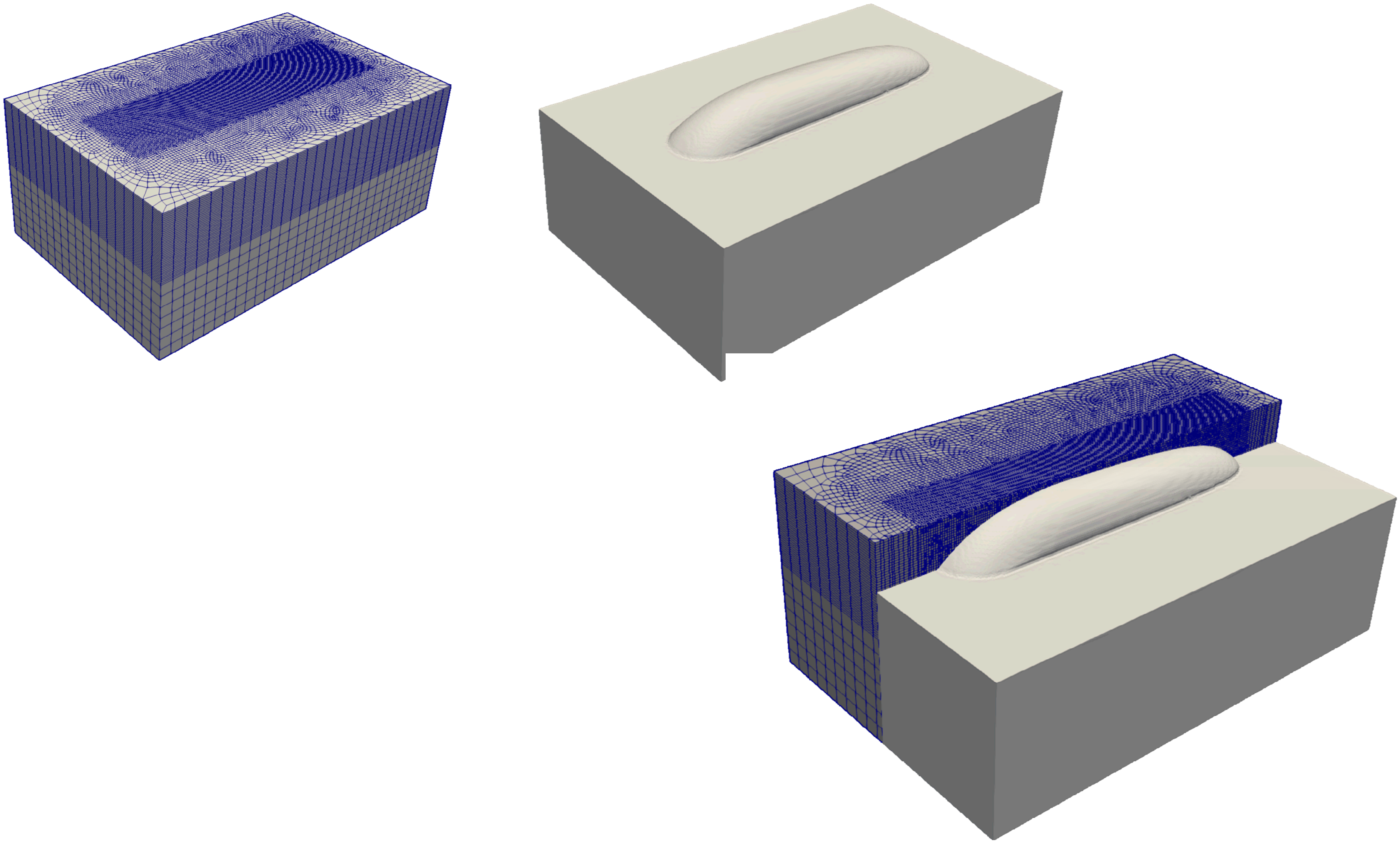


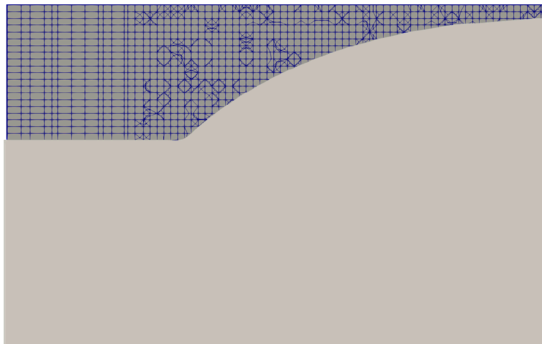
Generate STL of Evolving Geometry

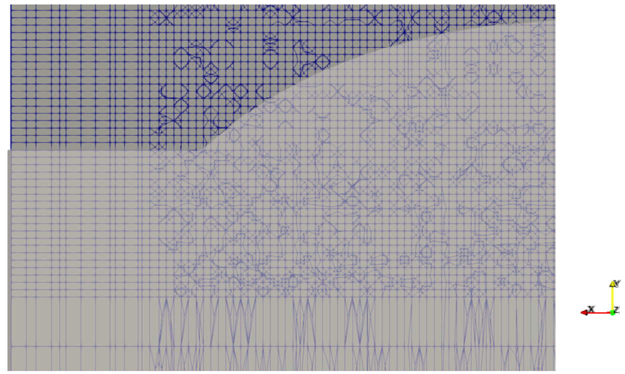


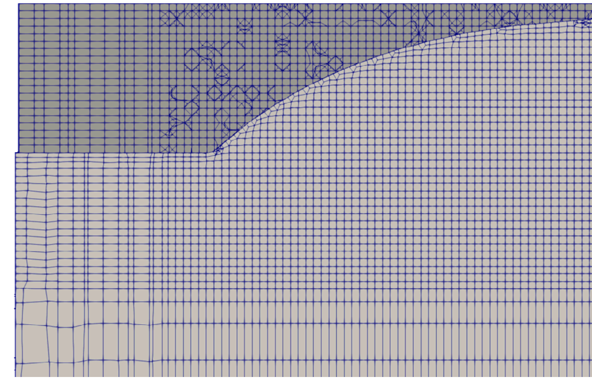


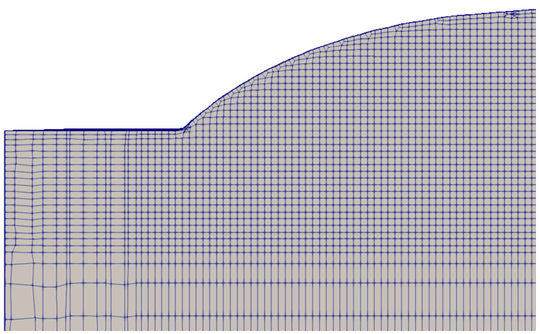
Mesh Evolving

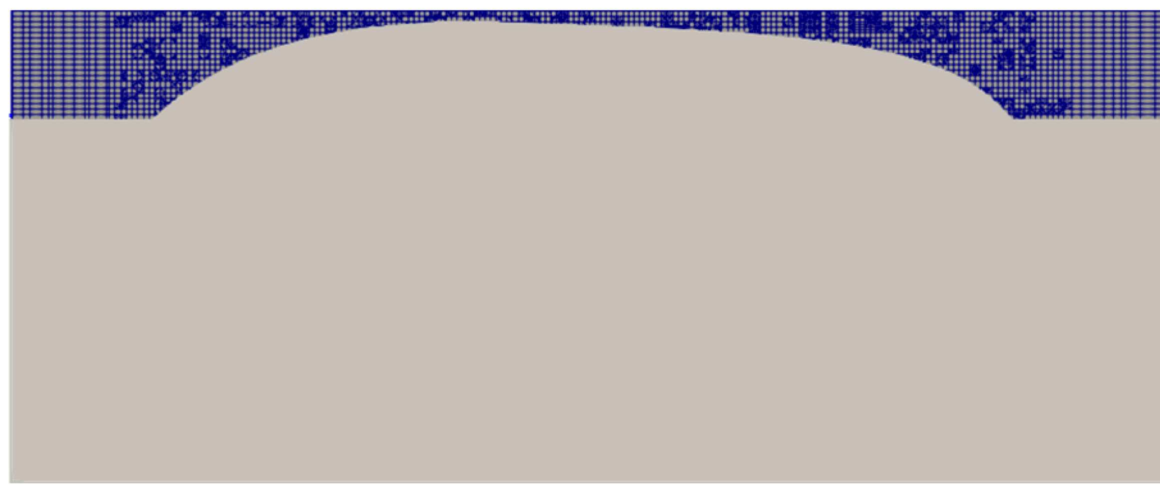




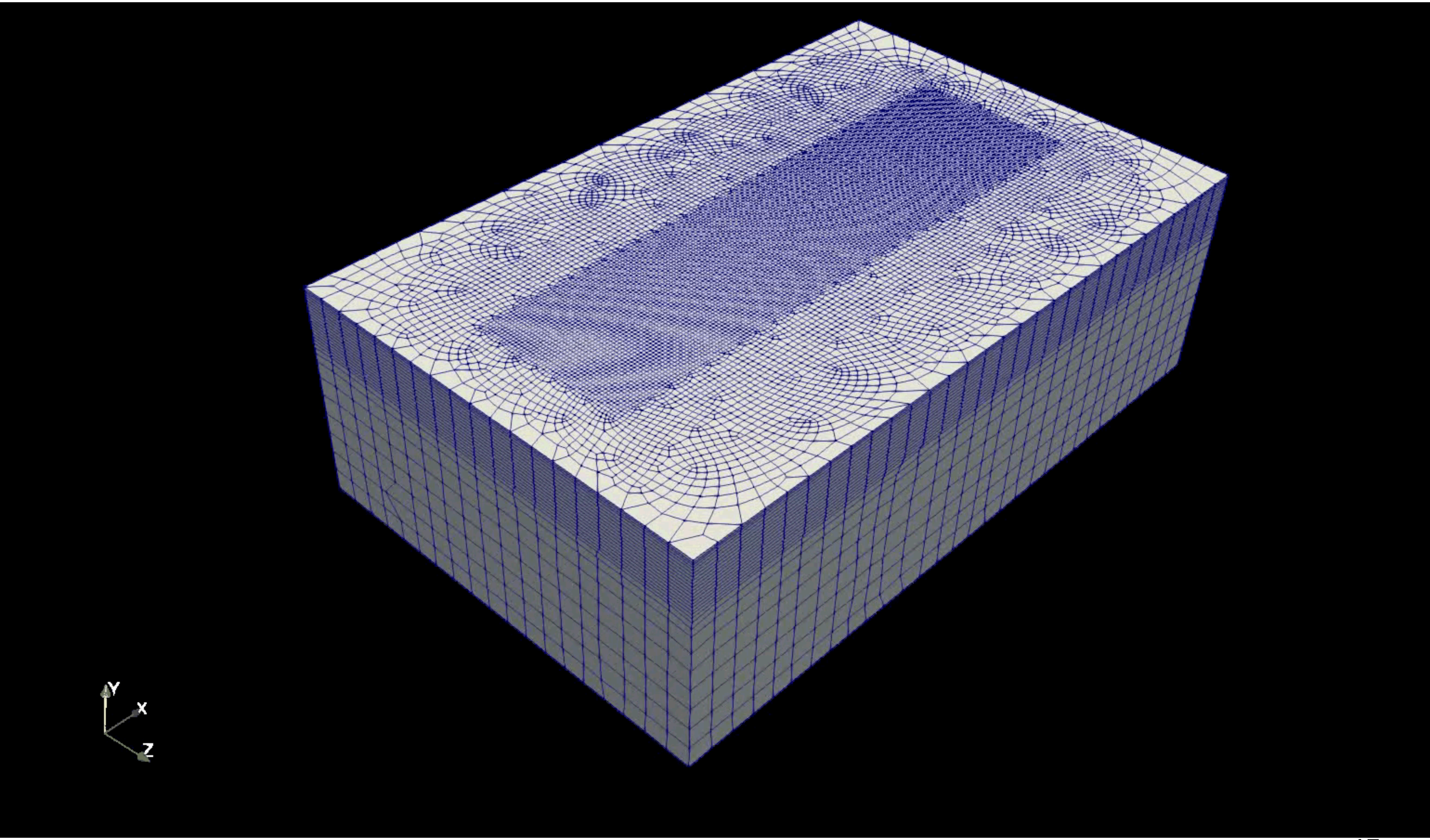








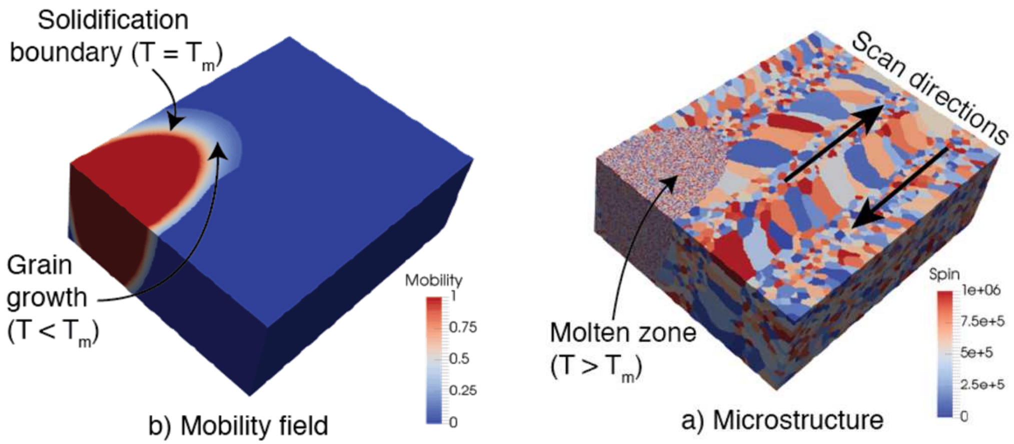
High Quality Hex Mesh



The KMC method

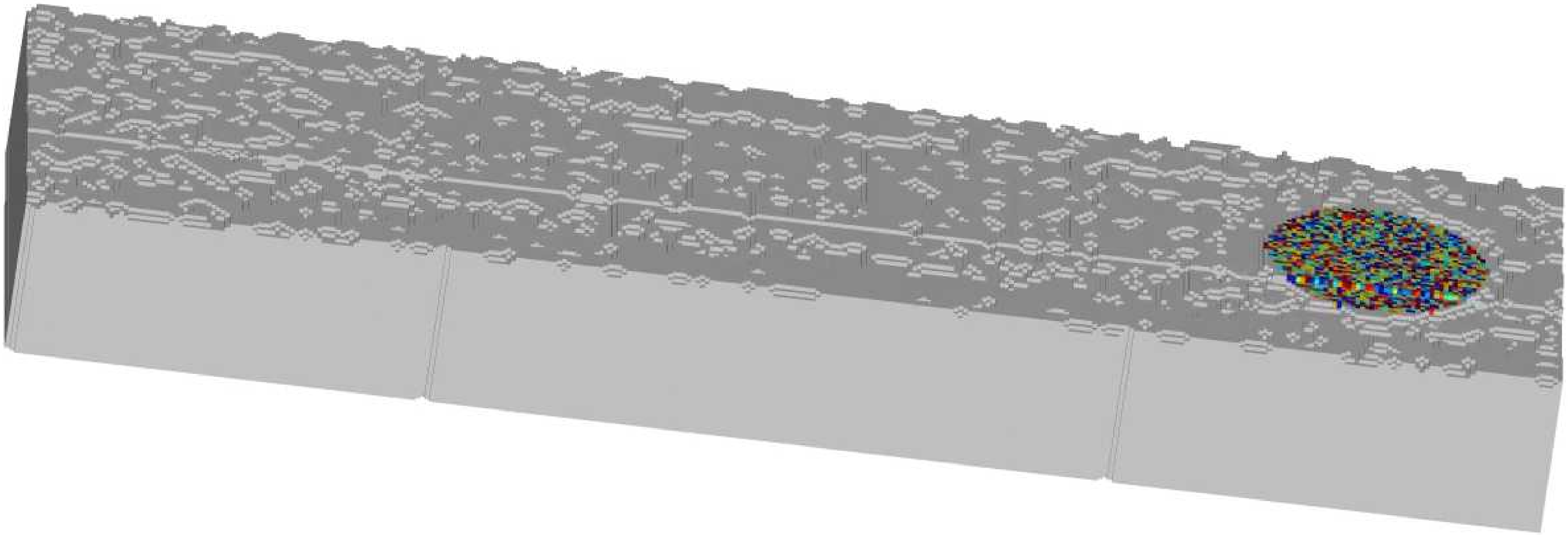
$$M(T) = M_o \exp\left(\frac{-Q}{RT}\right)$$

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

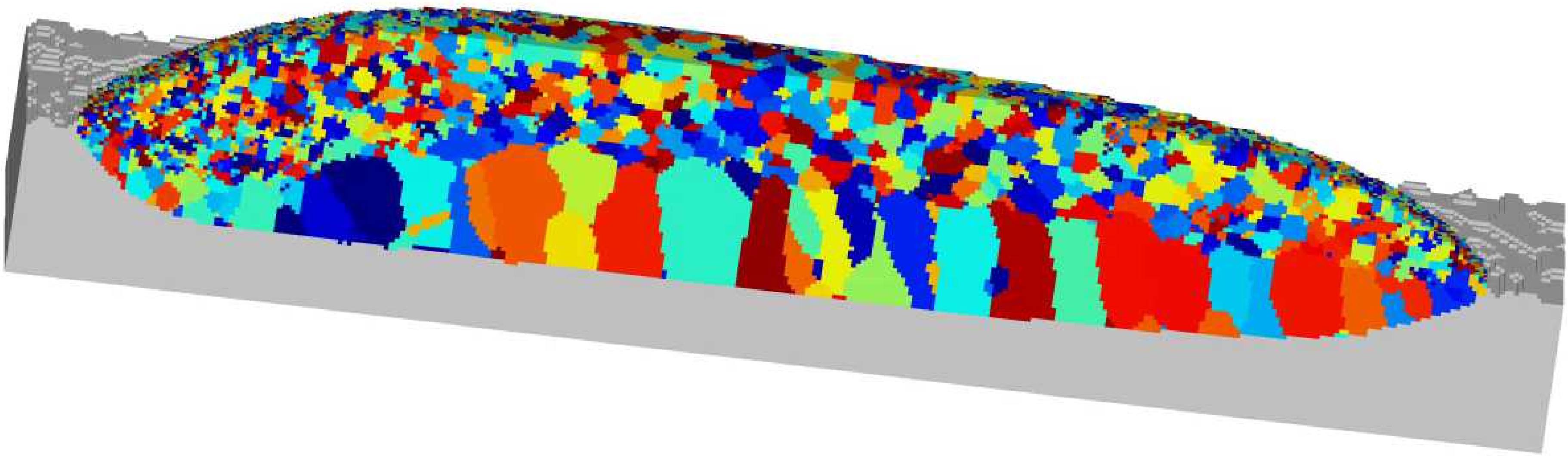


- The molten zone randomizes grain identities when it enters a region.
- Along the trailing surface, voxels either join existing columnar grains or form new grains.
- The temperature gradient creates a corresponding gradient of grain boundary mobilities via an Arrhenius relationship.

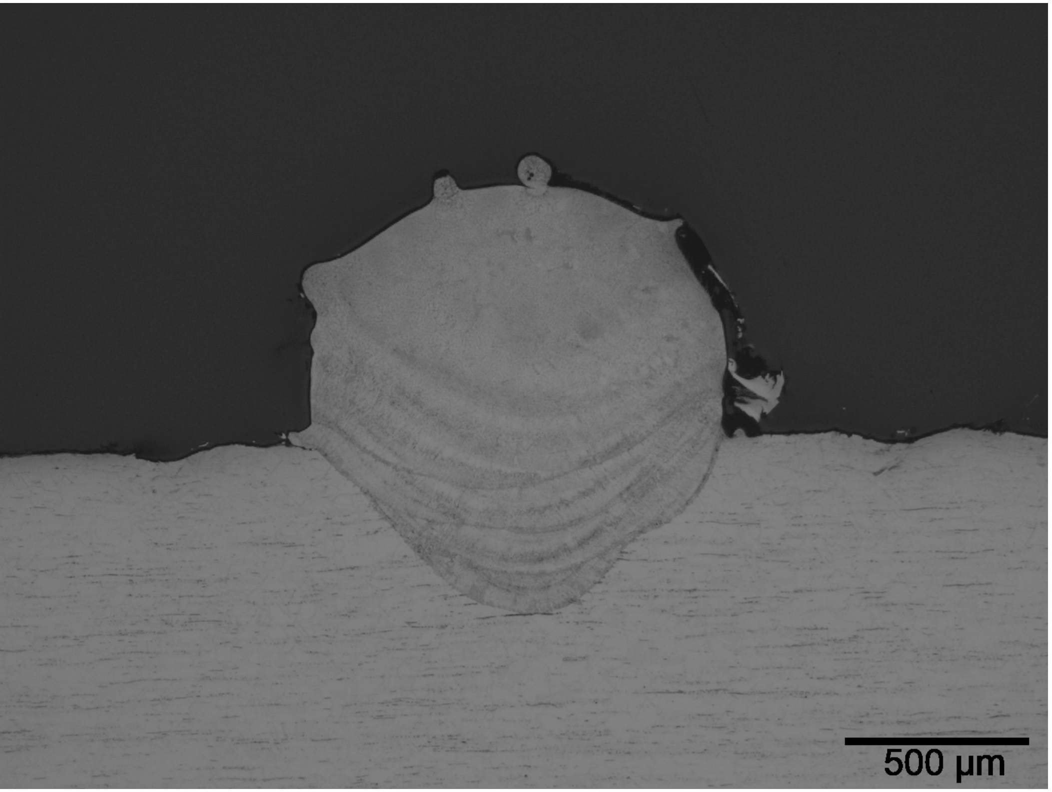
Micro Structure



Micro Structure Cross Section

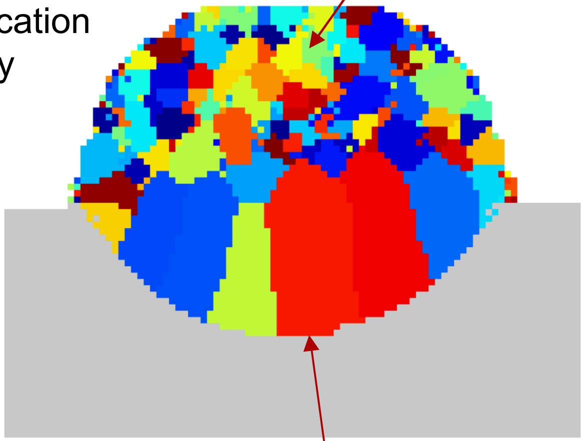


Microstructure Data Compared to Model



The top has the slowest solidification velocity

Equiaxed

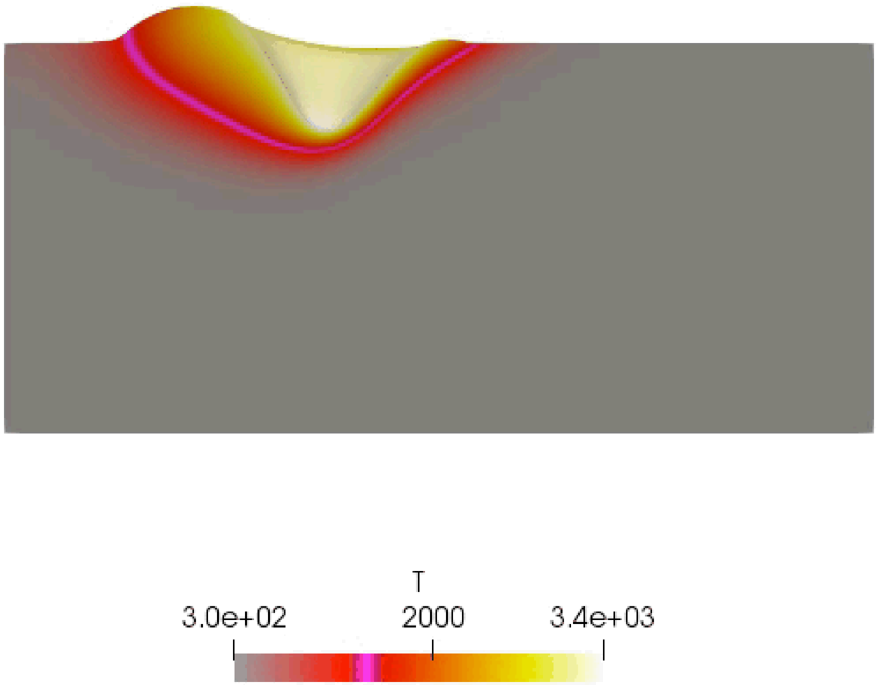


Columnar

After the first pass the grains are all equiaxed. When it gets remelted it begins to grow columnar grains because your solidification velocity higher (the boundary between the molten zone and the solid part of the material how fast that moves). The grains from the first pass seed the new growth and that causes a column. In the previously melted stuff there are nucleation sites.

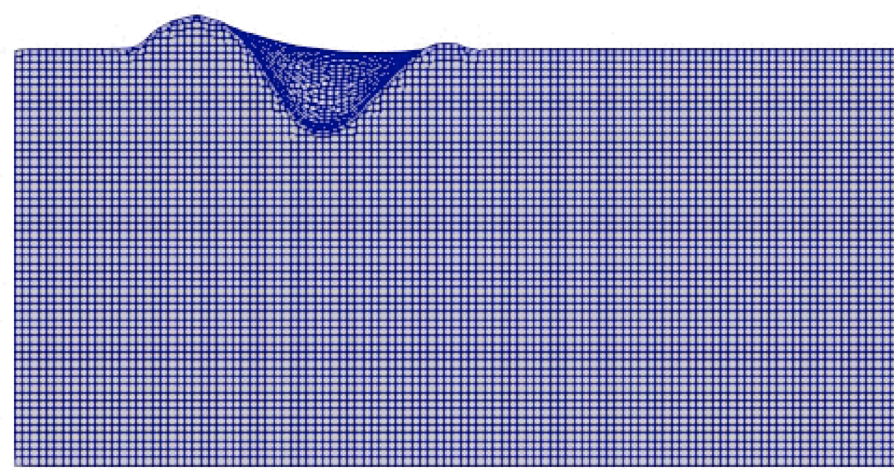
Every grain has a spin that is randomly assigned in the molten pool. At the solid liquid interface the spins are adjusted to minimize surface energy of the grain they are a part of. According to the Potts Monte Carlo Method. Spin refers to an arbitrary energy defined between each representative volume. The energy is based on how the local representative volumes compare to one another. In the pool the energy can be anything from 0 to 1e5. Which suggests that tehre are 1e5 unique nucleation grains. The number or spin is an identifier or a grain i.d. Its more energetically favorable to have common neighbors because your potential energy is minimized. The potential energy is normalized.

Solid mechanics Couple

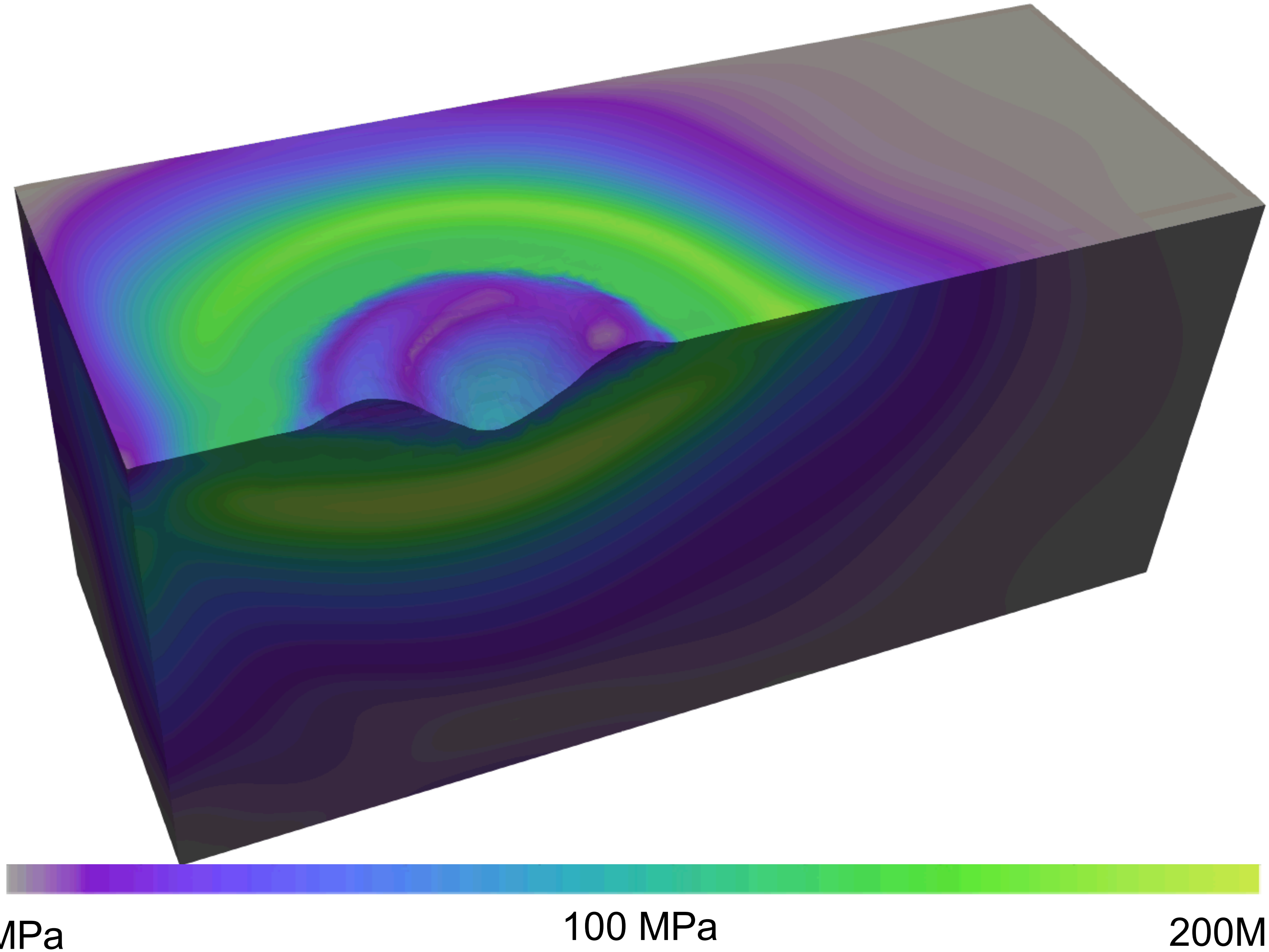


Map Temperature History to conformal mesh of CDFEM geometry

Drastically reduce stiffness of “melted Elements



Process Stress Predicted by Model



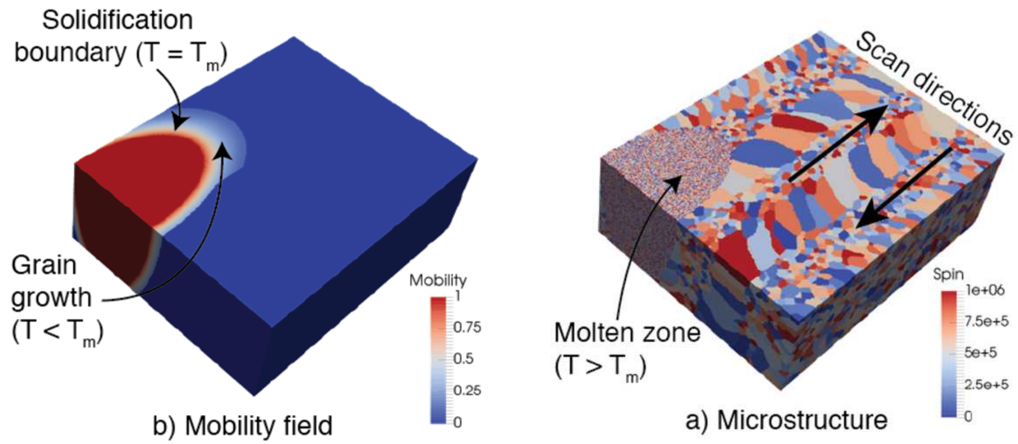
Conclusion

- Neglecting fluid mechanics leads to incorrect morphology
- CDFEM mesh can be converted to a Hex mesh using sculpt
- Mapped temperature history has been used to generate a microstructure that compares well with experimental measurements
- Temperature histories can be used to map a residual stress

The KMC method

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

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

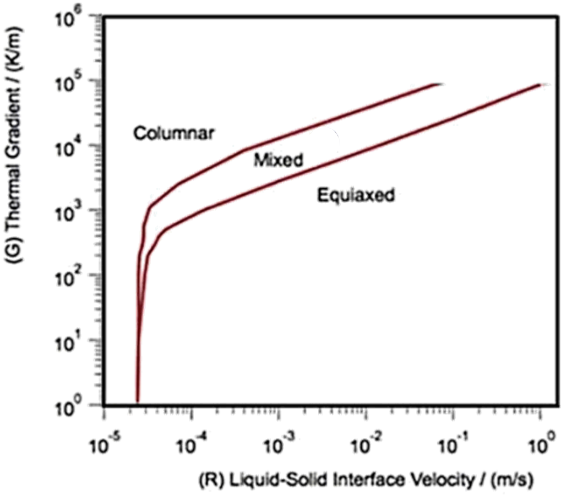


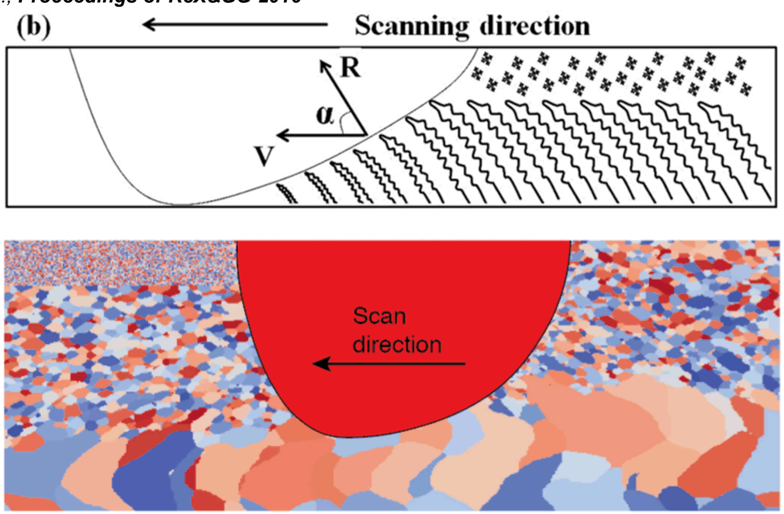
- The molten zone randomizes grain identities when it enters a region.
- Along the trailing surface, voxels either join existing columnar grains or form new grains.
- The temperature gradient creates a corresponding gradient of grain boundary mobilities via an Arrhenius relationship.

Columnar vs equiaxed microstructures

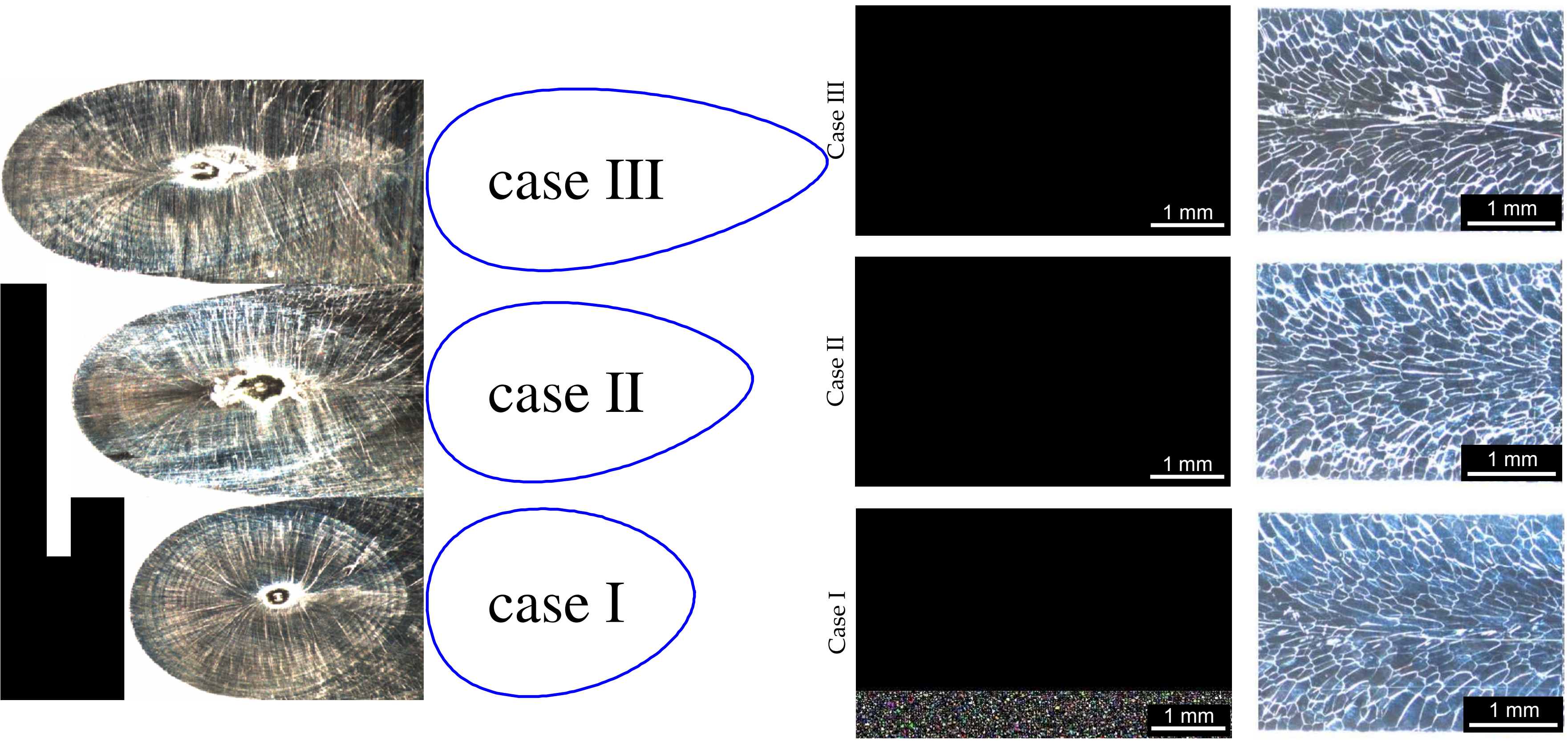
- Solidification grain morphology can be predicted through the ratio of temperature gradient (G) and solidification front velocity (R).
- For many melt pool geometries, G is smaller at the top (where curvature is lowest) and larger at the bottom. Resulting in smaller, equiaxed grains at the top and larger, columnar grains at the bottom.

Wei et al., ***Proceedings of ReX&GG 2016***



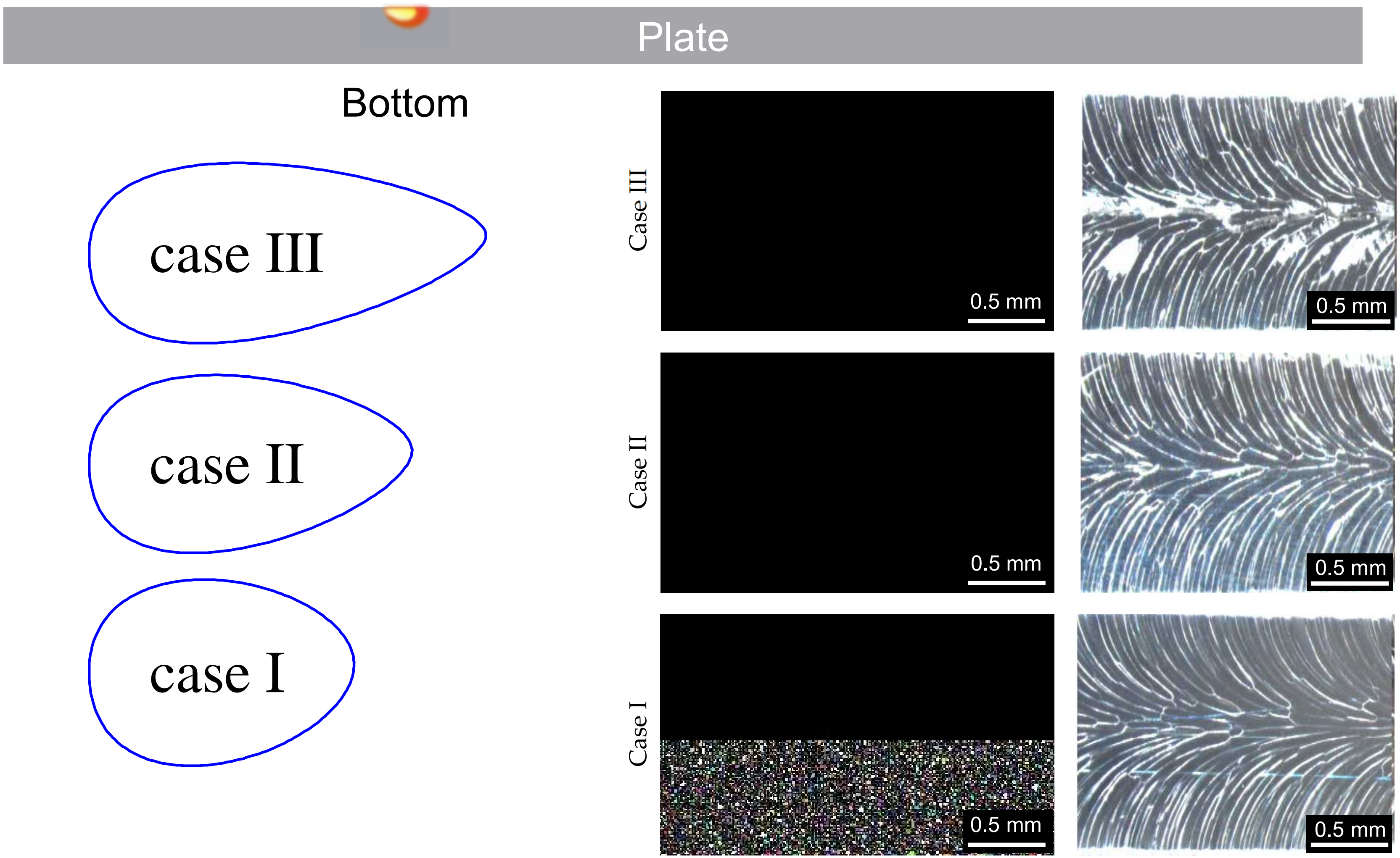


Grain Shape Sensitivity to Melt Pool



Rodgers et al., MSMSE 2017

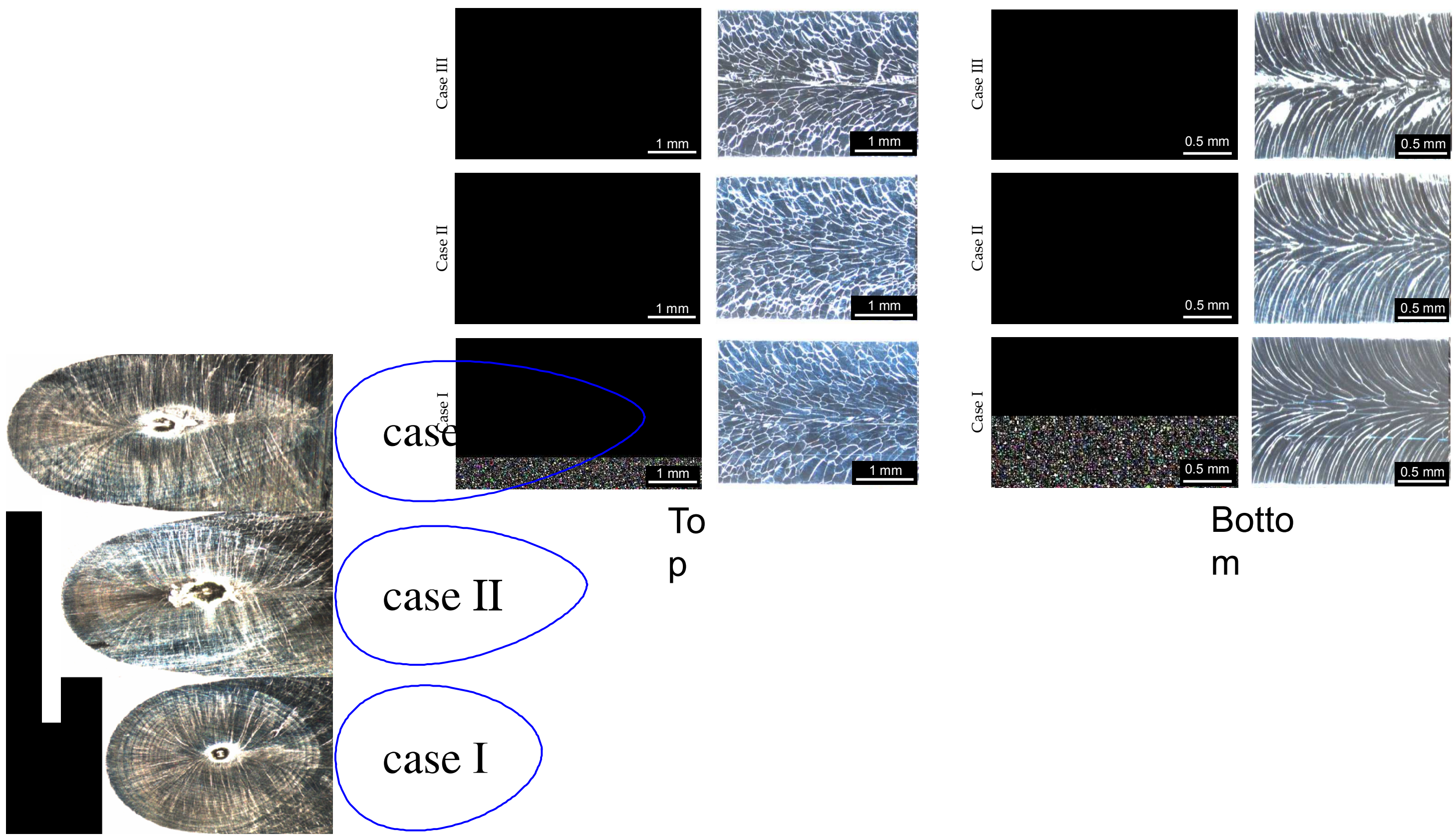
Grain Shape Sensitivity to Melt Pool



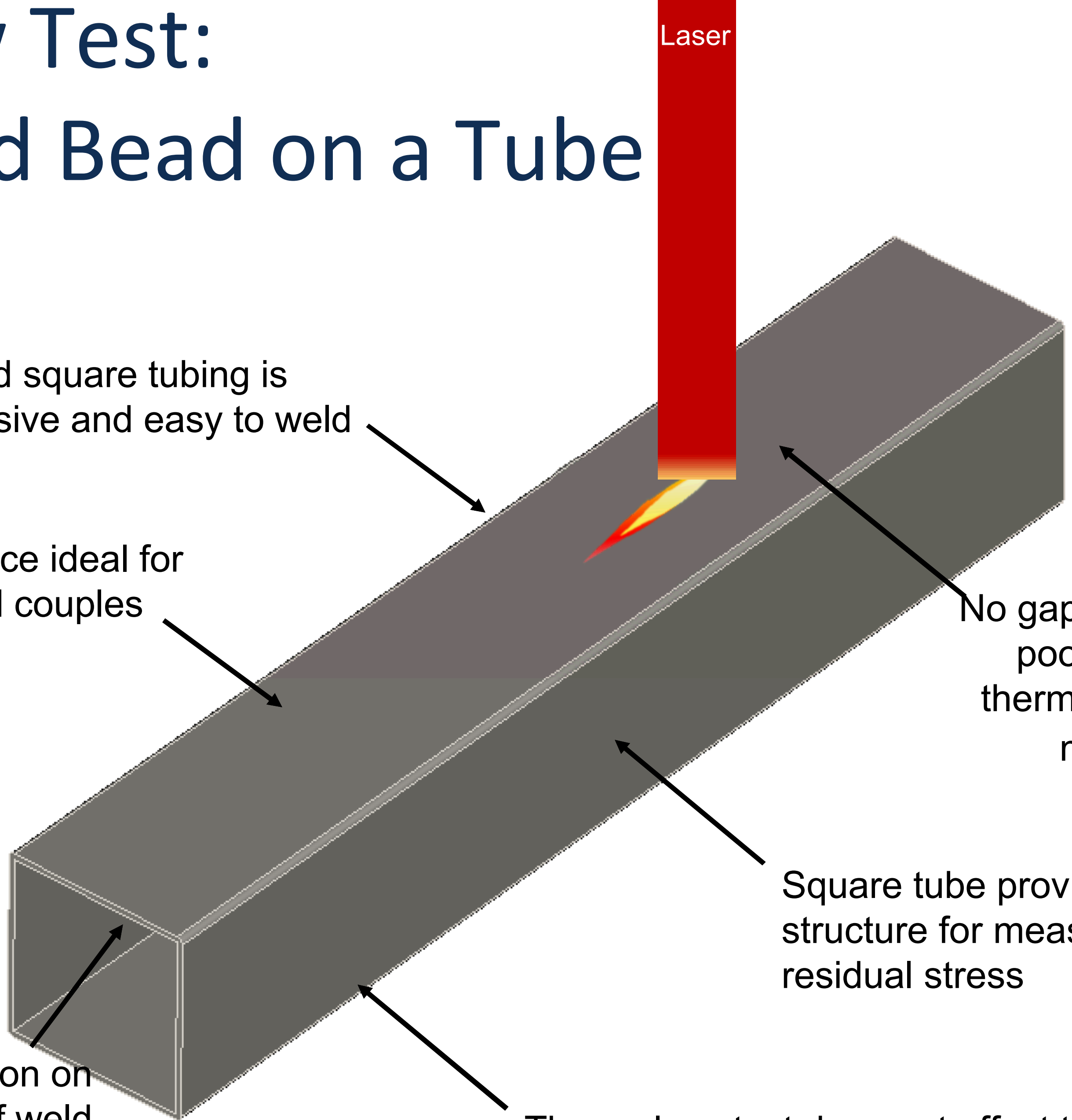
Rodgers et al., MSMSE 2017

Application to welding

Rodgers et al., MSMSE 2017



New Test: Weld Bead on a Tube



Standard square tubing is Inexpensive and easy to weld

Large flat surface ideal for placing thermal couples

No gap ahead of the melt pool creating complex thermal interactions and mechanical contact

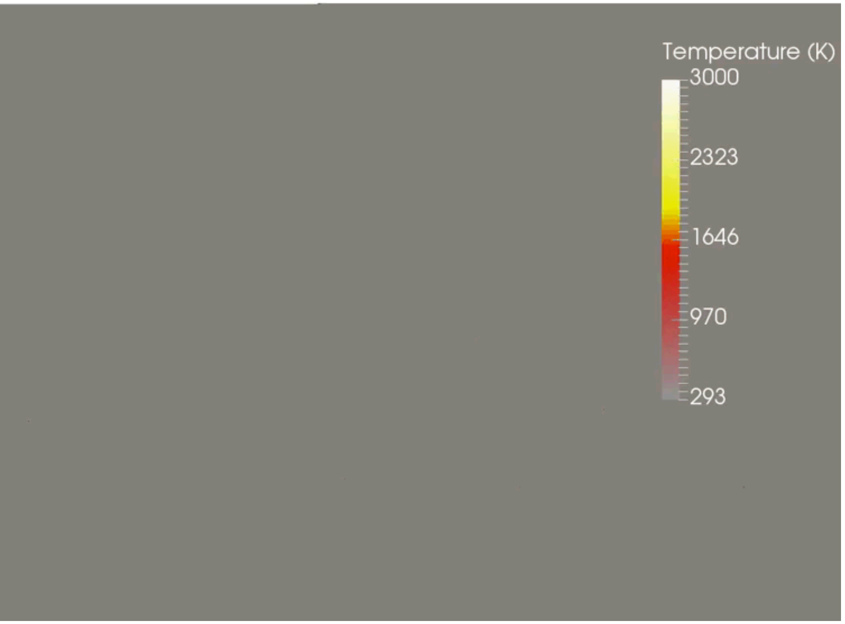
Square tube provides a stable structure for measuring distortion and residual stress

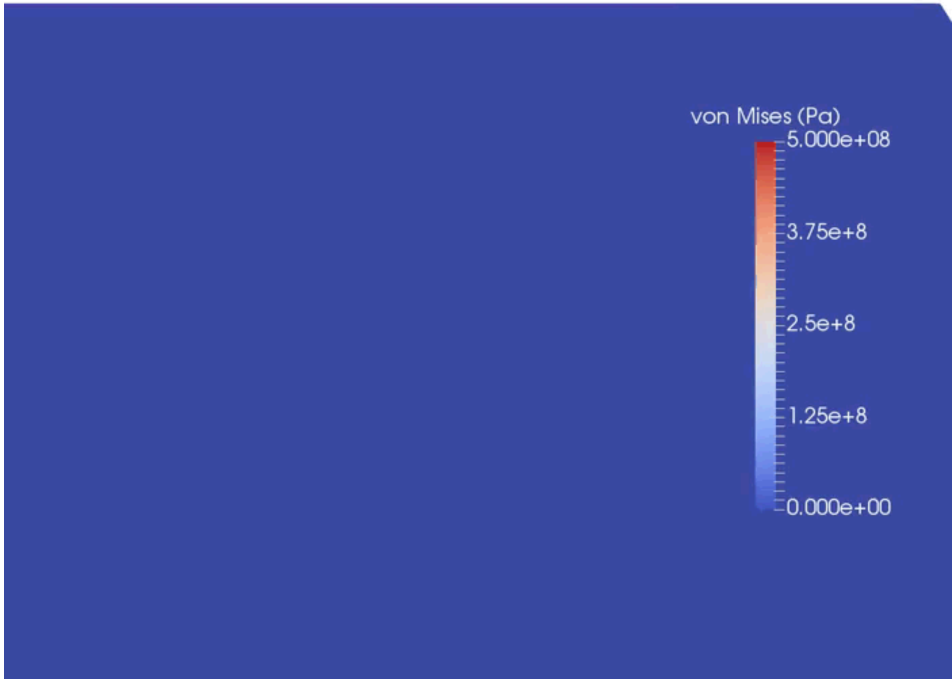
Convection on opposing side of weld is simple to model

Thermal contact does not affect the temperature distribution created by the weld

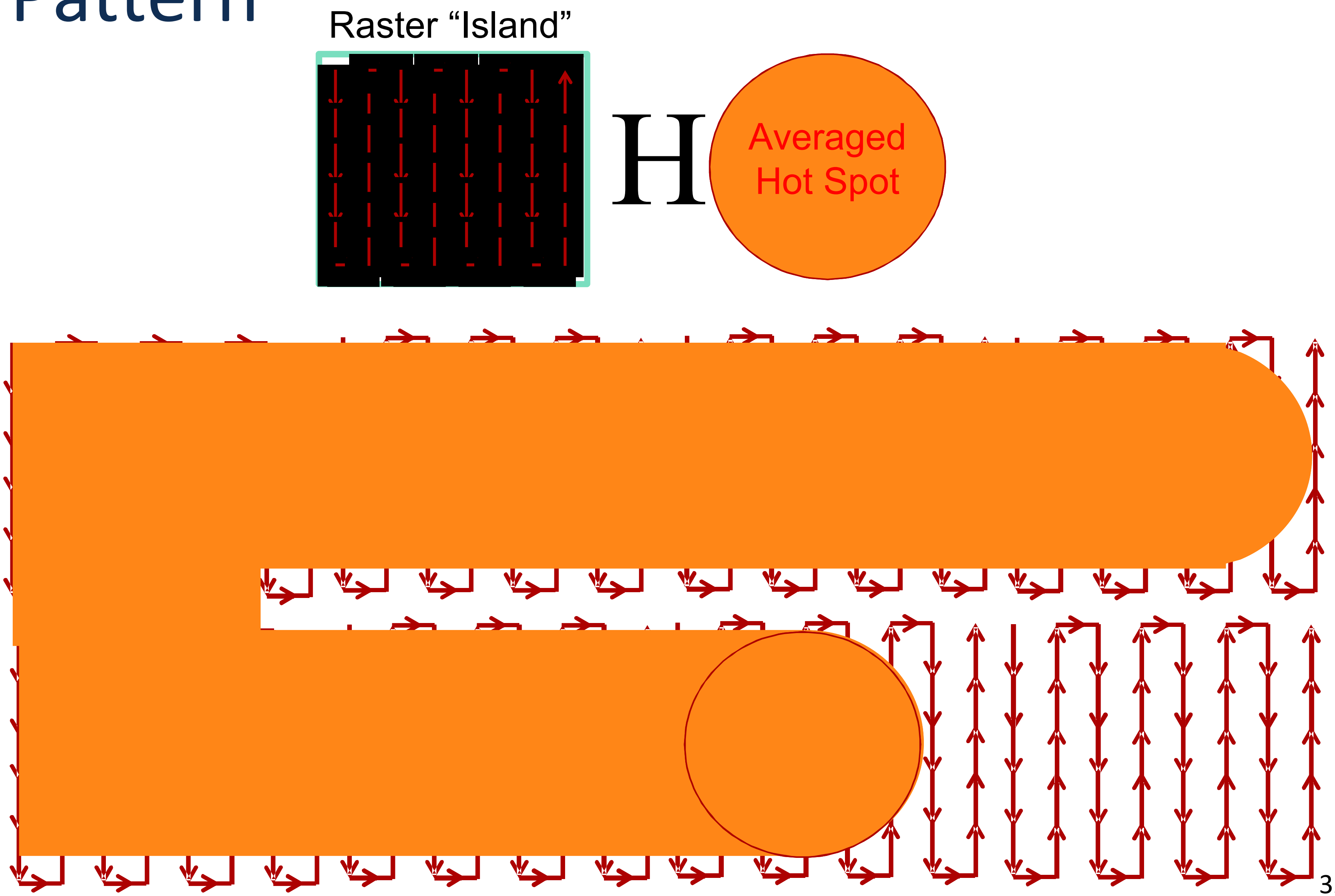
Hot Spot to Approximate Melt Pool

Time: 0.00 s

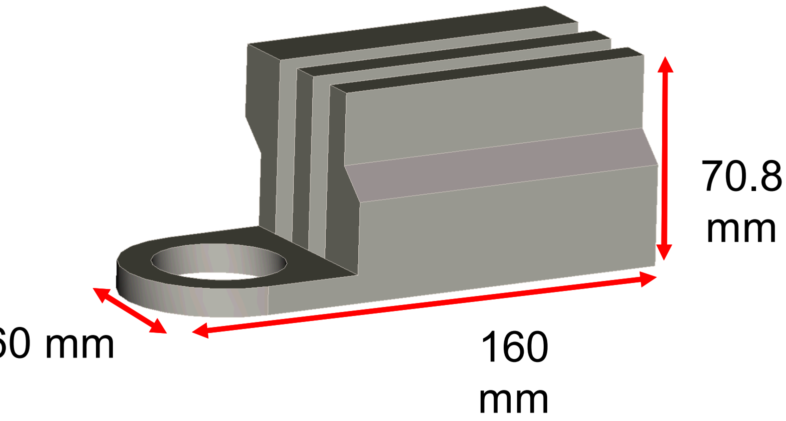


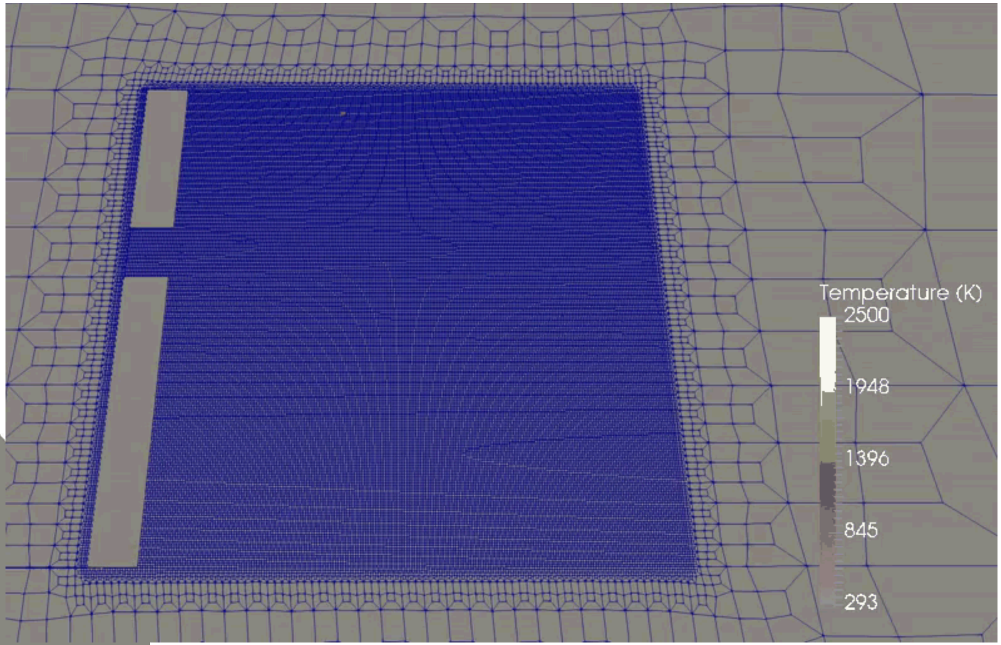


Hot Spot to Approximate Raster Pattern



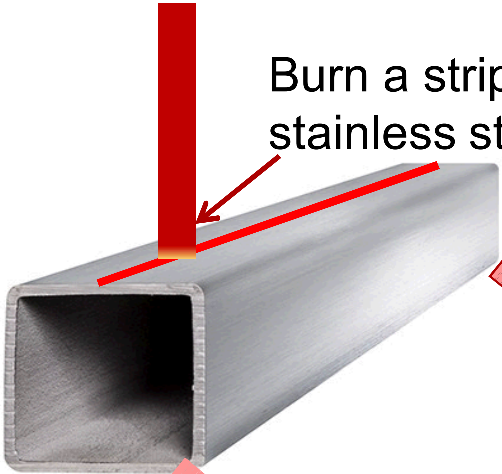
Hot Spot to Approximate Raster Pattern



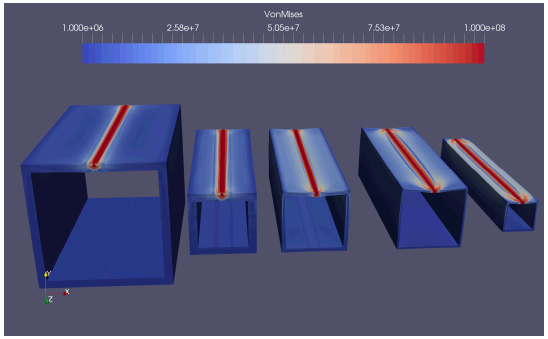


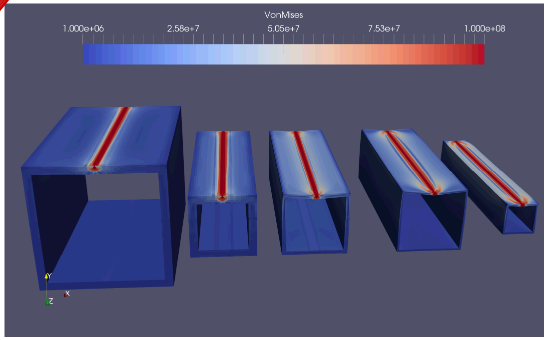
Model a Bead with Both Methods

Burn a strip into a stainless steel tube

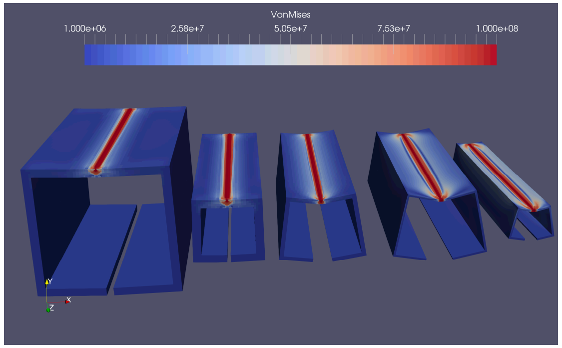


Model Stress of Bead with a part solid thermal model



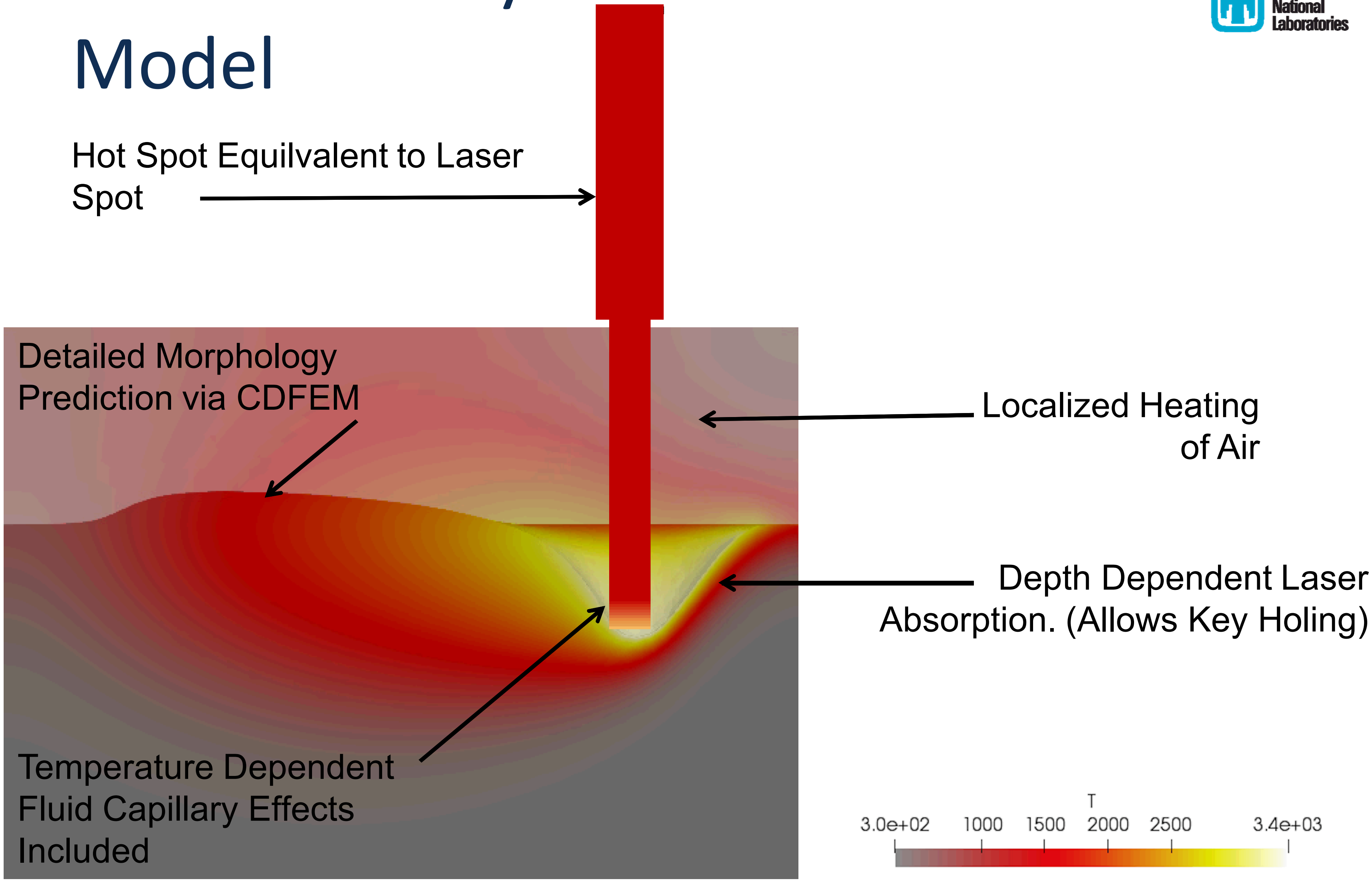


Model Stress of Bead with a meso scale fluid model



Measure Stress Experimentally

Additional Physics in Meso Scale Fluid Model



Additional Physics in Meso Scale Fluid Model Continued

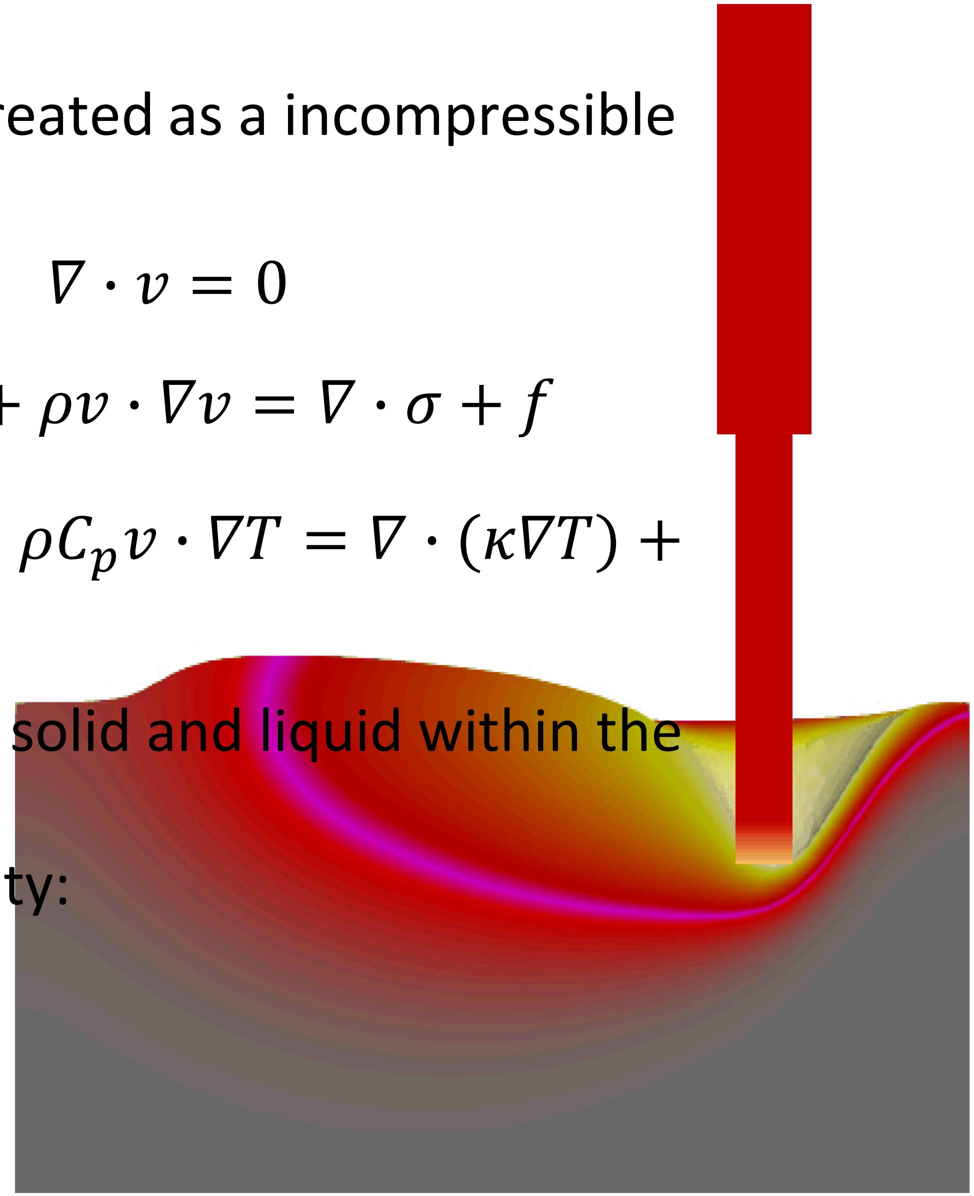
- The entire metal medium is treated as a incompressible liquid:

Continuity: $$\nabla \cdot v = 0$$

Momentum: $$\rho \frac{\partial v}{\partial t} + \rho v \cdot \nabla v = \nabla \cdot \sigma + f$$

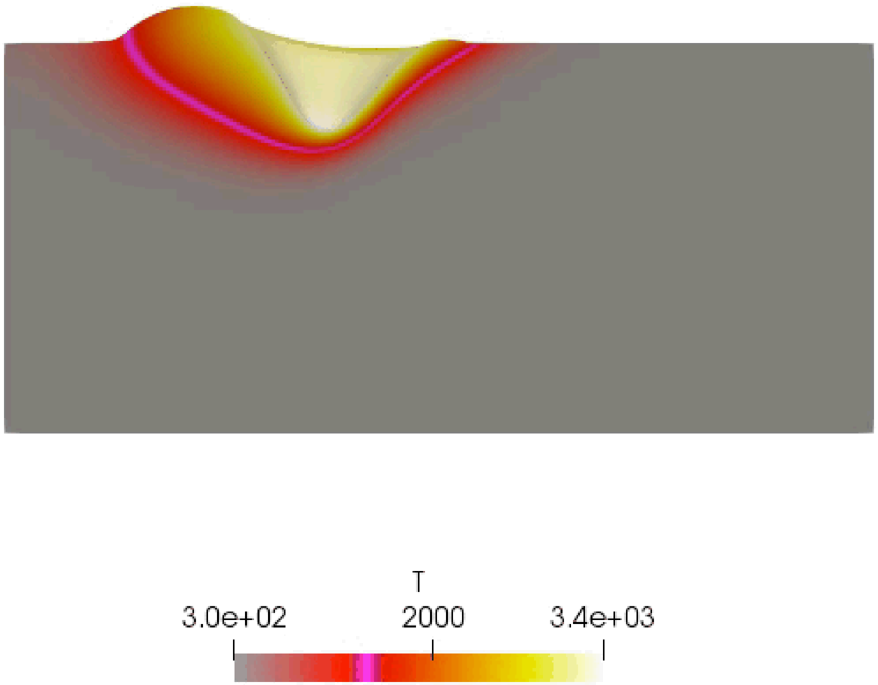
Energy: $$\rho C_p \frac{\partial T}{\partial t} + \rho C_p v \cdot \nabla T = \nabla \cdot (\kappa \nabla T) + H_v$$

- Phase transition between the solid and liquid within the metal
is handled through the viscosity:



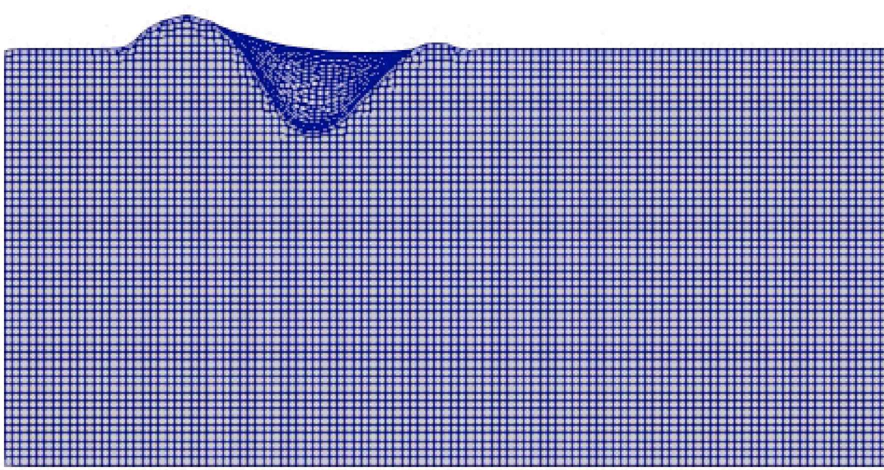
Solid Liquid phase transition created Sudden Increase in Viscosity at Melt Temperature

Solid mechanics Couple

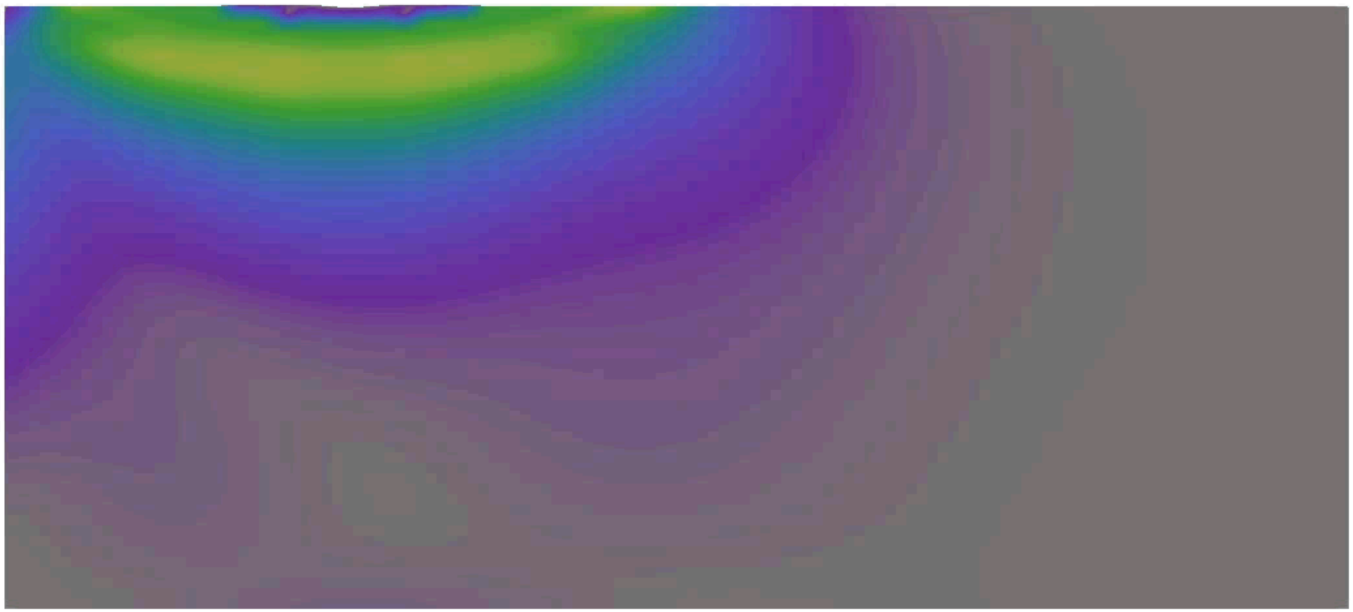


Map Temperature History to conformal mesh of CDFEM geometry

Drastically reduce stiffness of “melted Elements

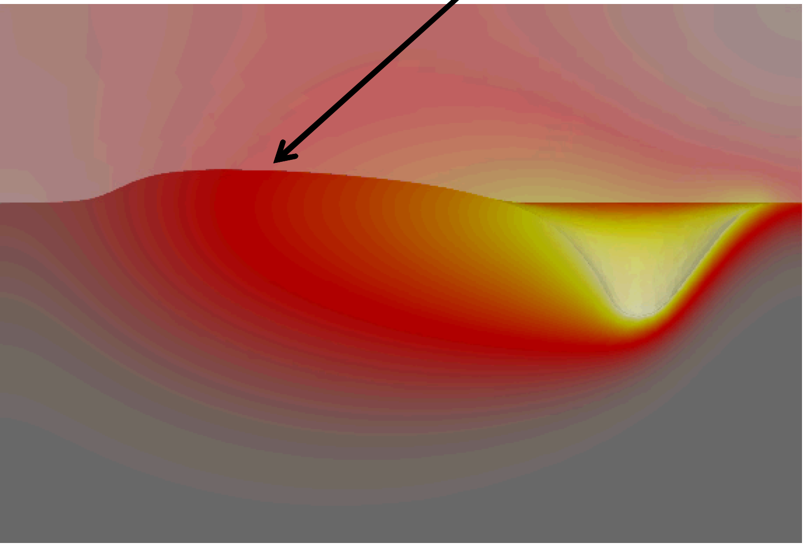


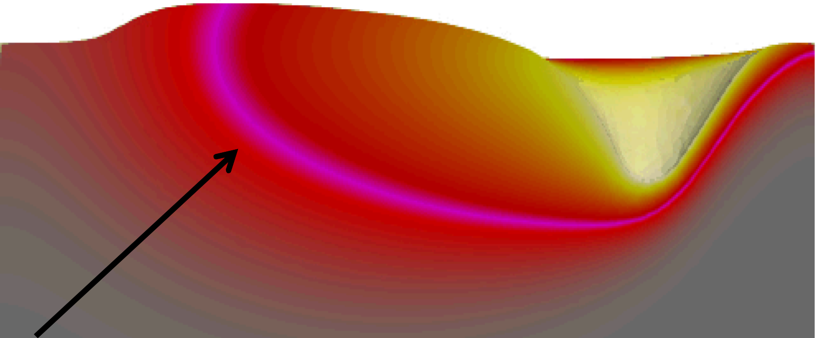
Residual Stress Predicted By Fluid Model



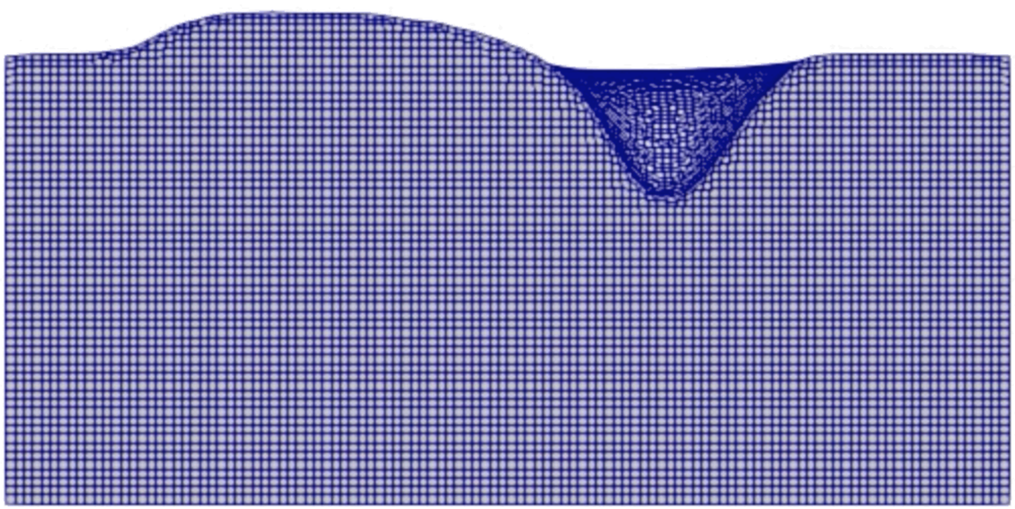
Residual Stress from Fluid Model

Fluid model predicts an evolving gas boundary



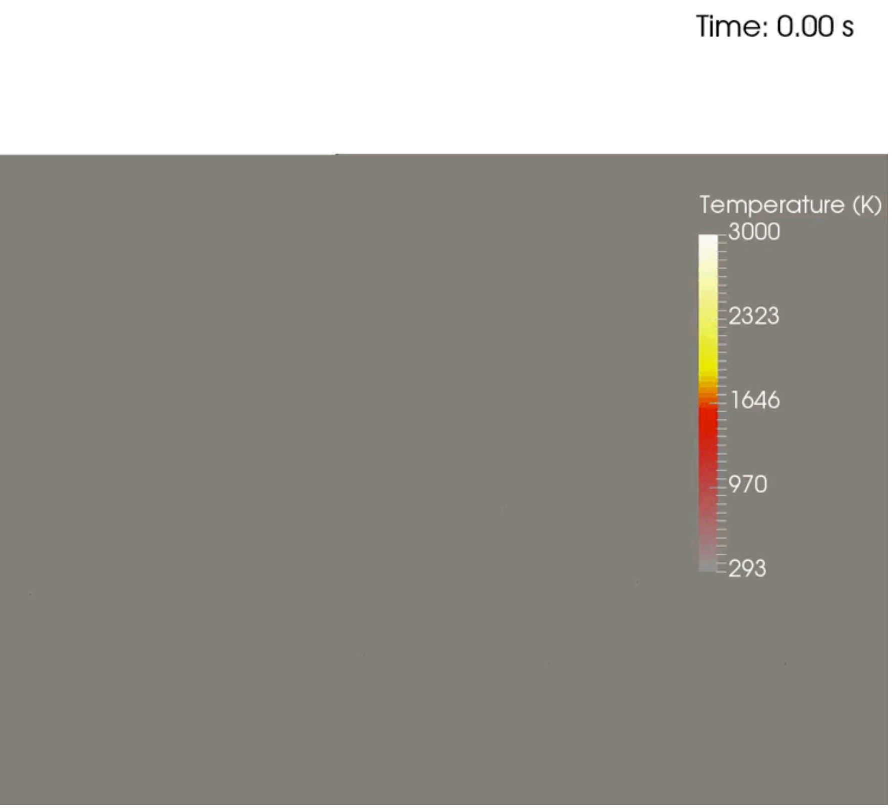


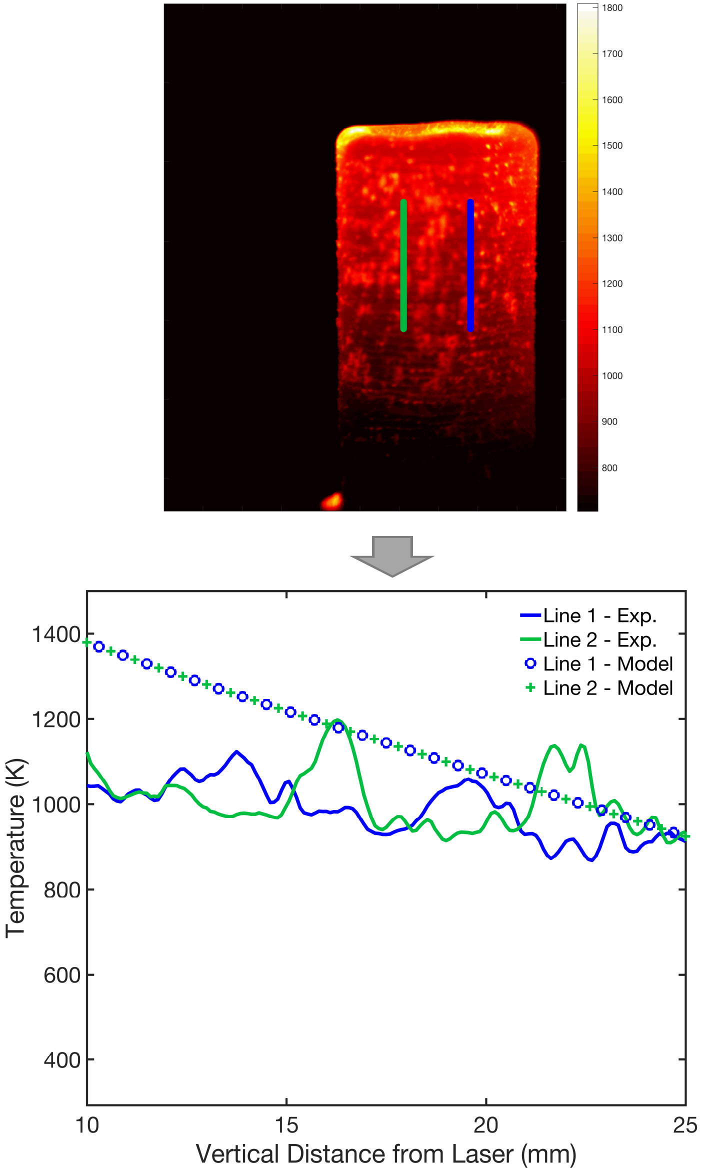
Fluid contains a solidus wave front where material



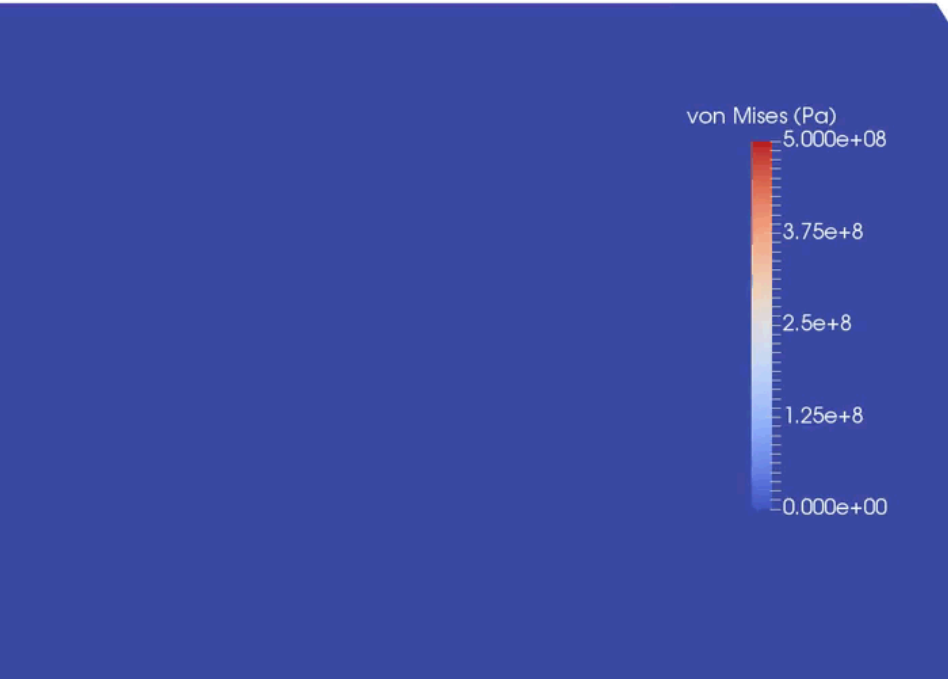
Generate a Lagrangian mesh from fluid model results to use for Solid mechanics calculation. Element stiffness transitions from soft to stiff based on the solidous wave front.

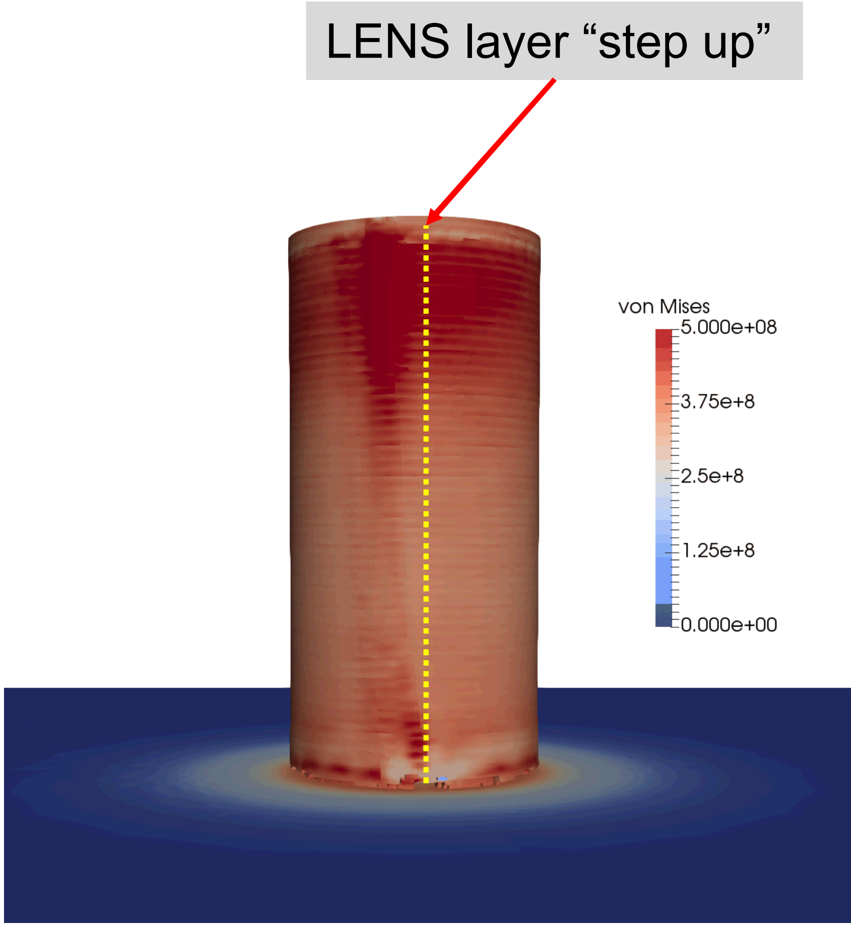
Experimental Comparison - Thermal



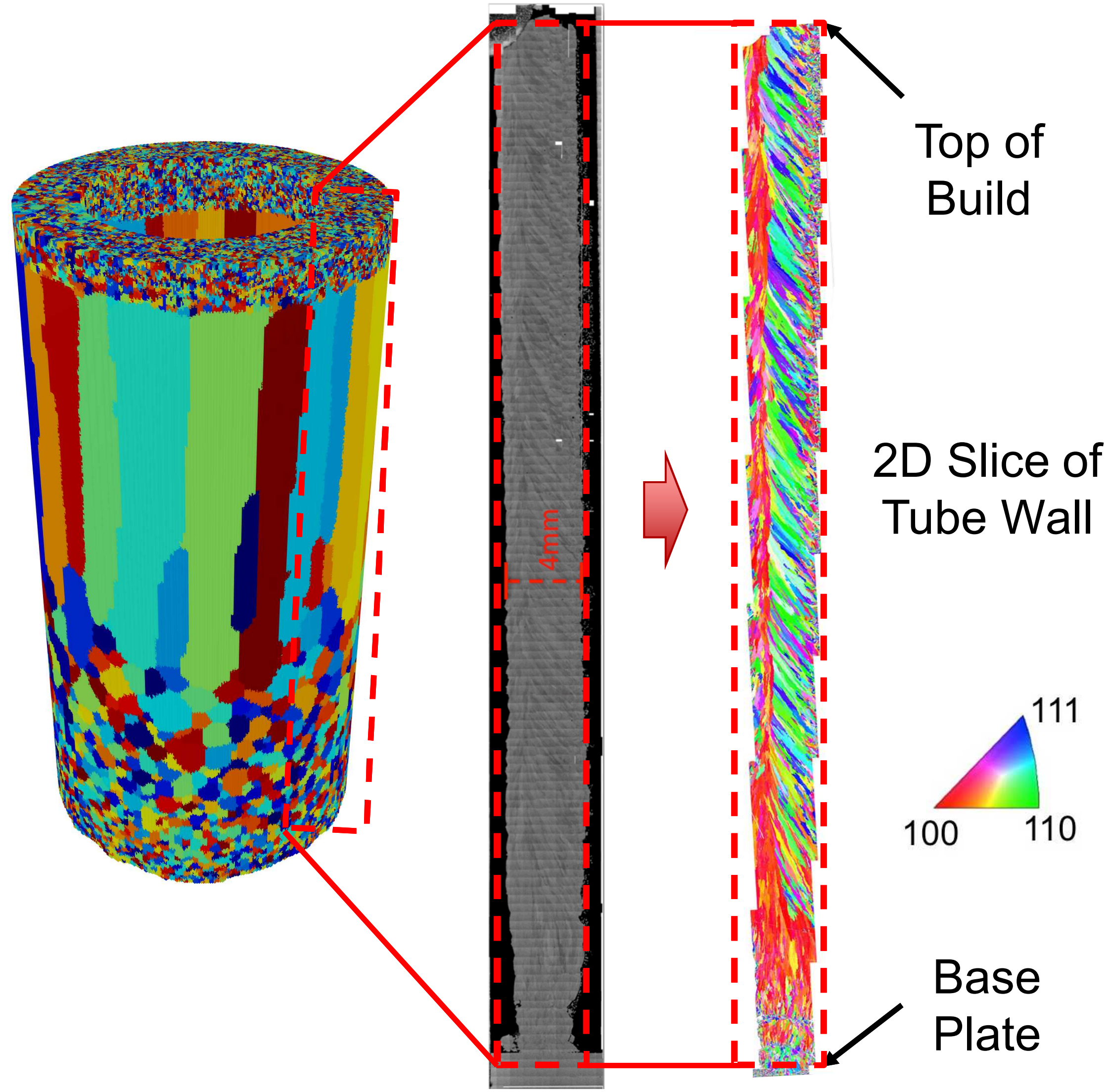


Experimental Comparison - Residual Stress





Experimental Comparison - Microstructure



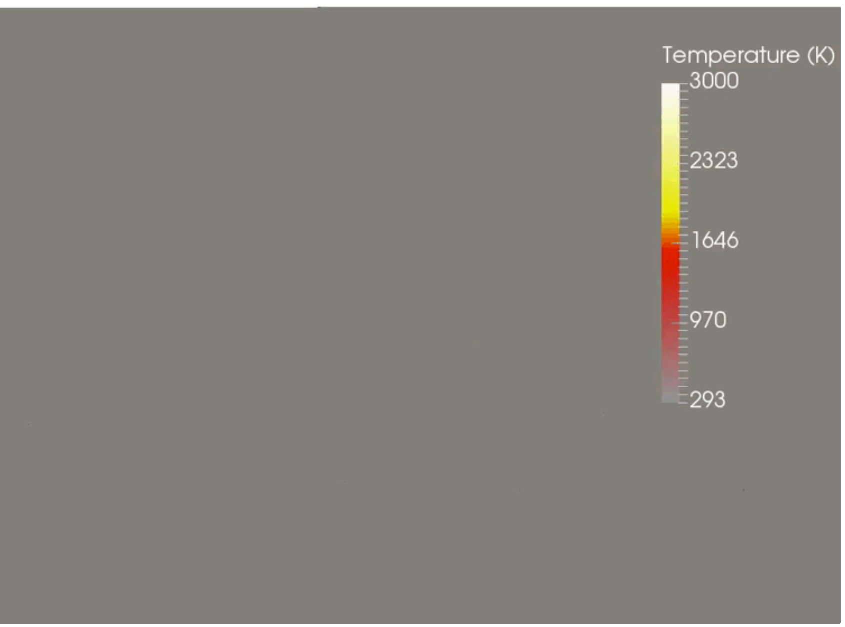
EBSD: O. Underwood, J. Madison, A. Kilgore, J. Michael, S. Dickens

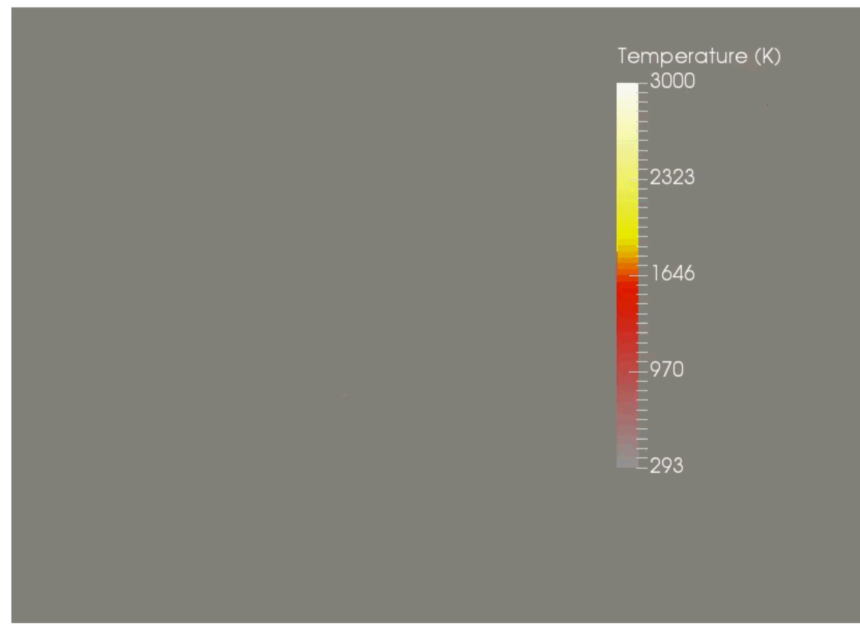
Thermal Comparison

Single Build

Double Build – 8 Second Inter-layer Delay

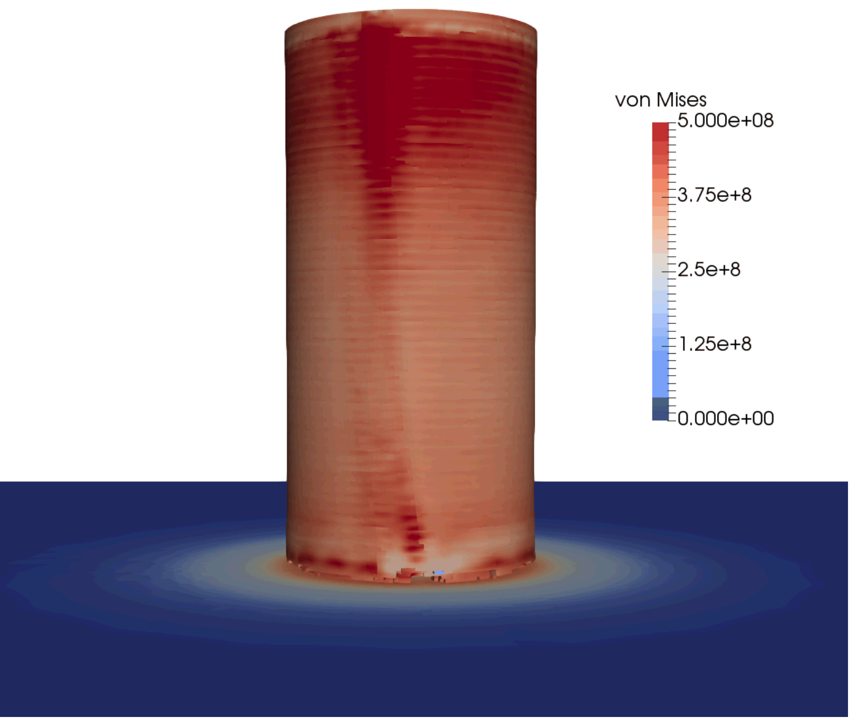
Time: 0.00 s



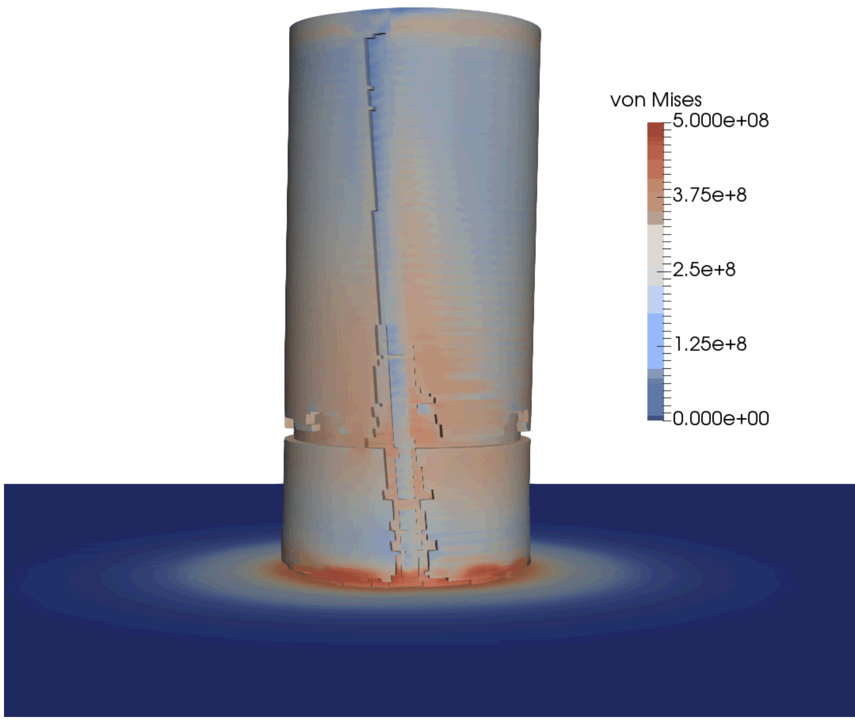


Delay time causes lower overall von Mises stress

Single Build

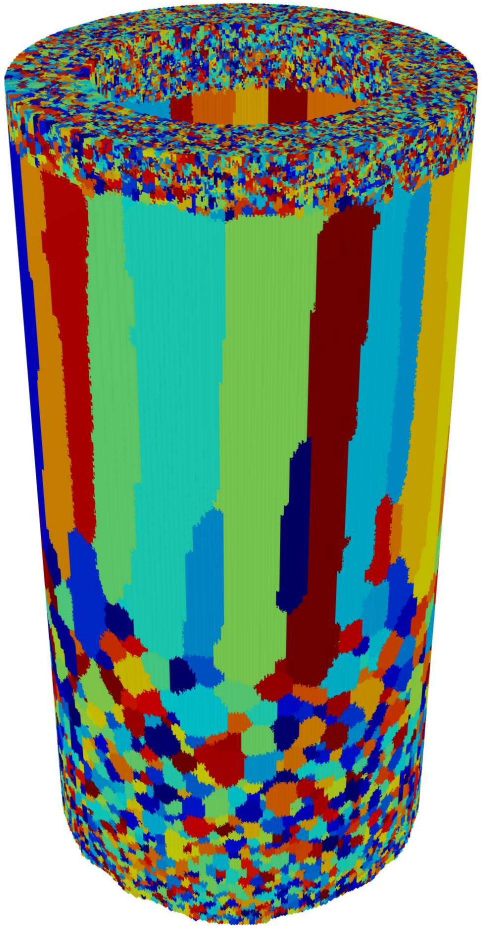


Double Build – 8 Second Inter-layer Delay

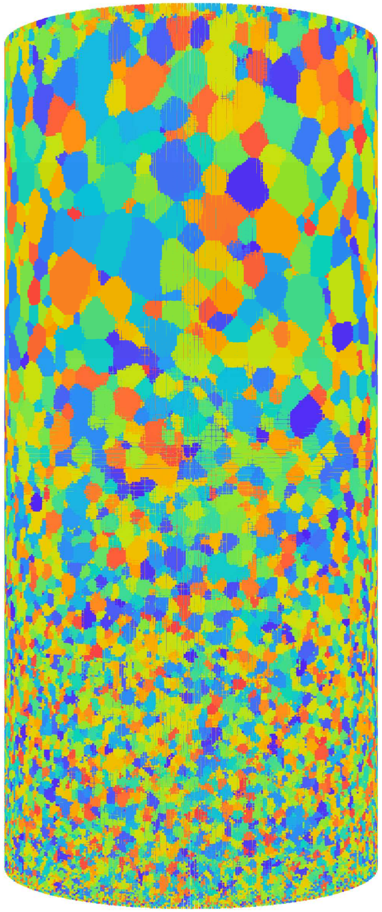


Delay time inhibits equiaxed to columnar transition

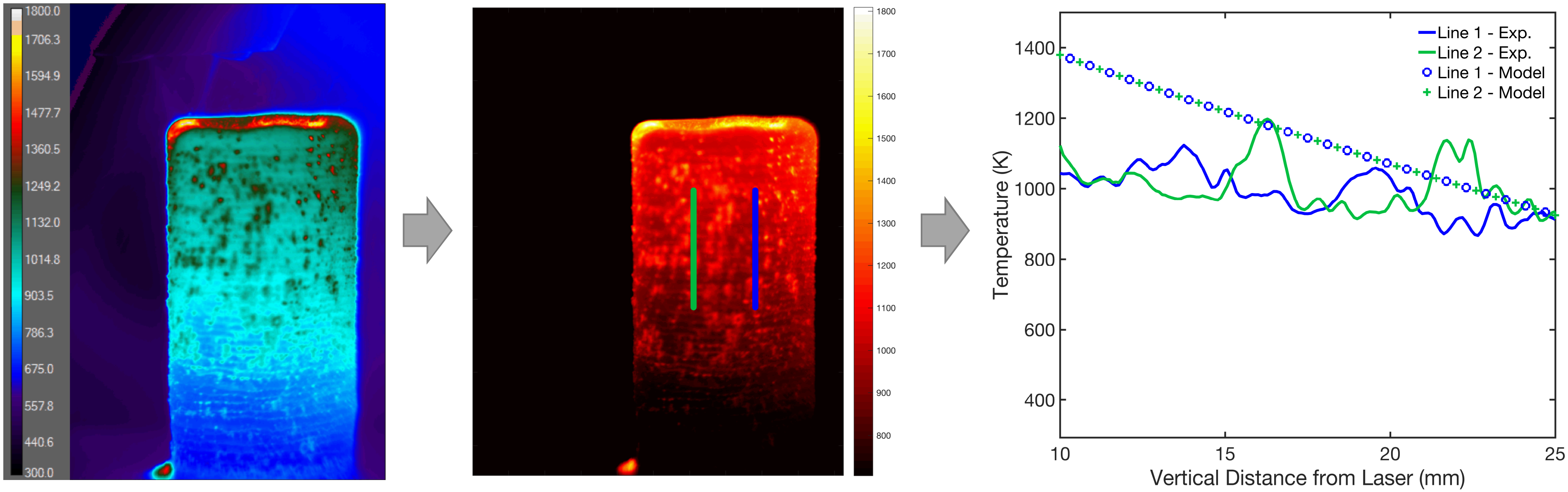
Single Build



Double Build – 8 Second Inter-layer Delay

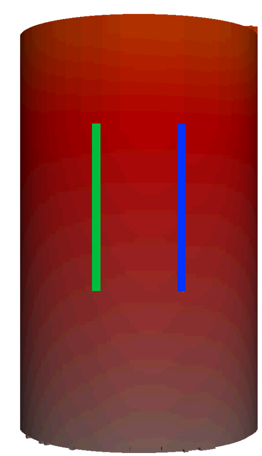


Comparison to IR Imaging



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

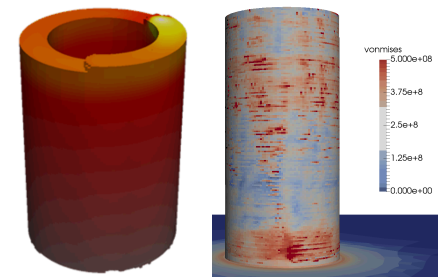
Simulation Results



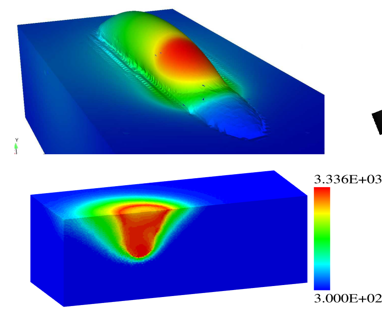
SNL Modeling Work

<u>Codes</u>
LAMMPS, SPPARKS, Sierra/Aria, Sierra/Adagio

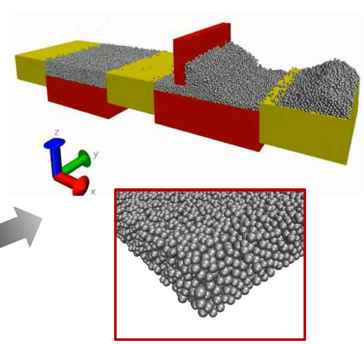
<u>Part Scale Thermal & Solid Mechanics</u>
Kyle Johnson, Kurtis Ford & Joe Bishop



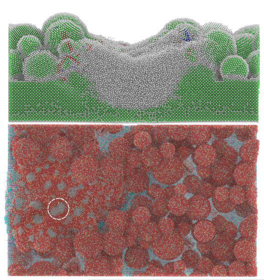
<u>Mesoscale Thermal Behavior</u>
Mario Martinez & Brad Trembacki



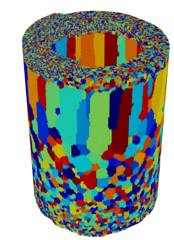
<u>Powder Spreading</u>
Dan Bolintineanu



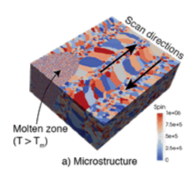
<u>Powder Behavior</u>
Mark Wilson



<u>Part Scale Microstructure</u>
Theron Rodgers



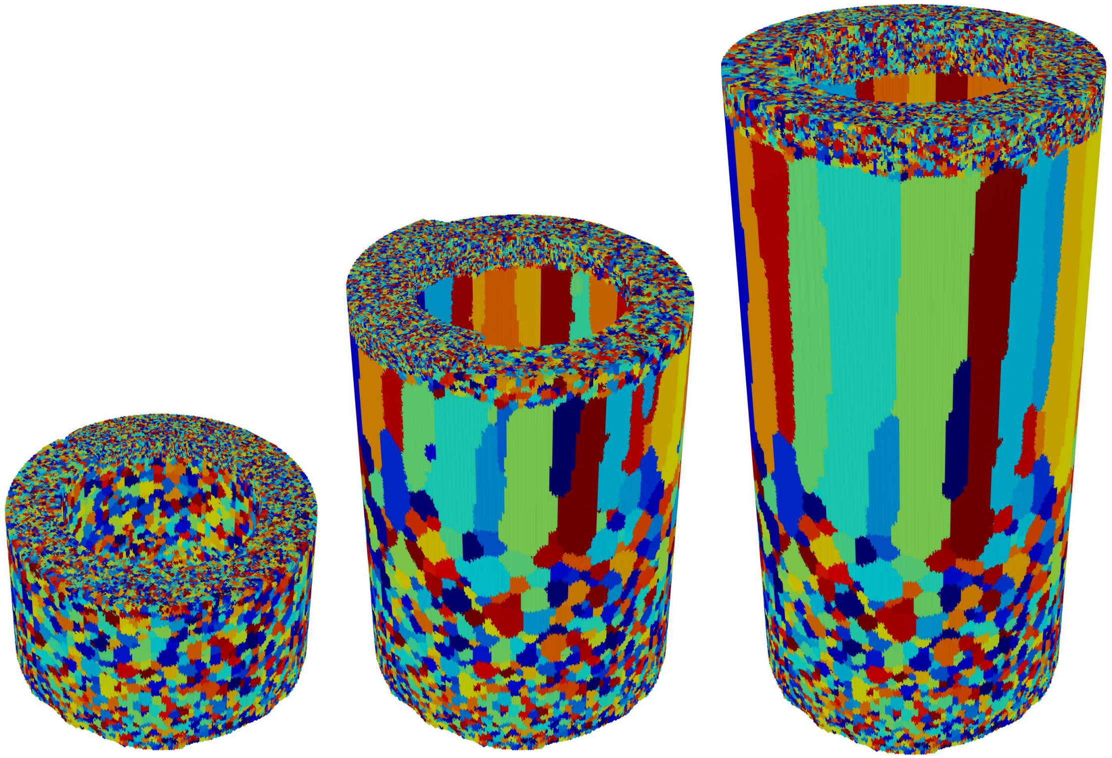
<u>Mesoscale Texture/Solid Mechanics/CX</u>
Judy Brown, Theron Rodgers and Kurtis Ford



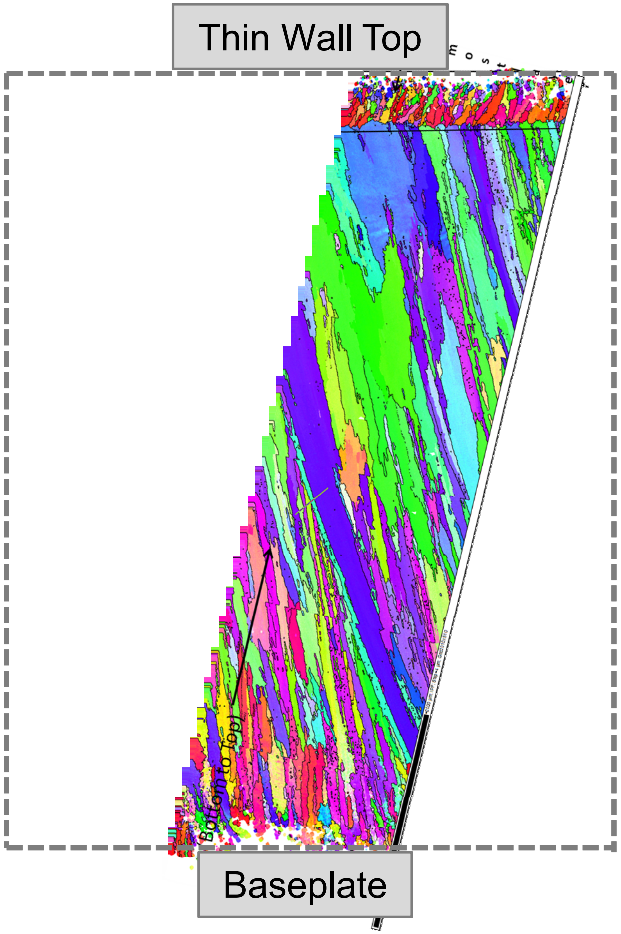
10^{-6} — 10^{-3} — 1

Length Scale (m)

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

- **Multi Scale Solid Mechanics Models of Additive Manufacturing**
- **Kurtis R. Ford, Bradley Trembacki, Kyle Johnson, David Noble, Mario Martinez, Joe Bishop**
  Sandia National Laboratories, Albuquerque, NM
-
- TMS 2018 Target Symposium: *Additive Manufacturing of Metals: Establishing Location-Specific Processing-Microstructure-Property Relationships*
- In this work a continuum-scale thermal/fluid model is coupled to a history-dependent elasto-viscoplastic internal state variable model of 304L stainless steel to predict the residual stress in an additively manufactured part. The thermal/fluid model tracks an evolving metal-gas interface with a conformal decomposition finite element method (CDFEM). The resulting bead shape and thermal history inform the elastic-viscoplastic constitutive model and a residual stress is calculated. These results are compared to a second more scalable model that does not represent the fluid mechanics of the melt pool explicitly. Instead, an idealized heat generation source is used with element activation to simulate element solidification on a larger scale. The two models are compared and contrasted with experimental data.
- Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. Unclassified Unlimited Release: SAND####