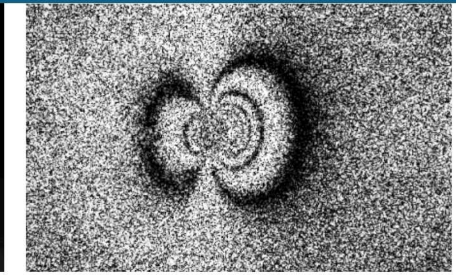
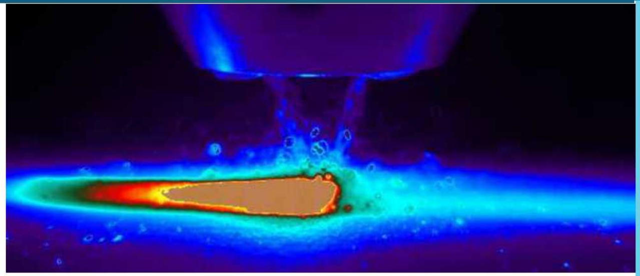
SAND2020-0914C

Toward Validation of Residual Stress Predictions in Additively Manufactured Parts: Destructive and Non-Destructive Characterization





PRESENTED BY

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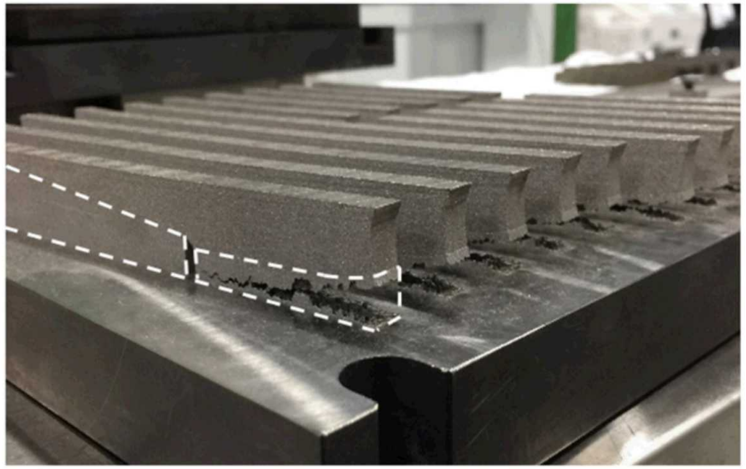
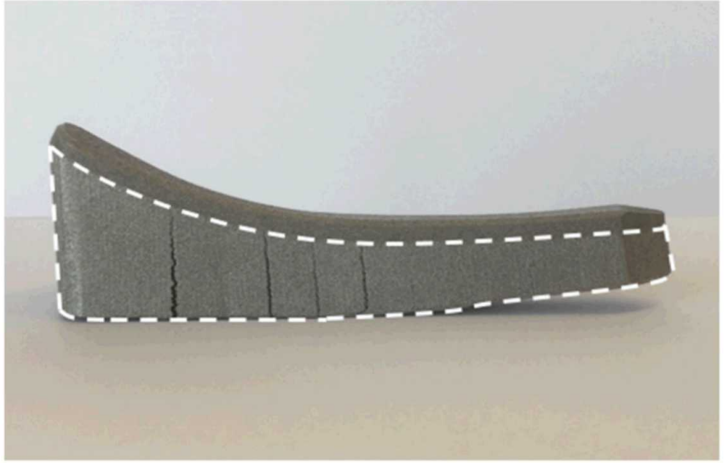
Residual Stress – A Self-Equilibrating Stress Field





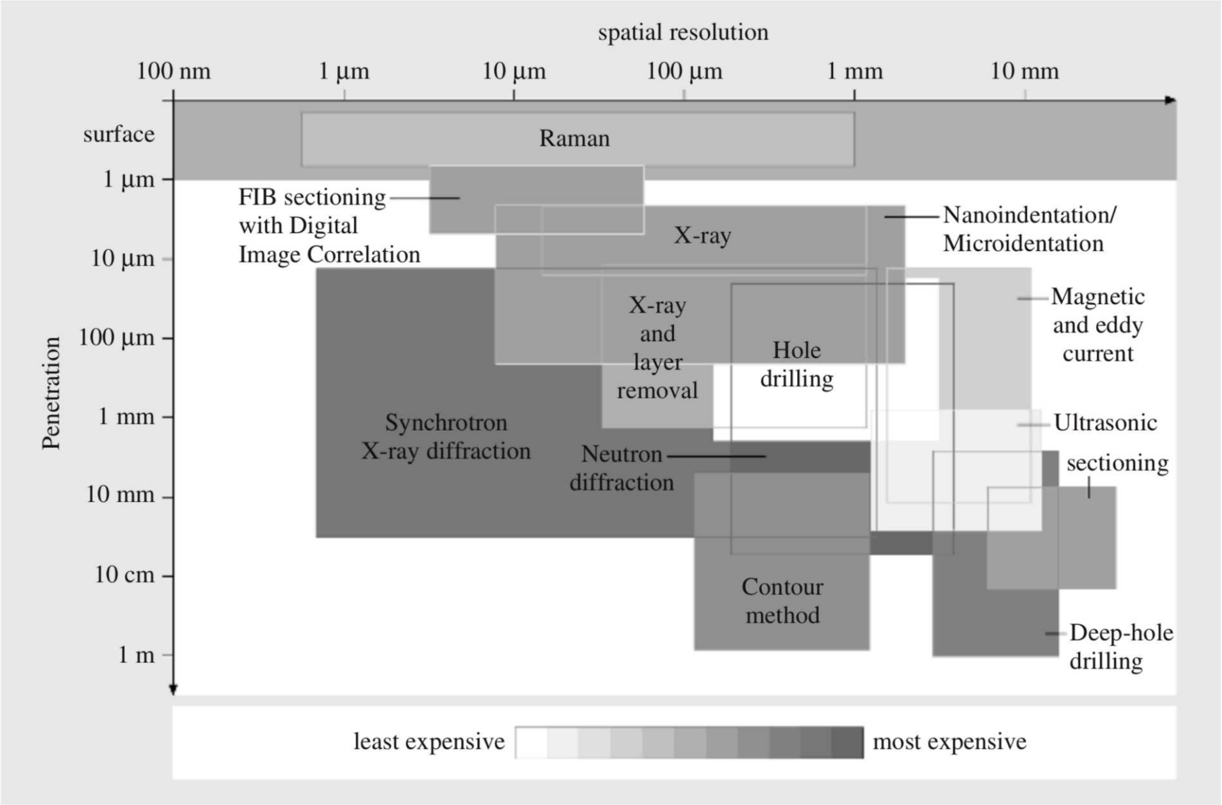
L. Cheng and A.C. To, *Computer-Aided Design* 2019

LENS 304L Build, T. Palmer (PSU) and D. Adams (SNL)

- High thermal gradients lead to high residual stresses, which can lead to failure during or after printing
- Can exacerbate environmental effects (corrosion, fatigue, etc.)
- Rarely accounted for in qualification modeling

Quantifying Residual Stress Remains a Challenge

- Cannot directly measure stress - always measuring a surrogate (strain, displacement, etc.)
- Two main groups of methods:
  - Relaxation-based: measure displacements caused by material removal
    - Hole-drilling
    - Slitting
    - Contour method
  - Diffraction-based: Measure lattice spacing between atoms
    - Neutron diffraction
    - X-ray diffraction

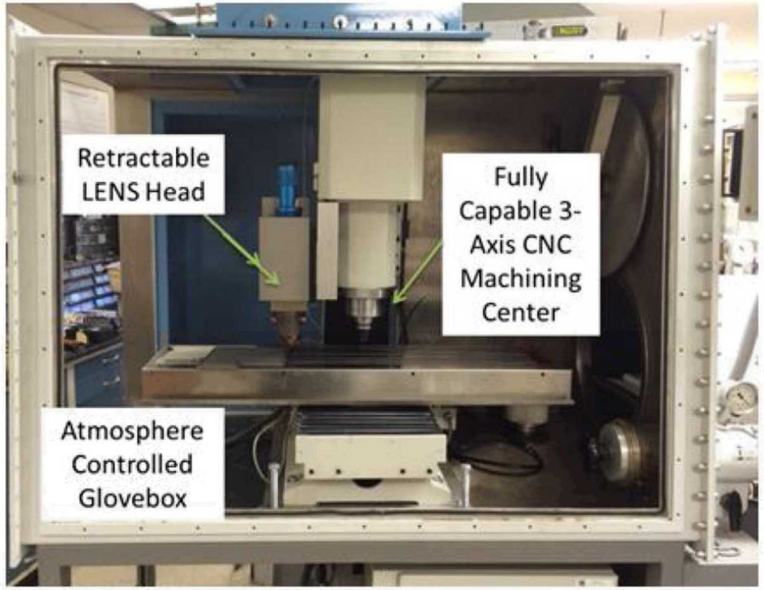


Schajer, G.S., *Practical Residual Stress Measurements* 2013

Outline for Characterization Examples

- Laser Engineered Net Shape (LENS) thin wall hole drilling
- Laser Powder Bed Fusion (LPBF) Neutron Diffraction
- Generalized Residual Stress Inversion
- Nonlinear Ultrasound

LENS Thin Wall Study: Quantifying Residual Stress Reduction from Baseplate Preheating

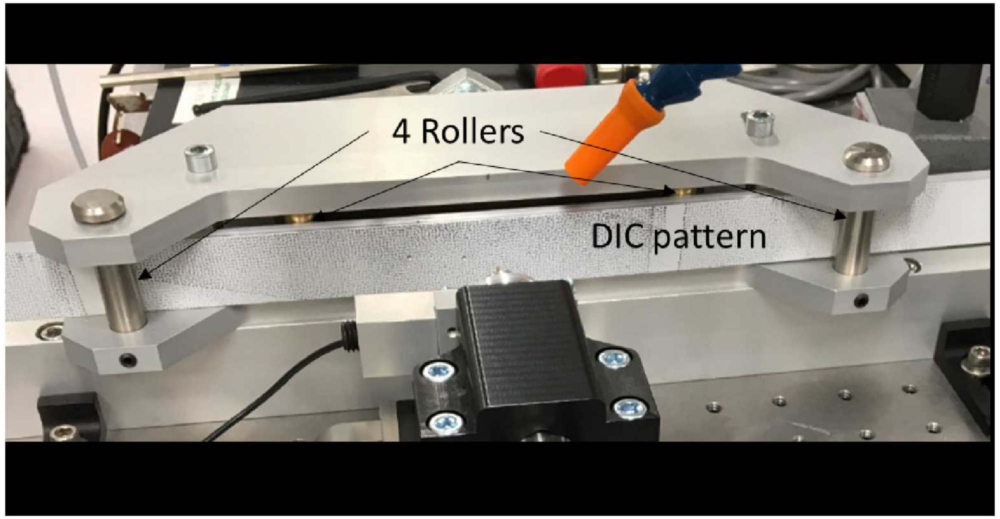


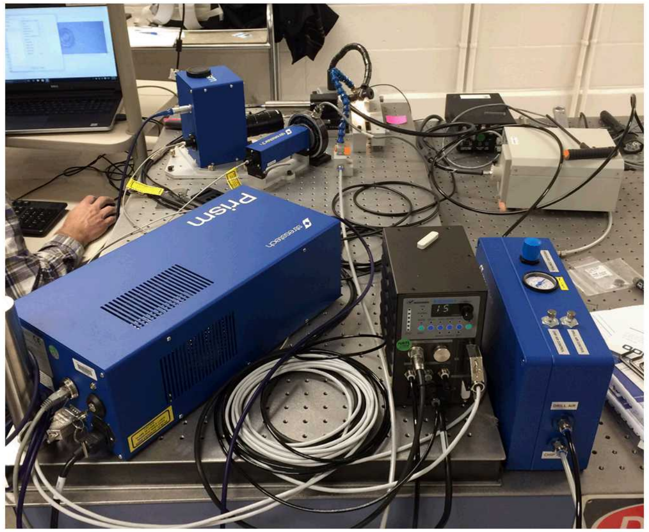
SNL LENS System

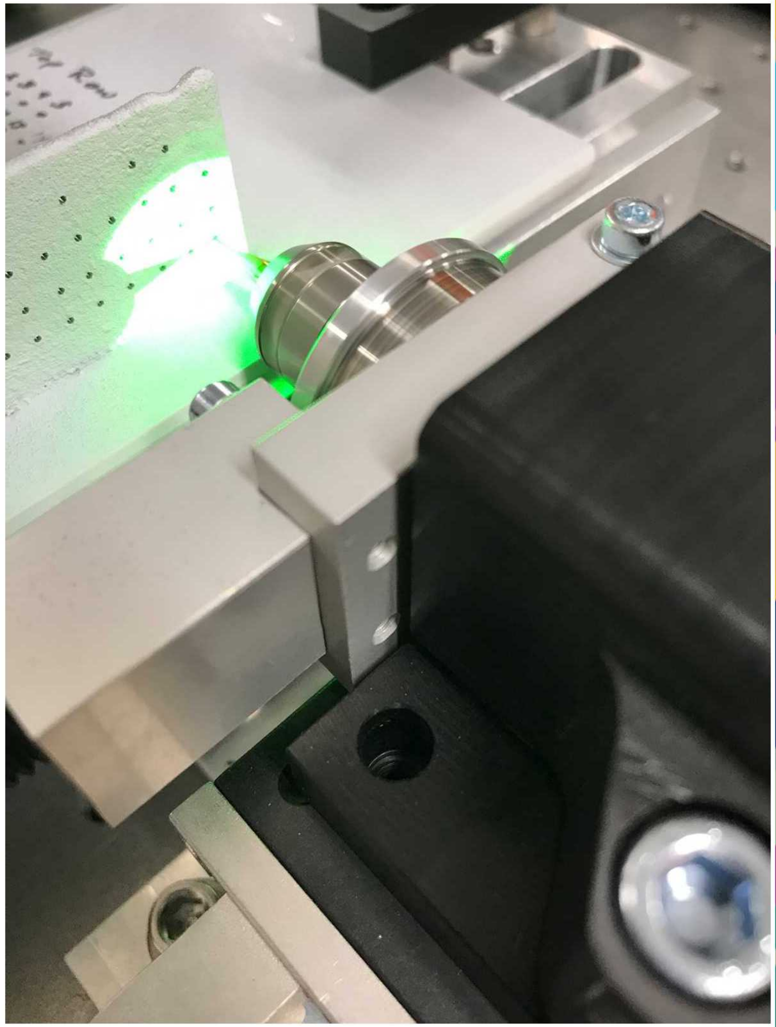
A.B. Kustas, *Additive Manufacturing* 2019

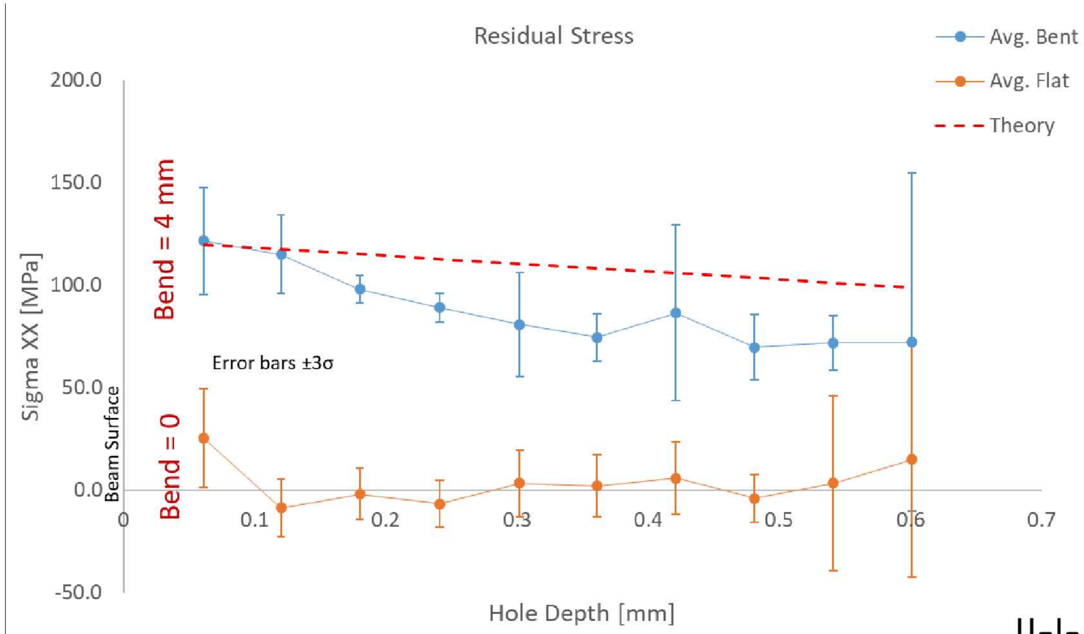
- Thin wall LENS build
  - 0.95 mm laser diameter
  - 400 W
  - 7.5mm/s laser speed
  - Serpentine path, 2 passes per layer
- 2 Cases: Baseplate at 20C and 450C
- Hole drilling performed using StressTech Electronic Speckle Pattern Interferometry (ESPI) System
- Not shown - EDM cut down centerline of wall for stress relaxation with Digital Image Correlation (DIC) to measure distortion before and after cut

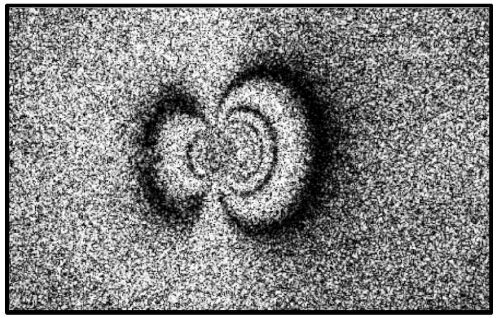
StressTech ESPI Hole Drilling System Validated Using 4-Point Bend











Hole drilling results from Phil Reu

Process Models Simulate Different Thermal Histories

Room Temperature Baseplate

450C Baseplate

- Thermal models performed in Sierra/Aria
- Elements are activated upon reaching melt temperature
- Conduction, convection, and radiation are considered.

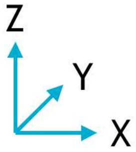
Baseplate Preheating Reduces Residual Stress

Room Temperature Baseplate

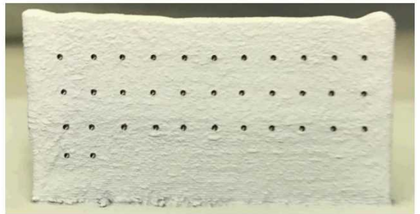
450C Baseplate

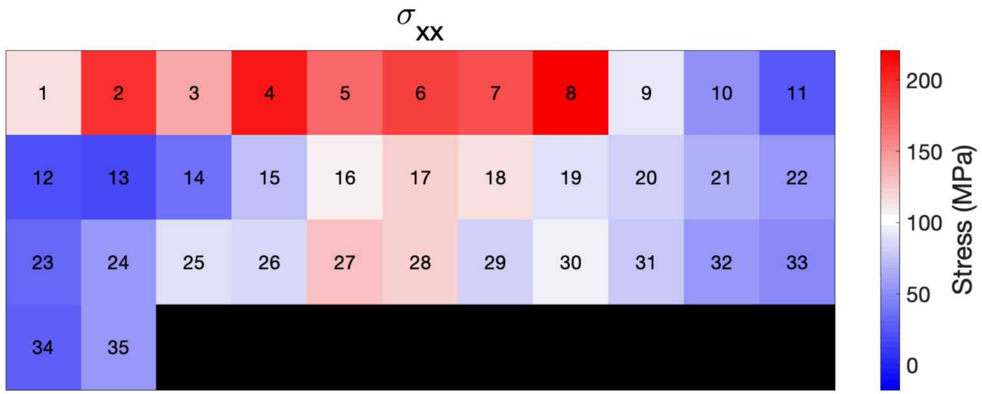
- Solid Mechanics models performed in Sierra/Solid Mechanics (Sierra/SM)
- Elements are activated when melted
- Temperature-dependent viscoplastic material model captures residual stress due to thermal contraction
- See K.L. Johnson et al. *Computational Mechanics* 2018, 61, 559-574 for additional model details

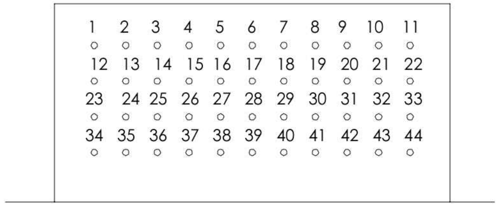
LENS 304L Thin Wall Hole Drilling Results and Model Comparison

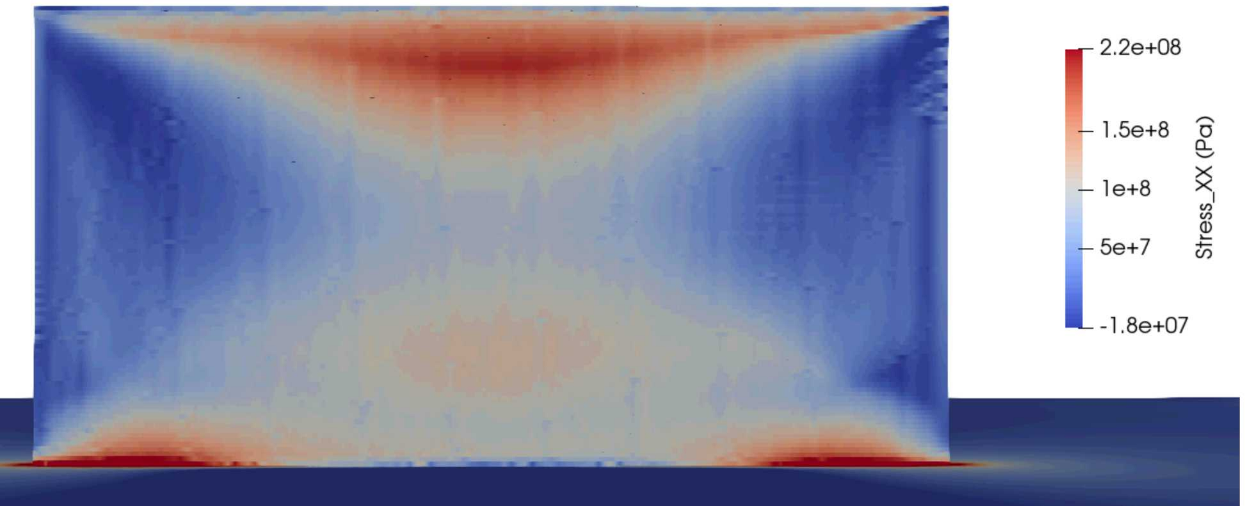


Room Temperature Baseplate

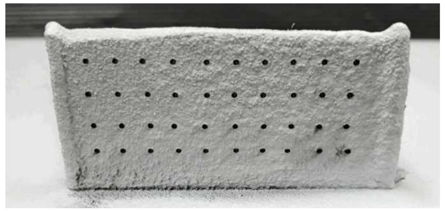


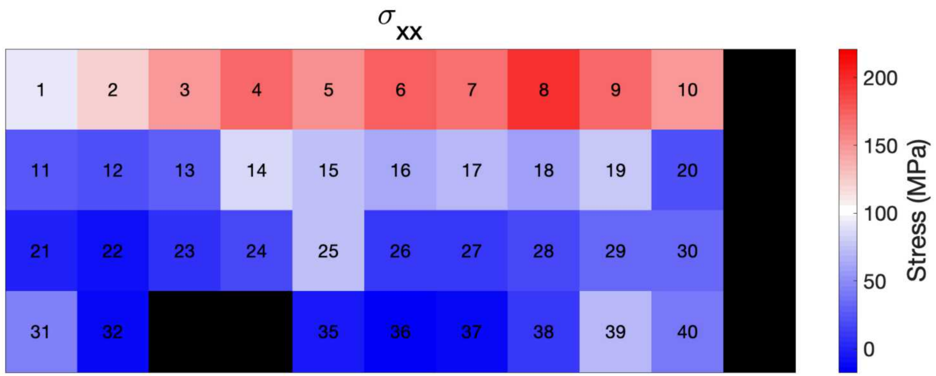


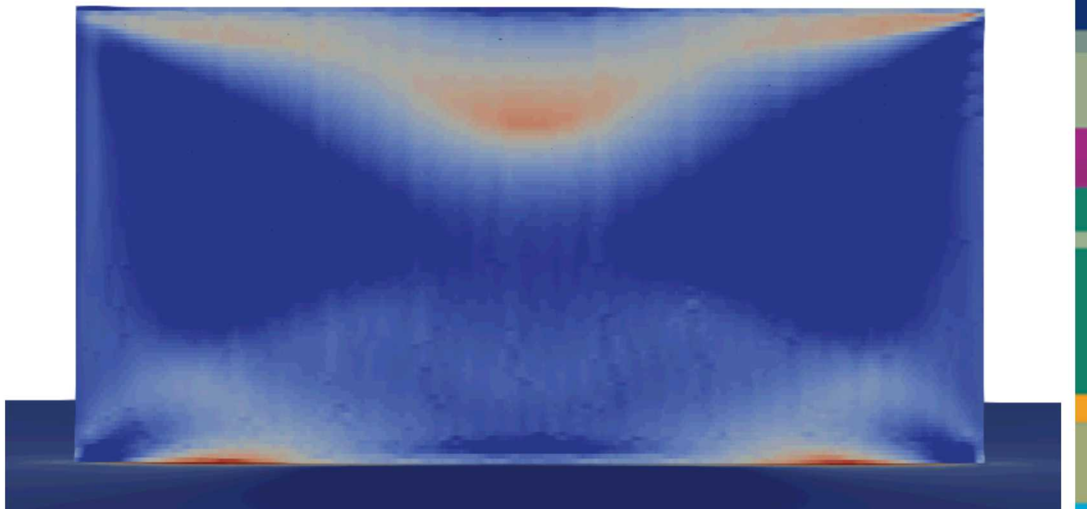




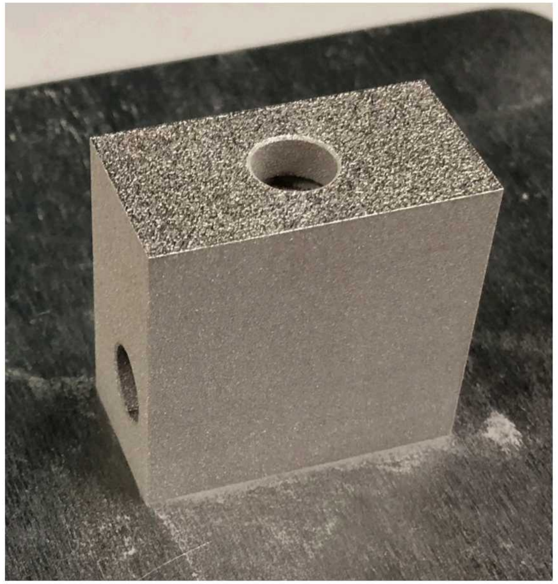
450C Baseplate

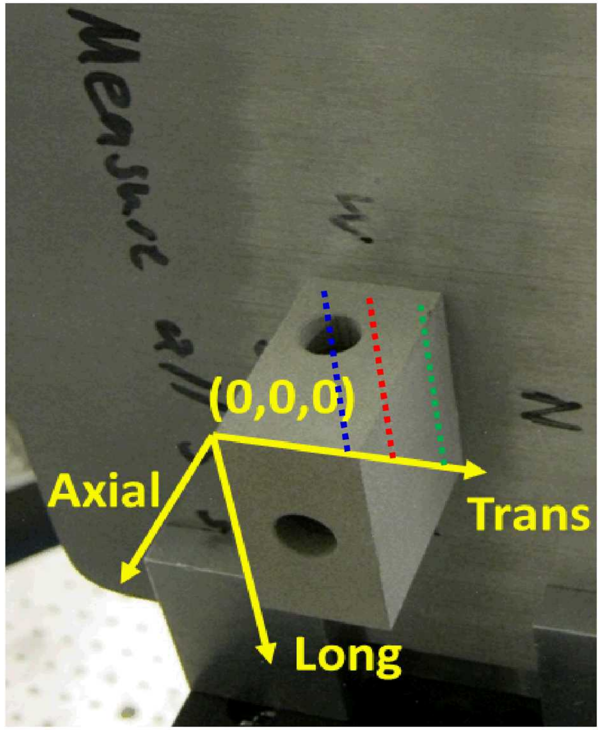


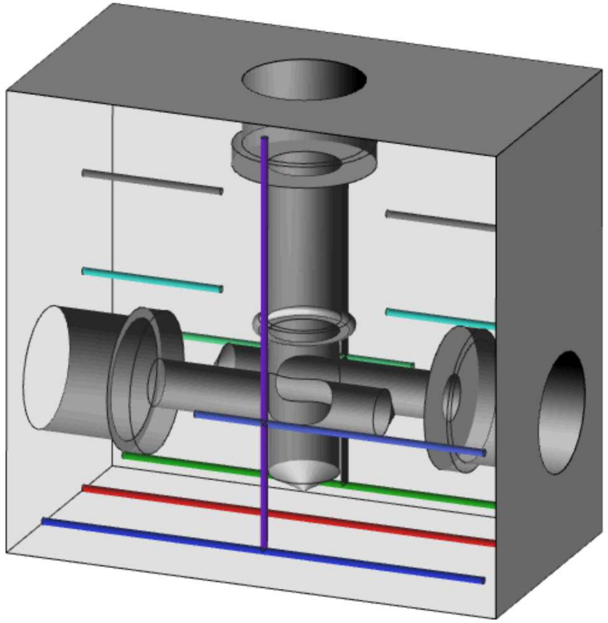




Neutron Diffraction (ND) Measurements on LBPF Part



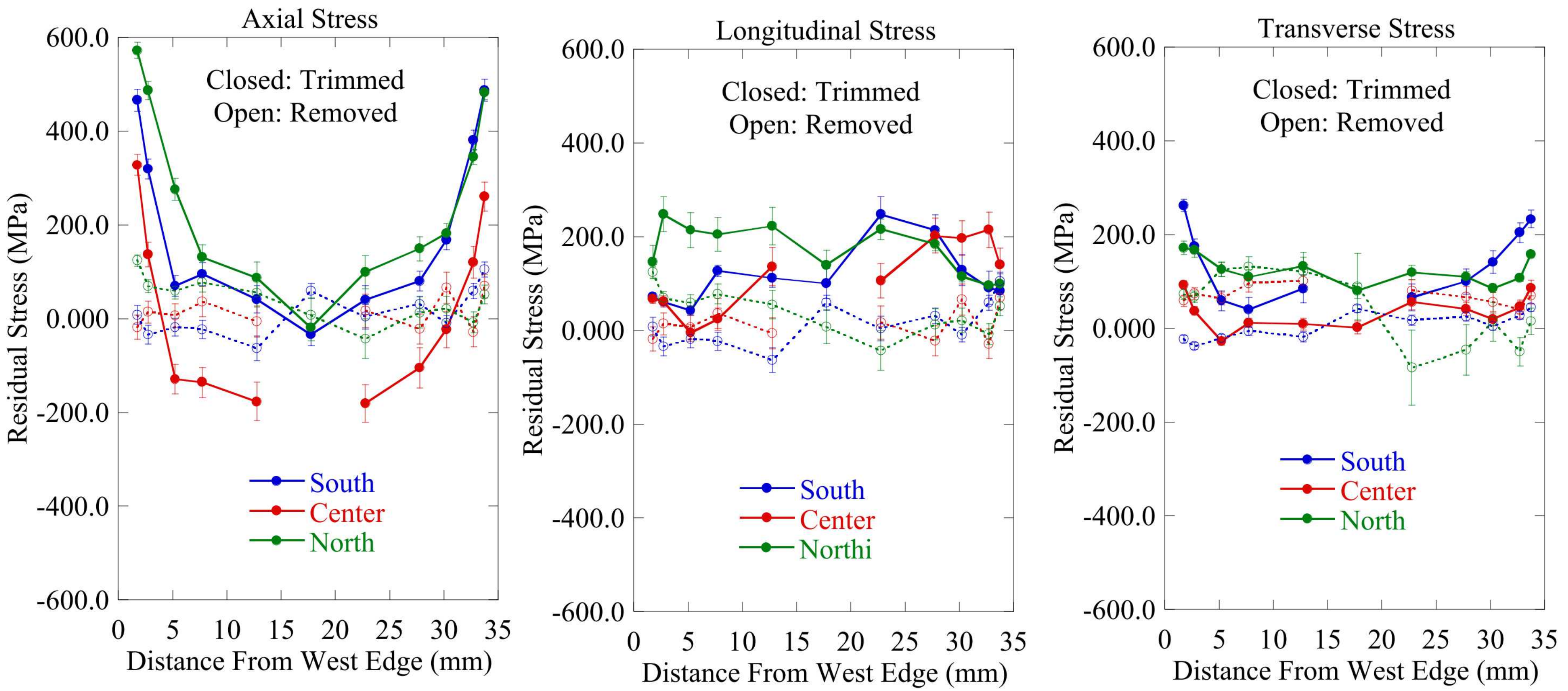


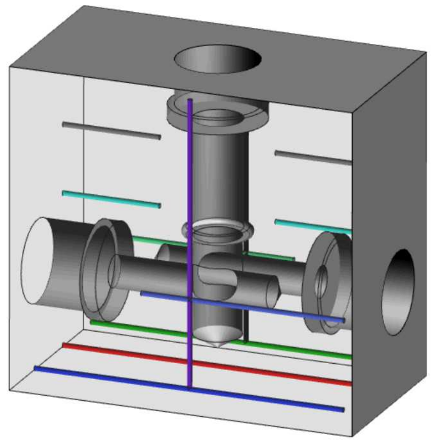


- 316L stainless steel part built on 3DSystems ProX200
- Serpentine laser path (90 degree rotation)
- >1000 layers
- Neutron Diffraction results from Don Brown, Bjørn Clausen at LANSCE

B. Clausen et al. *Additive Manufacturing,* 2020 (Under Review)

Neutron Diffraction Stress Results Before and After Base Plate is Cut





B. Clausen et al. *Additive Manufacturing*, 2020 (Under Review)

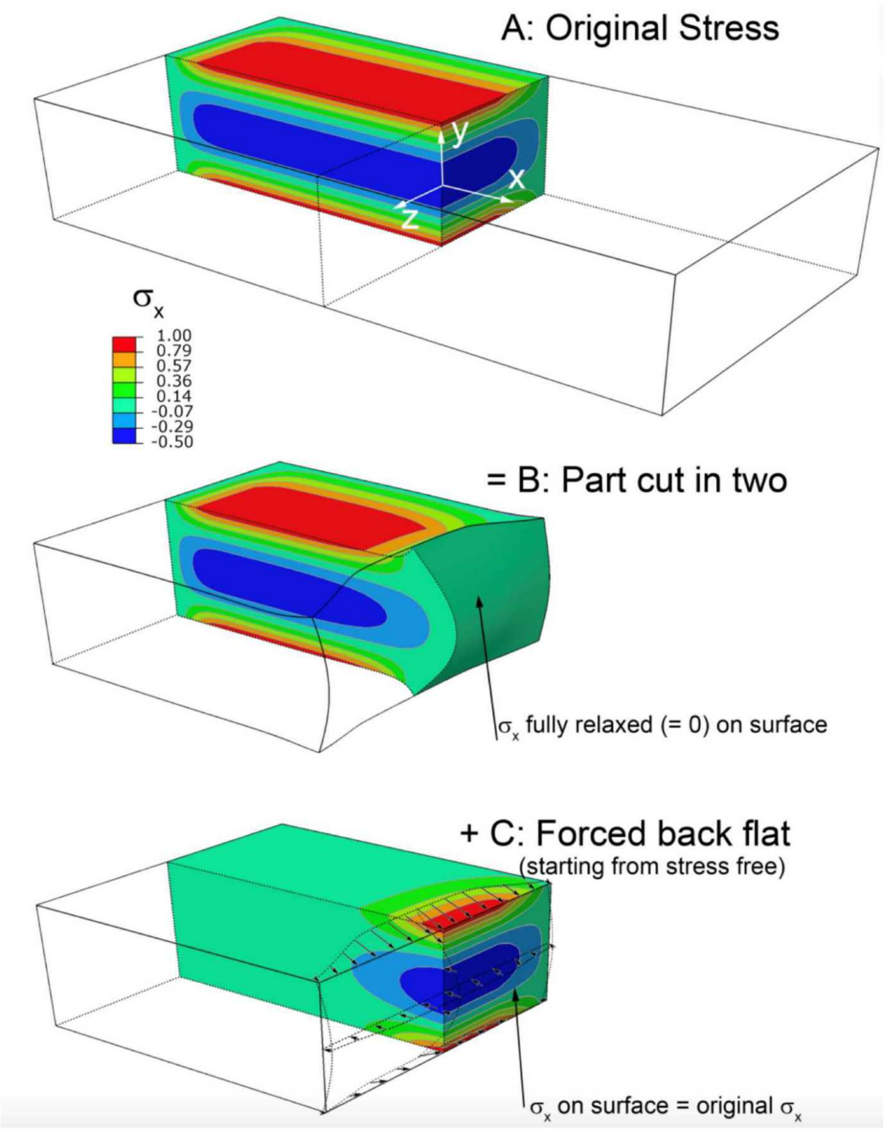
Contour Method Process

1. A part with an existing residual stress is securely fixtured and cut in a planar fashion, causing displacements on the cut surface due to released residual stresses.

2. The surface displacements are measured.

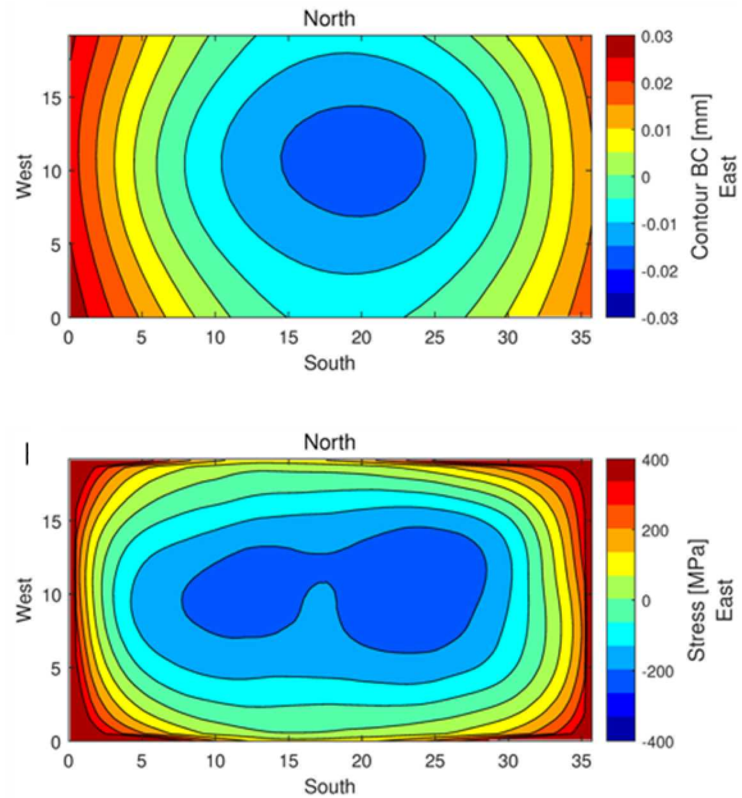
3. A finite element mesh of the deformed part is created.

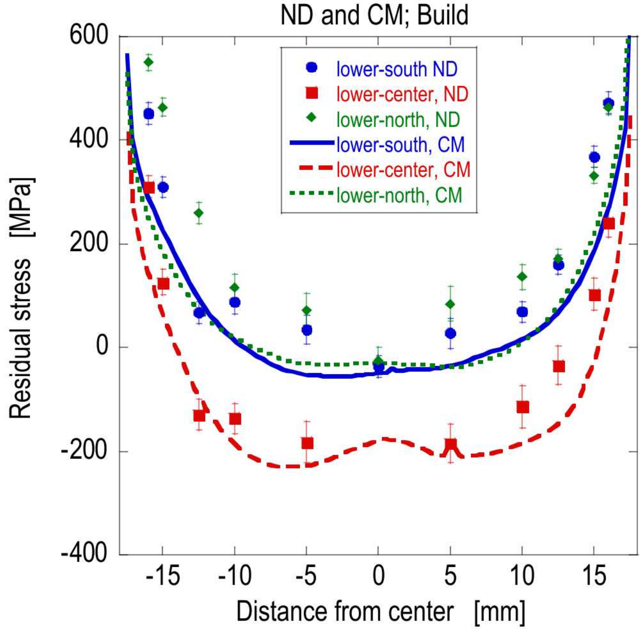
4. The deformed, cut surface is displaced to return to a flat configuration, inducing stresses in the part that correspond to the released residual stress.

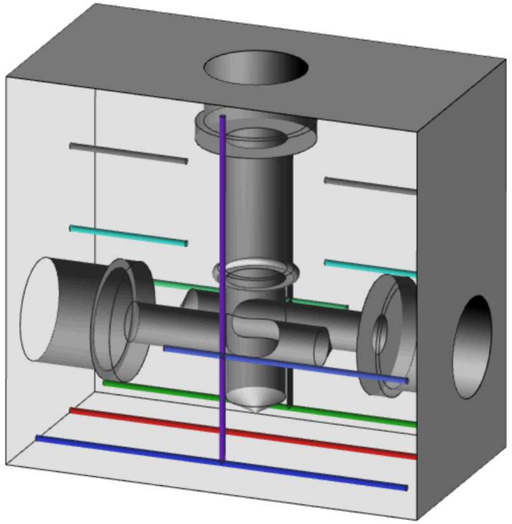


M.B. Prime and A.T. DeWald, *Practical Residual Stress Methods*, G.S. Schajer (ed.), 2013

Contour Method Stress Results Agree with Neutron Diffraction Results





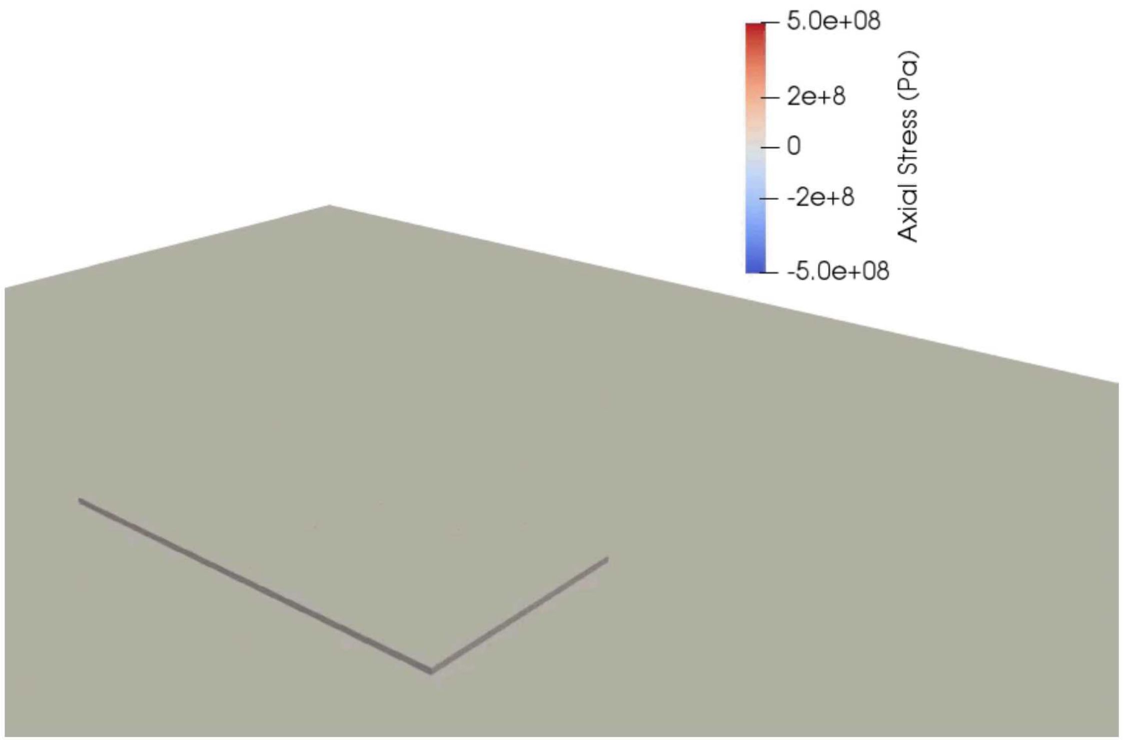


- Contour method was performed along plane corresponding to blue, red, and green lines
- Contour Method results from Mike Hill, Chris D'Elia, and Mike Prime

B. Clausen et al. *Additive Manufacturing,* 2020 (Under Review)

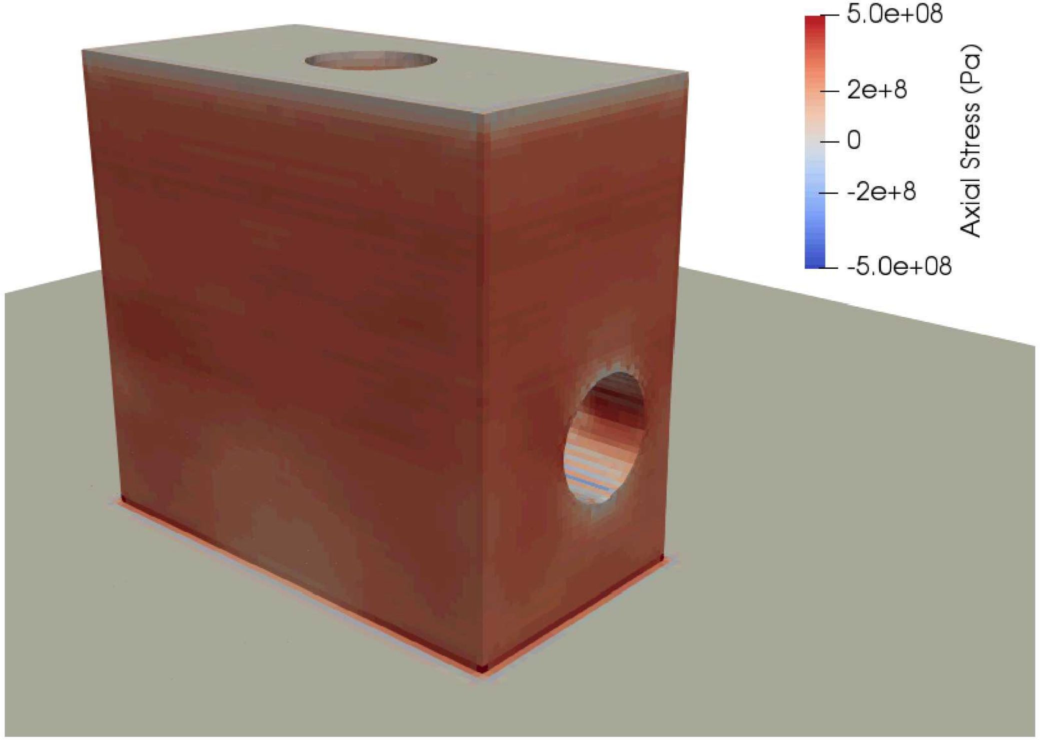
Inherent Strain Method for Rapid Stress Prediction

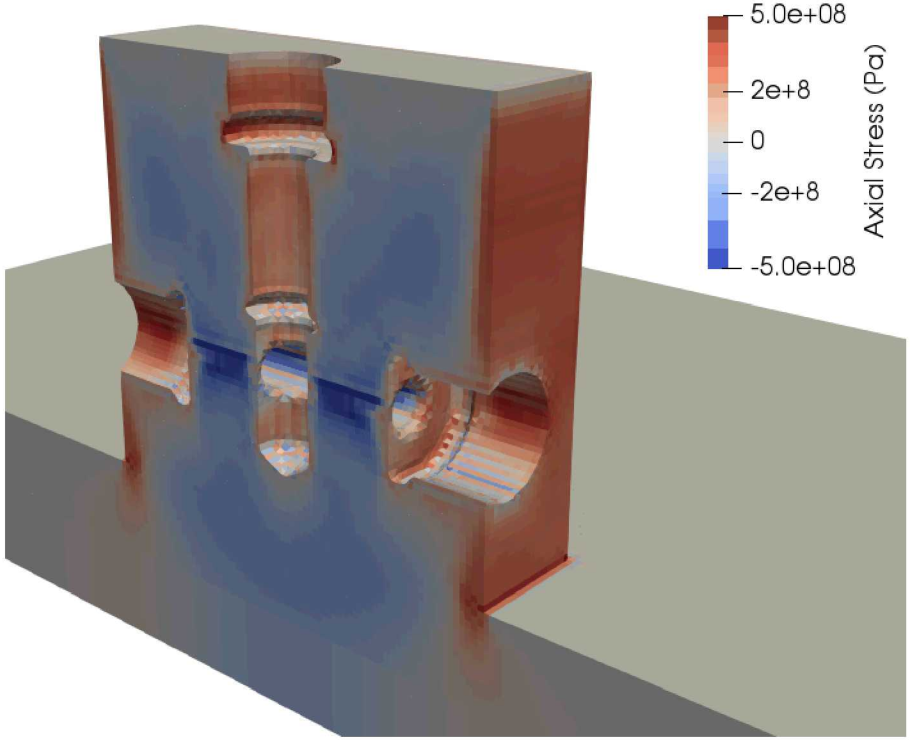
- Part size is challenging for full solution
- Inherent strain method developed for weld stress prediction
  - (Ueda, Fukuda, Tanigawa 1979; Ueda, Kim, Yuan 1980, Hill and Nelson 1995)
- Strain tensor is applied in layers over time
  - Quick approximation for distortion and stress
- Does not capture local variations due to different thermal gradients
- Fast: ~30 mins on 60 cpus



$$\bar{\varepsilon} = \begin{bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{22} & 0 \\ 0 & 0 & \varepsilon_{33} \end{bmatrix}$$

Inherent Strain Method Stress Contours

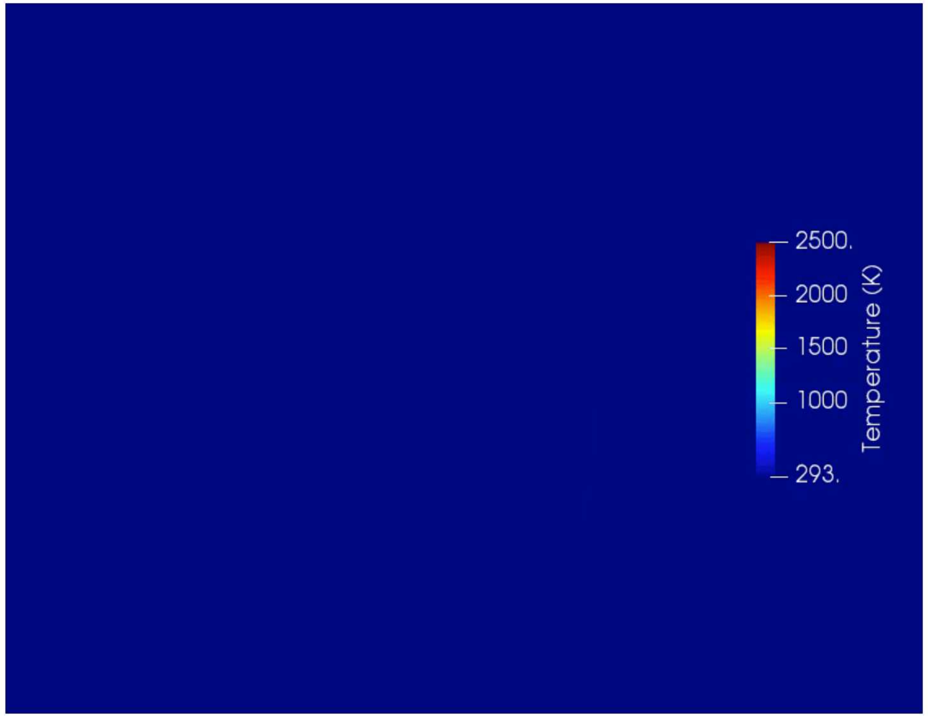




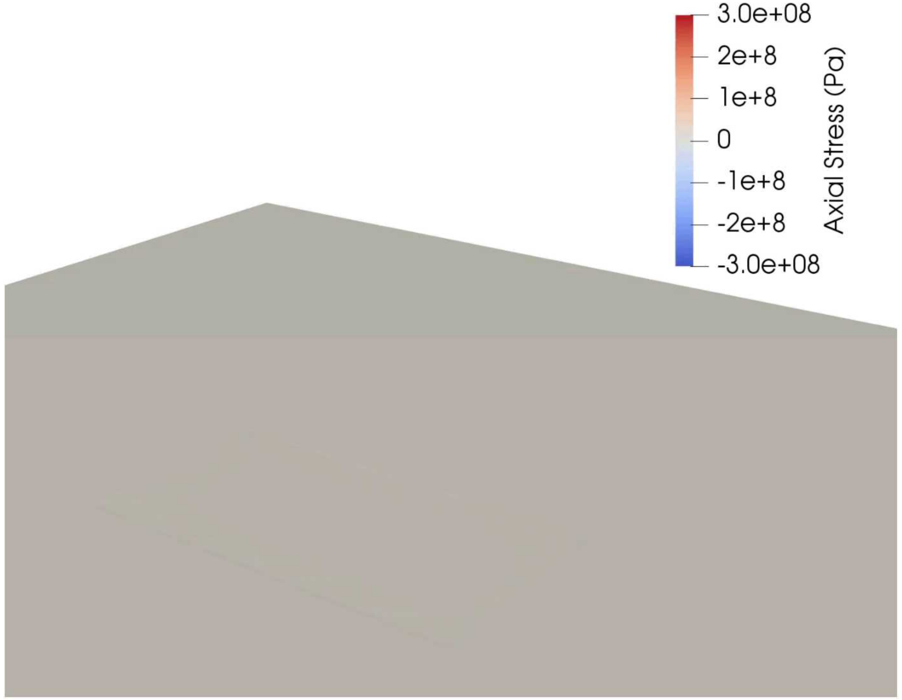
- Axial stress values show expected trends
  - ~ 300 MPa exterior, ~ -200 MPa interior
- Wall time ~30 min on 60 cpus (~12X faster than real-time 6 hr build)

Lumped Laser Method

Thermal

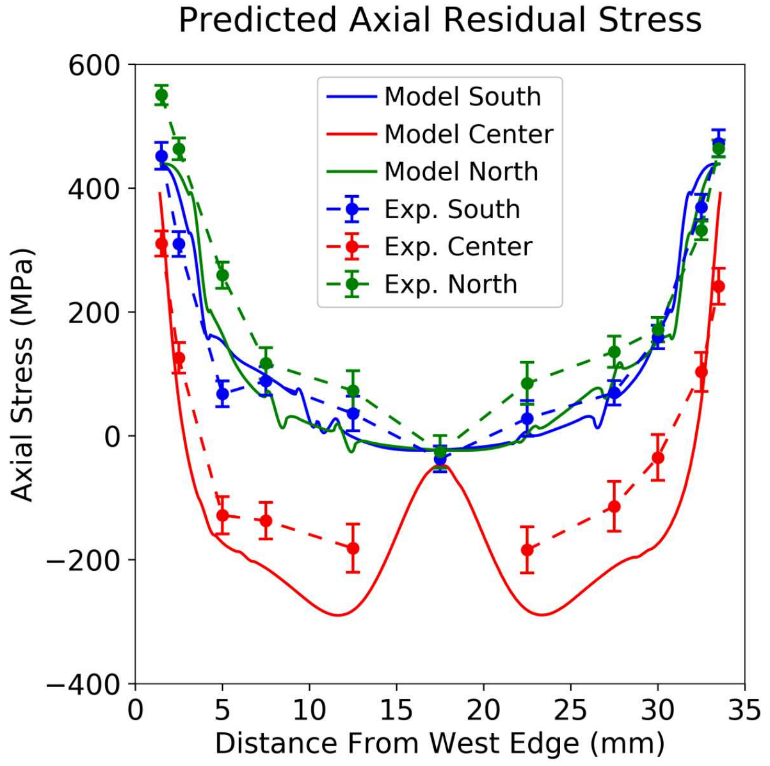


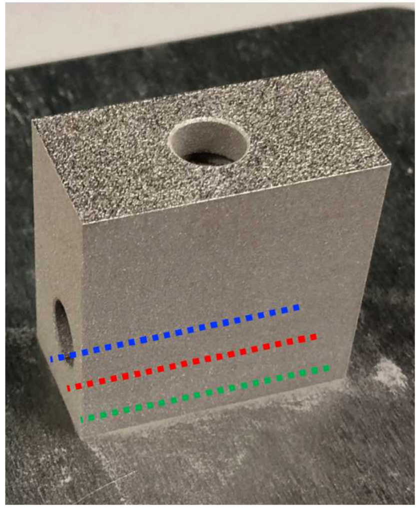
Solid Mechanics

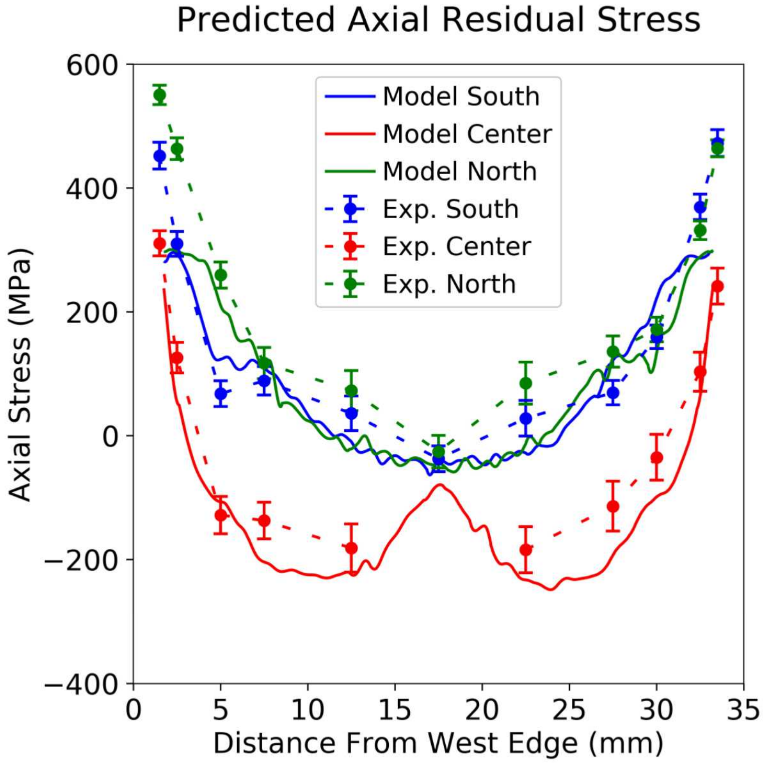


- Approach similar to N.E. Hodge et al. 2014 and 2016, M. Stender et al. 2018, R.K. Ganeriwala et al. 2019
- ~3 mm laser diameter, 0.84 mm layer height
- Laser radius to layer height ratio and total inter-layer cooling time held constant from actual conditions
- Laser speed unchanged – 1400 mm/s
- 40 layers
- Wall time ~6 hours on 100 cpus

Reduced Order Model Comparison to Neutron Diffraction





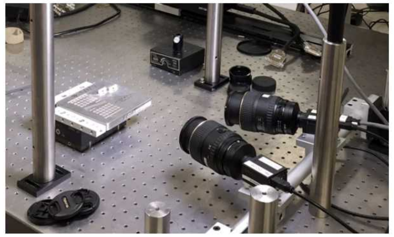


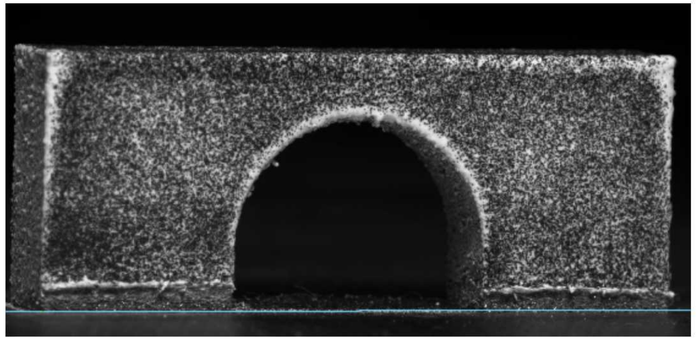
Mechanical Inherent Strain
60 cpus
30 minutes

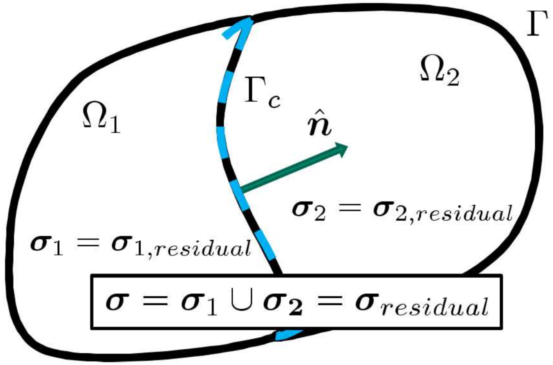
Enlarged Heat Source and Layer Thickness
100 cpus
6 hrs (~real time)

Generalized Residual Stress Inversion Method

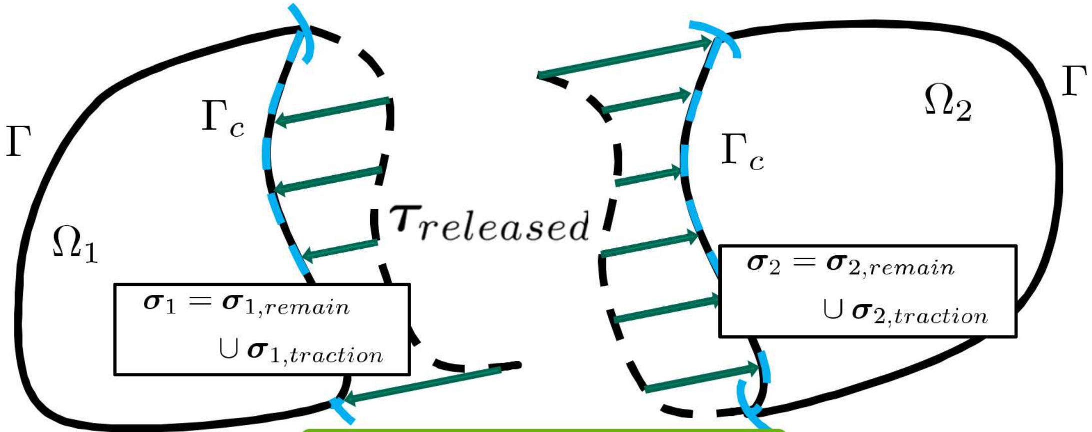
Benefits of Generalized Inversion Method:
1. Experimental simplicity
2. All traction components recovered



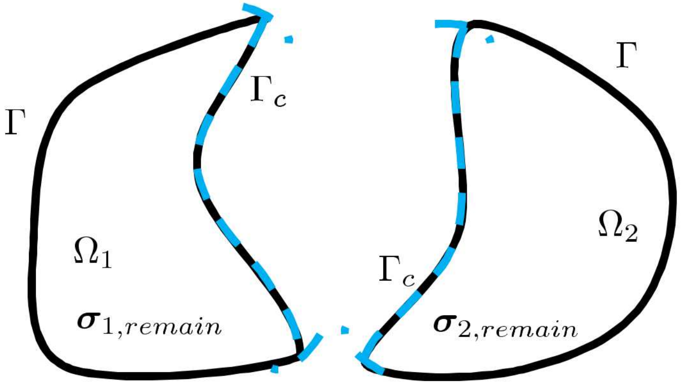




Initial Configuration



Cut Configuration



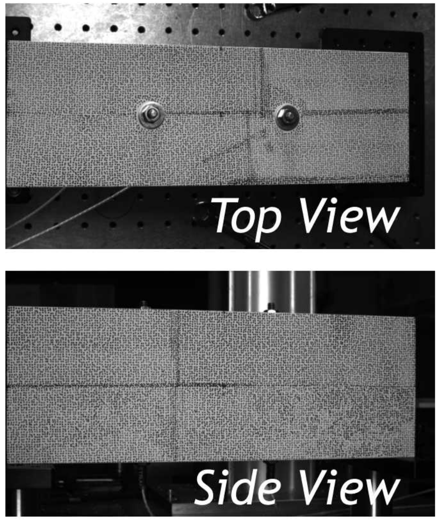
Deformation (u_m)

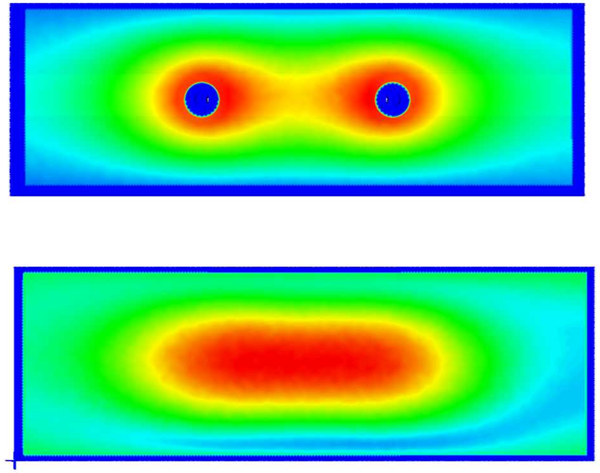
Invert for released stress by finding the (released) traction that causes the measured deformation:

Given $\boldsymbol{u}_m$ on $\Omega_m \subset (\Omega_1 \cup \Omega_2)$, find $\boldsymbol{\tau}_c := \boldsymbol{\tau}_{released}$ such that linear elasticity holds.

$$\min_{\boldsymbol{\tau}_c \in \mathcal{X}} J(\boldsymbol{\tau}_c) := \frac{1}{2} \|[Q]\mathbf{u} - \mathbf{u}_m\|_2^2 + \frac{\alpha}{2} \|\boldsymbol{\tau}_c\|_w^2 \qquad \text{subject to } [K]\mathbf{u} - \mathbf{f}(\boldsymbol{\tau}_c) = 0$$

Validation Using Force-sensing Bolts





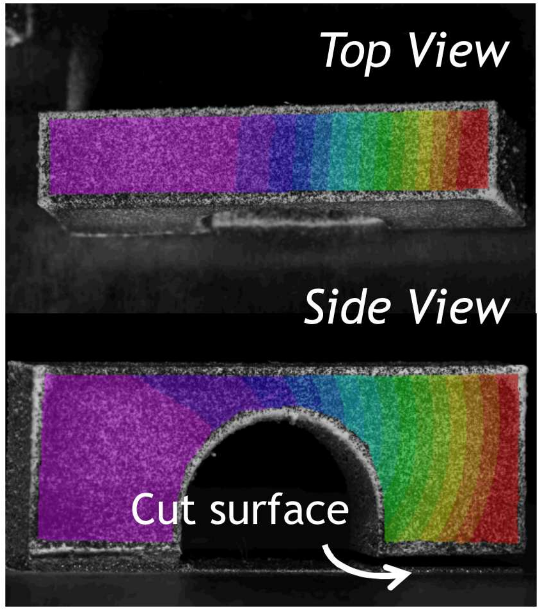
Displacement data

Verified model and force-sensing bolts by inverting for the loads on the bolts using DIC data:

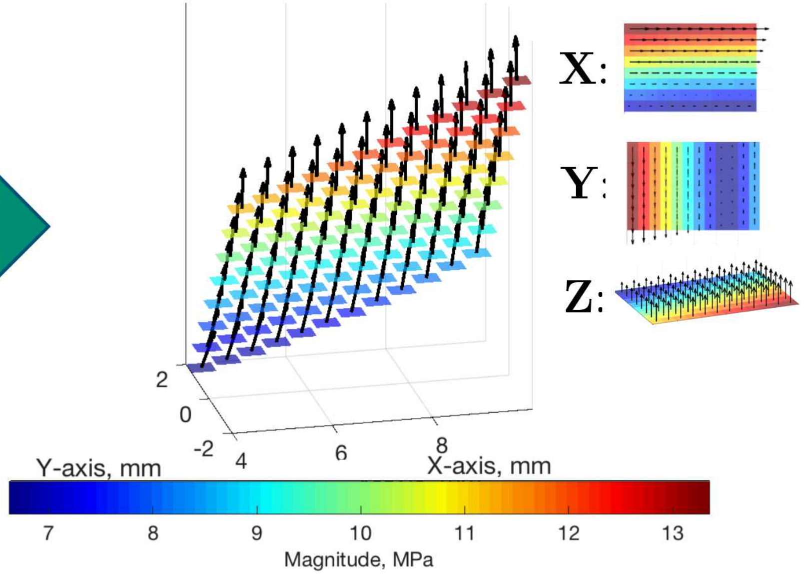
Case	Left (lbs)	Right (lbs)	Rel. L2 Error (%)
Top	441.18	447.394	1.45%
Side	502.93	486.05	10.06%

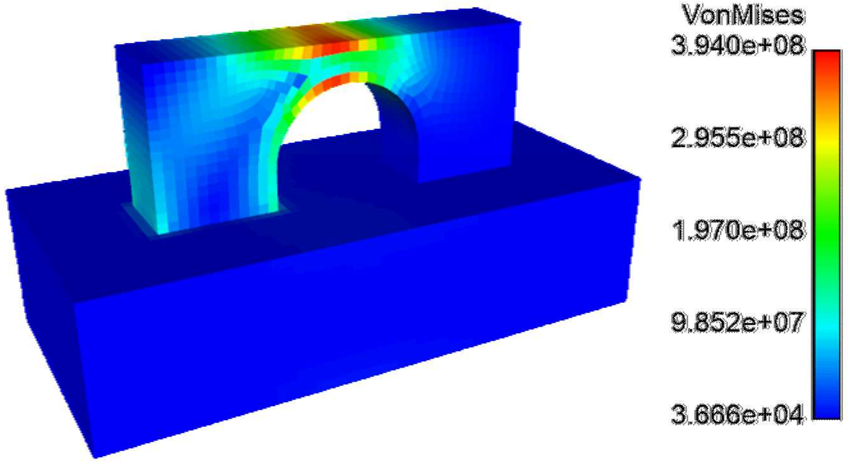
- Inversion method was validated by inverting for a measured load at two bolt locations using only DIC data
- DIC data measured on top and side surfaces while force-sensing bolts were loaded to 450 lbs

Inverse Methodology Results for LPBF Bridge



Traction Vector on Cut Plane





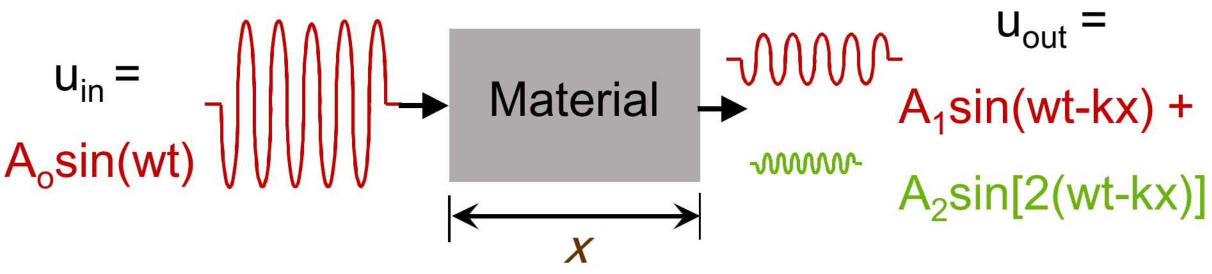
Stress profile due to released traction

- Inversion method is able to invert for 3D traction vector on cut surface using measured DIC data
- Use of DIC allows for more general shapes and cut locations
- Multiple cuts could be used to increase information about original stress state

Probing Material State With Nonlinear Ultrasound (Georgia Tech)

MEASUREMENT PRINCIPLE:

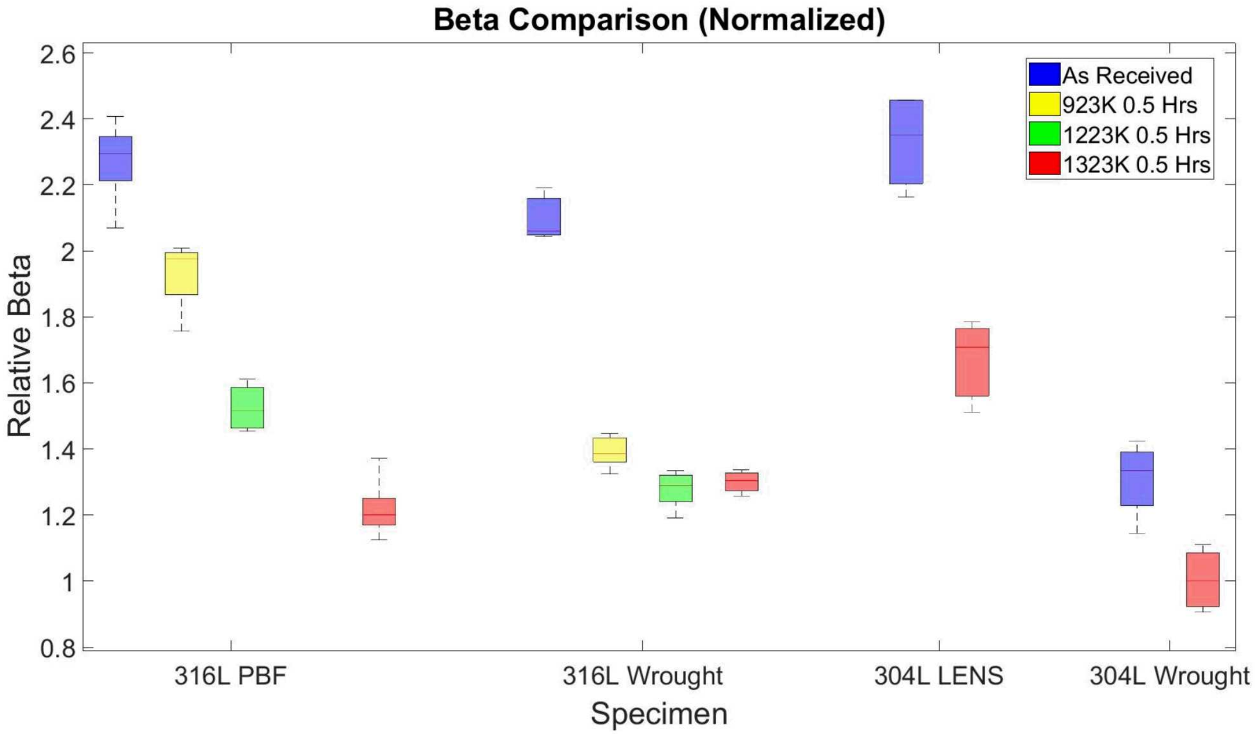
SECOND HARMONIC GENERATION



Determining β, the absolute acoustic nonlinearity parameter

$$A_2 = \frac{\beta A_1^2 x \kappa^2}{8} \Rightarrow \beta = \frac{A_2}{A_1^2}\left(\frac{8}{\kappa^2 x}\right)$$

$$\beta \propto \frac{A_2}{x \cdot A_1{}^2}$$



Conclusions

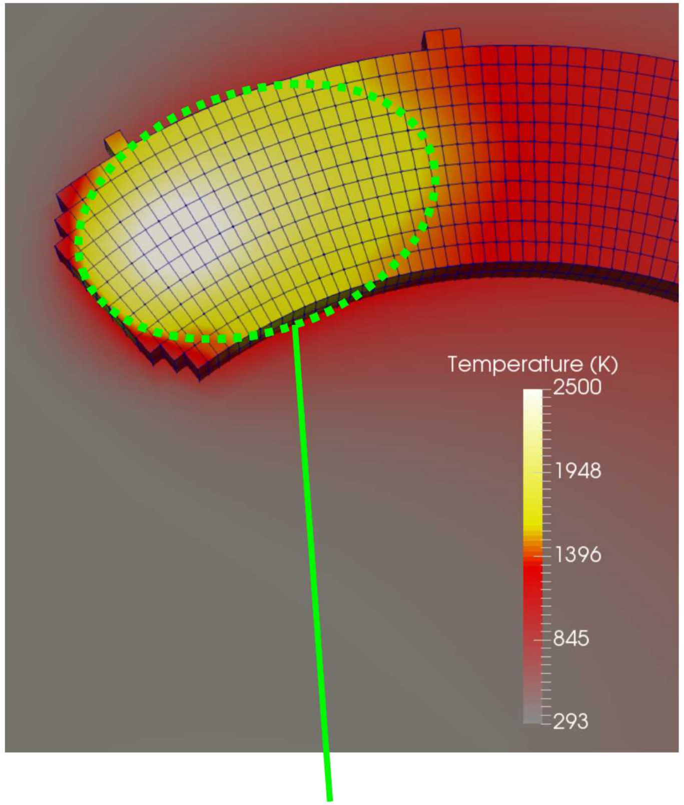
- Residual stress is an important consequence of laser-based AM processes that is sometimes ignored.
- Residual stress is often difficult to quantify.
- Multiple measurement methods may be needed to fully understand stress state.
- Neutron diffraction, hole drilling, and contour method are viable methods for stress measurement.
- Existing models can accurately predict residual stresses.
- Generalized inversion technique offers flexible option for residual stress quantification.
- Nonlinear ultrasound can detect material changes in AM Parts

- See Brett Clark talk tomorrow (9:20) on Optimization-based Design For Manufacturing

Extra Slides

Thermal Modeling Methodology

1. Pre-meshed part is initialized with "inactive" elements. Baseplate elements are active.
2. Laser heat source is scanned according to input path
3. Elements are activated by a thermal conductivity increase once they reach melt temperature
4. Conduction, convection, and radiation are considered.



Approximate Melt Pool

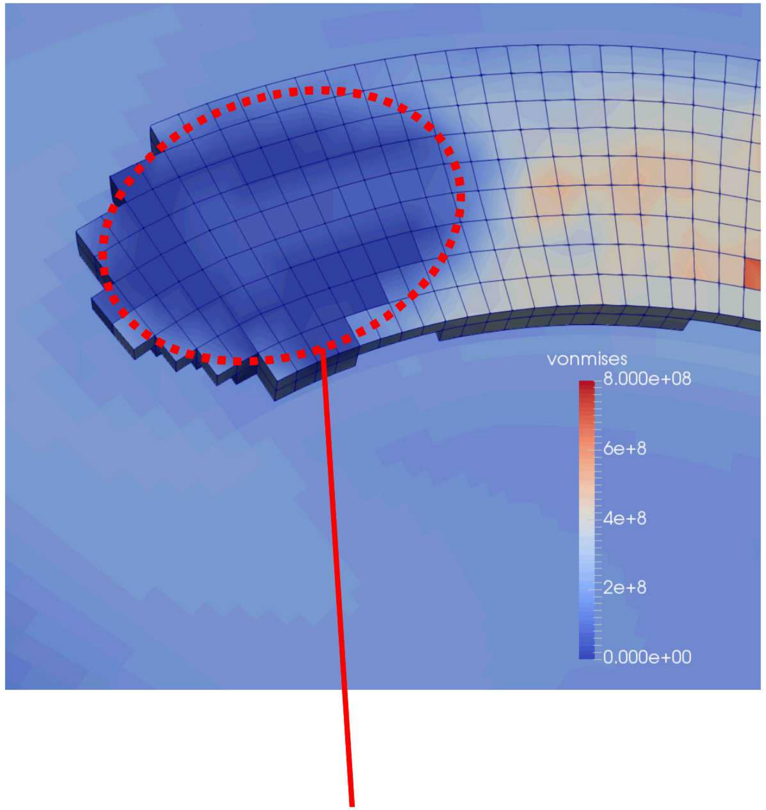
Solid Mechanics Modeling Methodology

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

Thermal output file is read at every time step to provide temperatures

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)

Bammann-Chiesa-Johnson (BCJ) Material Model

- Temperature and history-dependent viscoplastic internal state variable model
- Stress is dependent on damage ϕ and evolves according to

$$\dot{\sigma} = \left(\frac{\dot{E}}{E} - \frac{\dot{\phi}}{1-\phi}\right)\sigma + E(1-\phi)(\dot{\varepsilon} - \dot{\varepsilon}_p)$$

- Flow rule includes yield stress and internal state variables for hardening and damage

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

- Statistically stored dislocations are represented by isotropic hardening variable κ

$$\kappa = c_{\varepsilon_{ssds}} b\mu(\theta)\sqrt{\rho_{ssds}} \qquad \dot{\rho}_{ssds} = \left[\frac{k_1}{L_s} + \frac{k_2}{L_g} - R_d(\theta)\rho_{ssds}\right]\dot{\varepsilon}_p$$

- Geometrically necessary dislocations are represented by a misorientation variable ζ

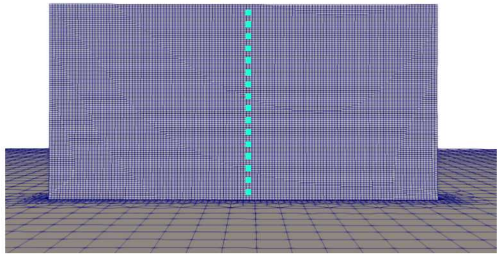
$$\dot{\zeta} = \frac{\zeta}{\mu(\theta)}\frac{d\mu}{d\theta}\dot{\theta} + h_\zeta \mu(\theta)\left(\frac{\zeta}{\mu(\theta)}\right)^{1-\frac{1}{r}}|\dot{\varepsilon}_p|$$

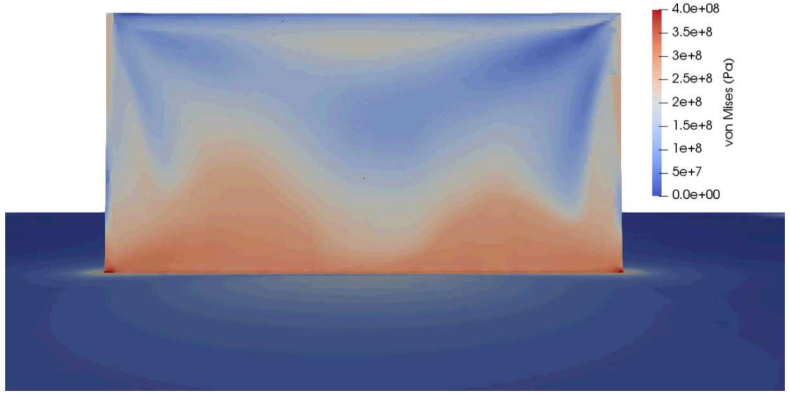
- The hardening variable κ evolves in a hardening minus recovery form.

$$\dot{\kappa} = \frac{\kappa}{\mu(\theta)}\frac{d\mu}{d\theta}\dot{\theta} + \left[H(\theta)\left(1 + \frac{\zeta}{\kappa}\right) - R_d(\theta)\kappa\right]\dot{\varepsilon}_p$$

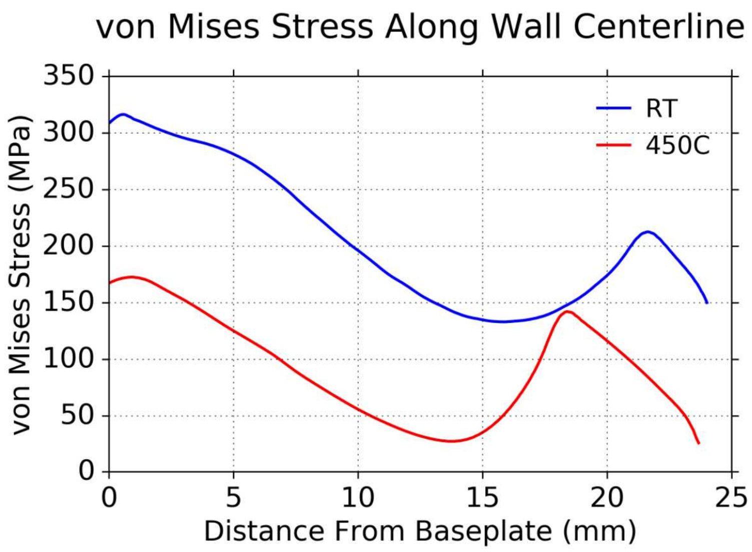
(Bammann *et al.* 1993, Brown and Bammann 2012)

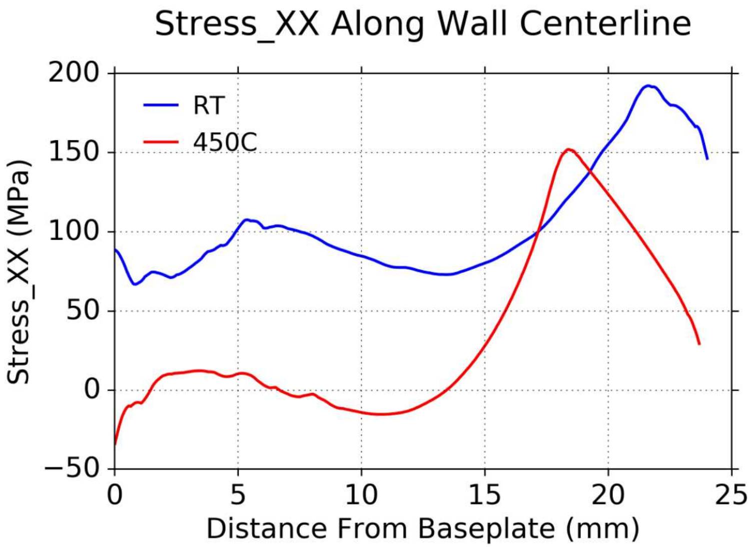
Full Process Models Provide Resolution at Each Laser Pass





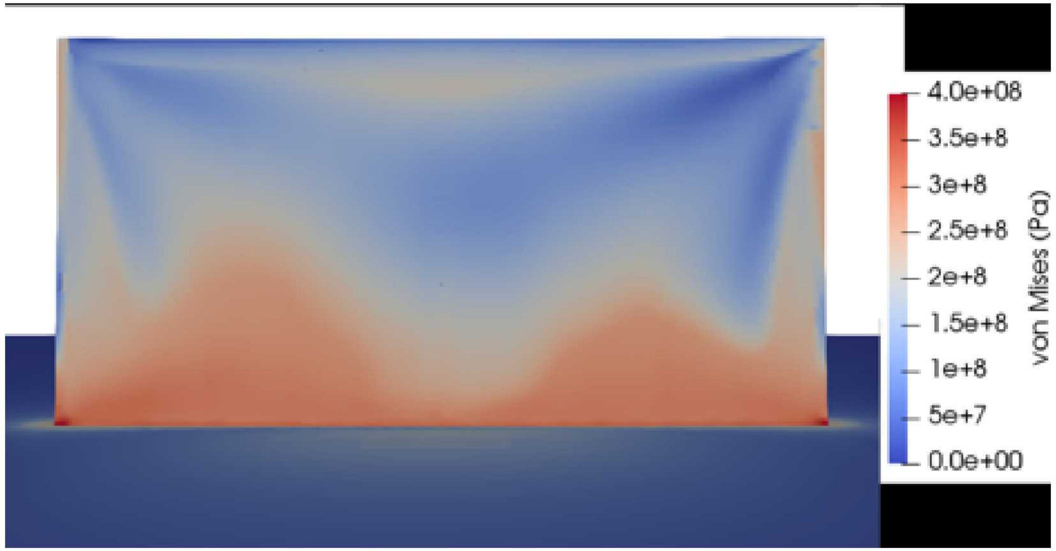
304L Two Pass LENS Thin Wall Build Study Examining Baseplate Preheating Effects





Residual stresses are greatly reduced by preheated baseplate

Room Temperature Baseplate



450C Baseplate