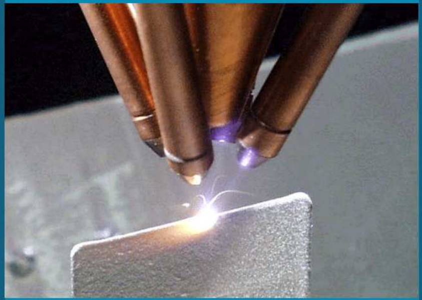
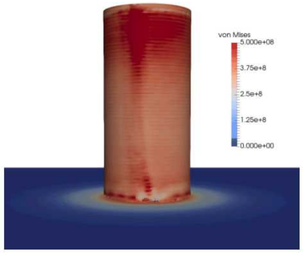
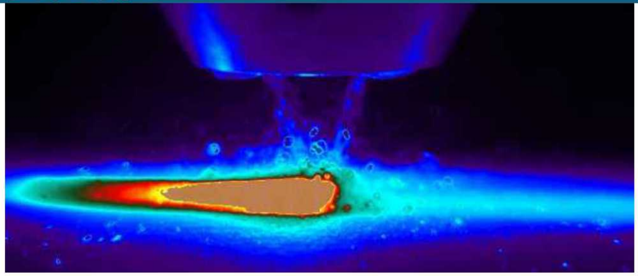
SAND2018-9316C

"Understanding the Impact of Thermal Constraints on Residual Stress in 3D Metal Printed Parts"







Shaun Whetten, Kyle Johnson, Joe Bishop, Phil Reu, Paul Farias, Andrew Kustas, and David Keicher

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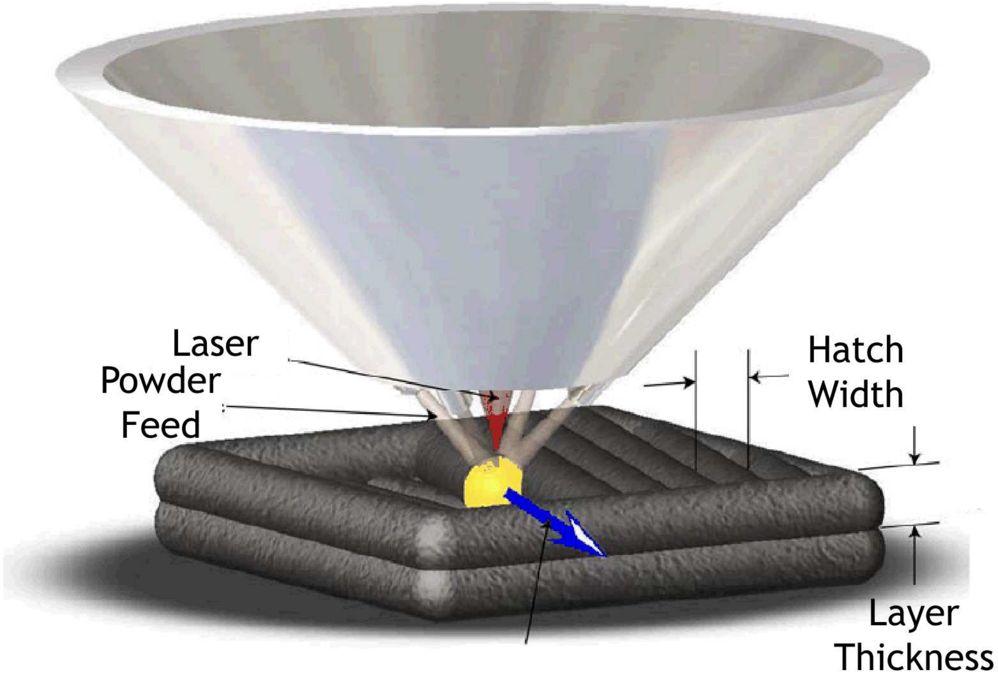
LENS

Work done on LENS printer, however this work impacts all thermally driven 3D print technologies

Material used in this work 304L stainless steel



Schematic of LENS 3D printer [1]

[1]Smugeresky, J.E., *On the interface between LENS deposited stainless steel 304L repair geometry and cast or machined components.*

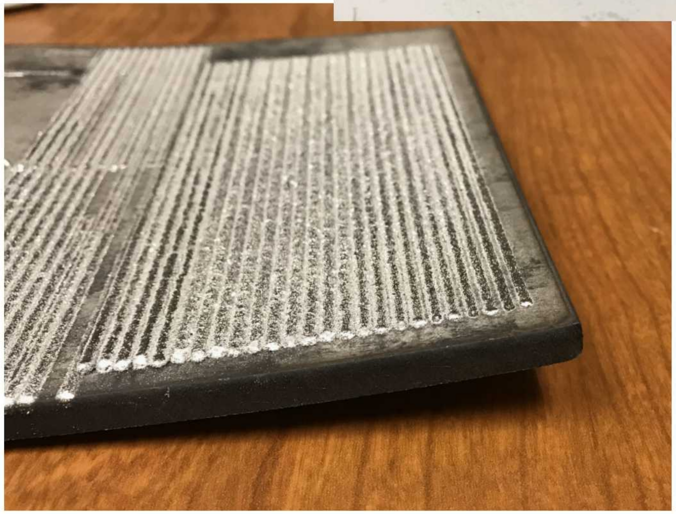
What is the problem?

Rapid heating and cooling during print causes residual stress buildup

Stress buildup causes distortion, warping, and even cracking of printed part

Problematic when higher tolerances or repair jobs are desired

Stress often manifests itself in substrate deformation



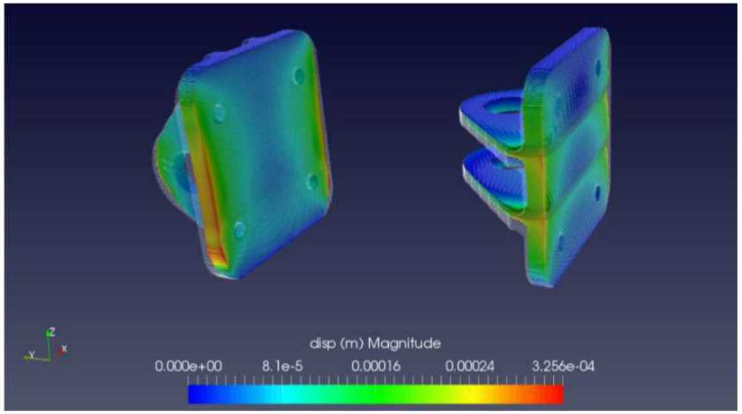
Dealing with residual stress

Very little work done to reduce stress

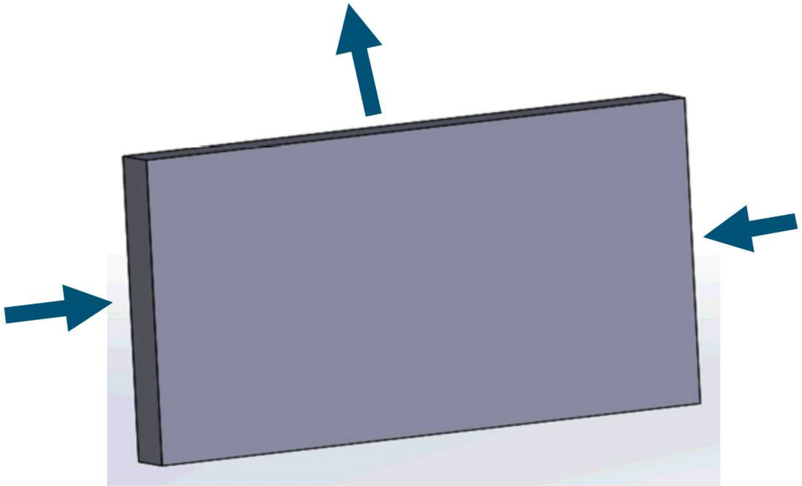
Predictive software packages
- Creates support material
- Change geometry

Direct displacement compensation
- Uses distortion measurements to compensate part geometry

Post processing of Heat treatments or other methods



Model residual stress [1]



Change dimensions of printed part so stress distorts part into tolerance

The welding solution

Why do welders preheat?

- Can raise some metals above brittle fracture temperature
- Reduces shrinking stresses between weld and base material
- Reduces cracking

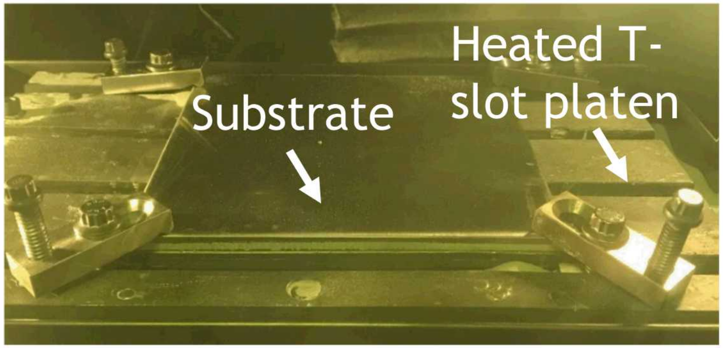
Our approach

- Use electrically heated platen to preheat substrate
- Measure deformation of substrate at various heat levels

Electrical heating [1]

Torch heating [3]

Induction heating [2]



LENS heated platen system

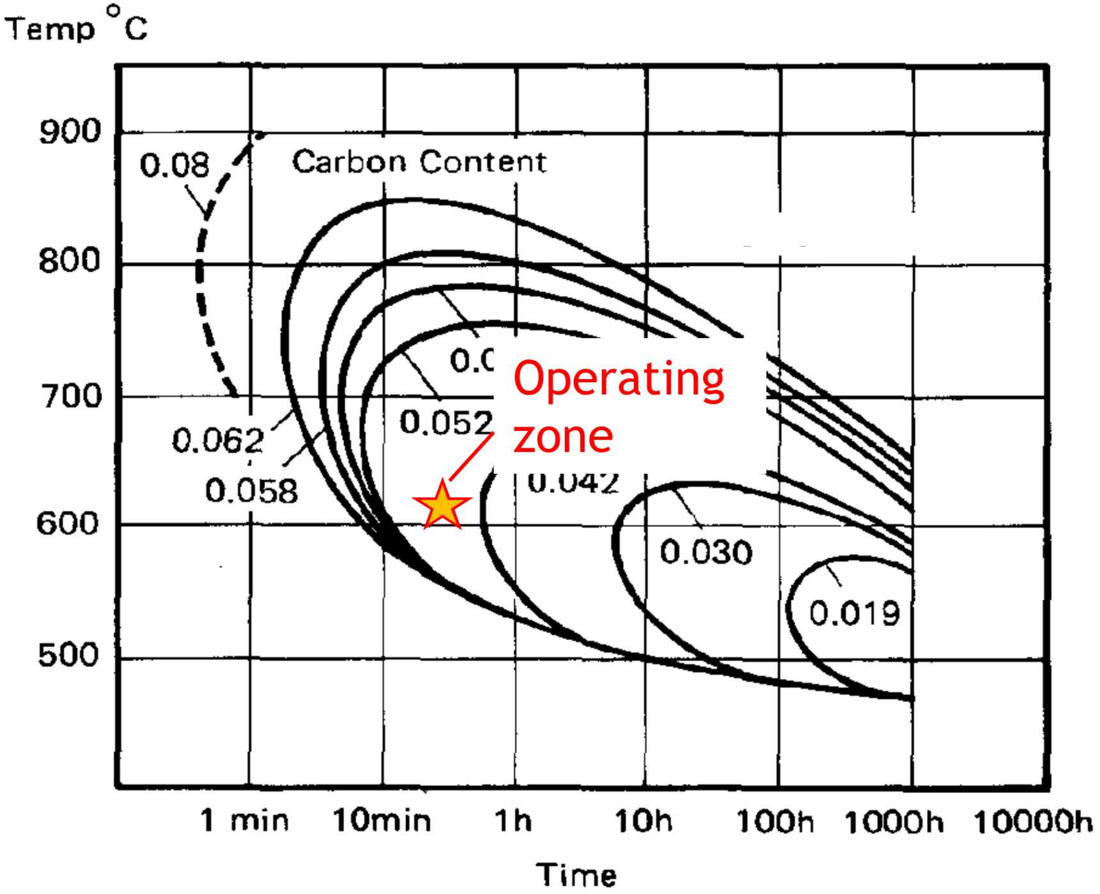
[1] http://thermotest.com.my/index.php/services/
[2]https://www.bakersgas.com/weldmyworld/2015/07/06/preheating-true-or-false/
[3] https://www.youtube.com/watch?v=KAwb6-rElTY

Sensitizing in 304L Stainless Steel

Referencing the British Stainless Steel Association

- Dimensional stability heat treatment
  - Heat to 475°C
  - Slow Cool (approx. 4hrs per 25mm of section)
- In general (to avoid sensitizing the stainless steel) stay away from 480°C - 900°C range
- The low carbon 304L or 316L should not be at risk of corrosion sensitizing

Stainless Steel 304 TTT diagram [1]



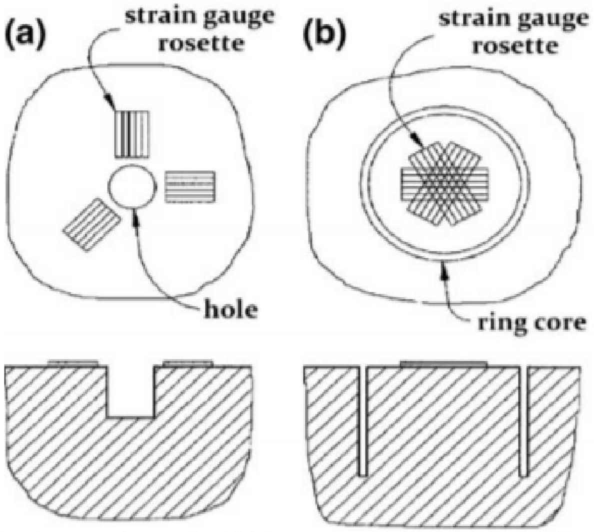
Methods toward residual stress

Non destructive

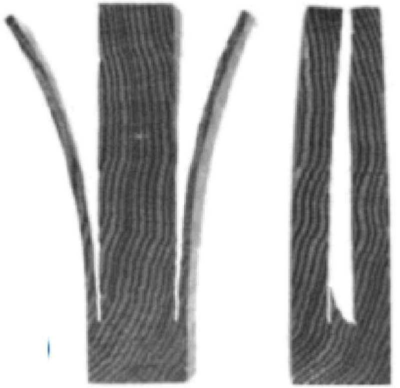
- Neutron Diffraction and X-ray Diffraction
- Sensitive to different materials and geometry

Destructive/Relaxation

- Use fundamental quantities such as displacements or strain
- Remove a section of specimen, then measure displacement
- Calculations can be made to solve for residual stress



(a) Hole drilling method [1]
(b) Ring core method [1]



Slitting Method [1]

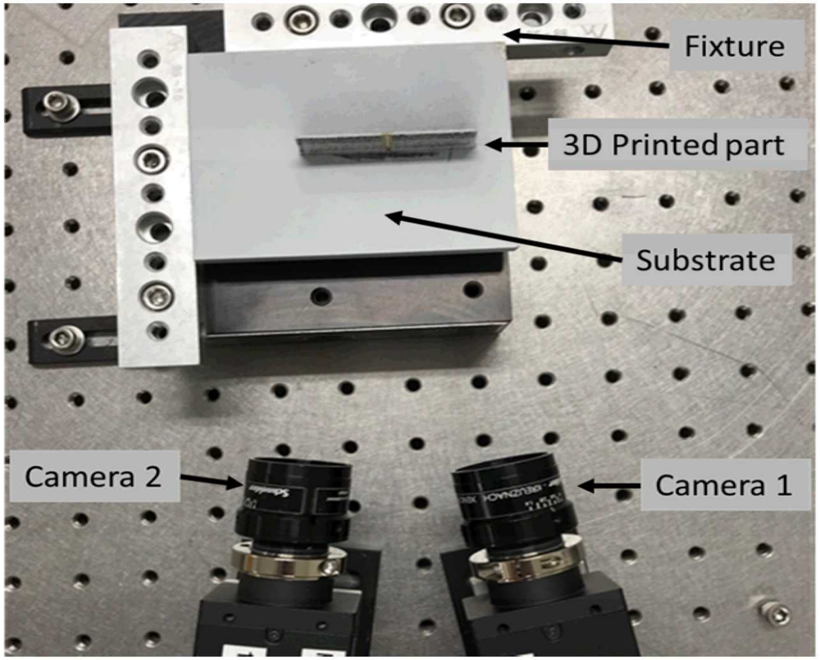
[1] Schajer, G.S. Relaxation Methods for Measuring Residual Stresses: Techniques and Opportunities

Digital Image Correlation (DIC)

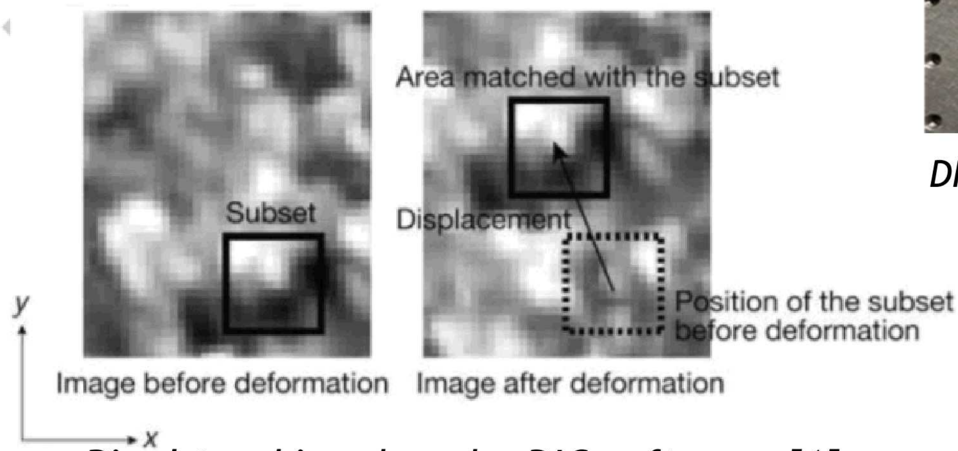
Uses photos of part from before and after material removal to measure distortion

Non contact measurement

Macro or micro scale measurements can be made



DIC setup for measuring stress relaxation



Pixel tracking done by DIC software [1]

Cameras- 12MP Point Grey Grasshoppers.
Lenses- Schneider 17mm.

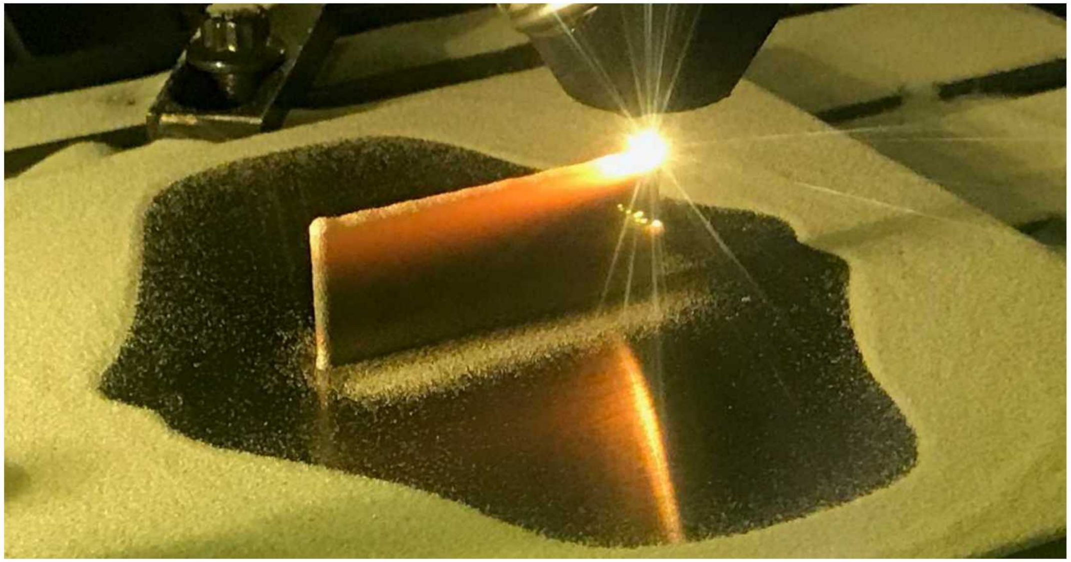
[1] Yoneyama, S. Digital Image Correlation

Material relaxation study

4 substrate clamps, one in each corner of the substrate

3 samples printed at each bed temperature of 50°C, 150°C, 250°C, 350°C, and 450°C

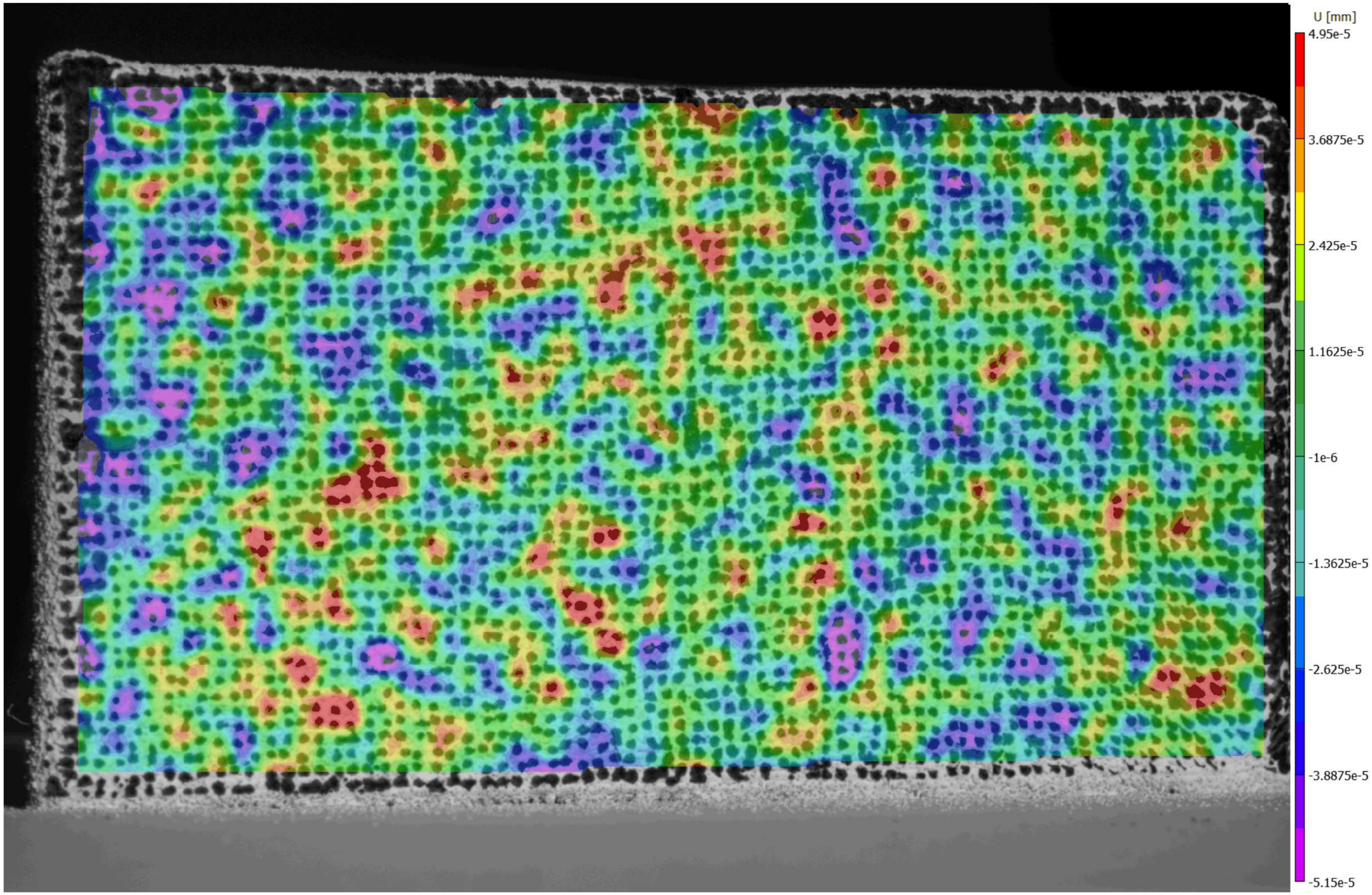
Printed a 2.0" x 0.04" x 1.0" thin wall



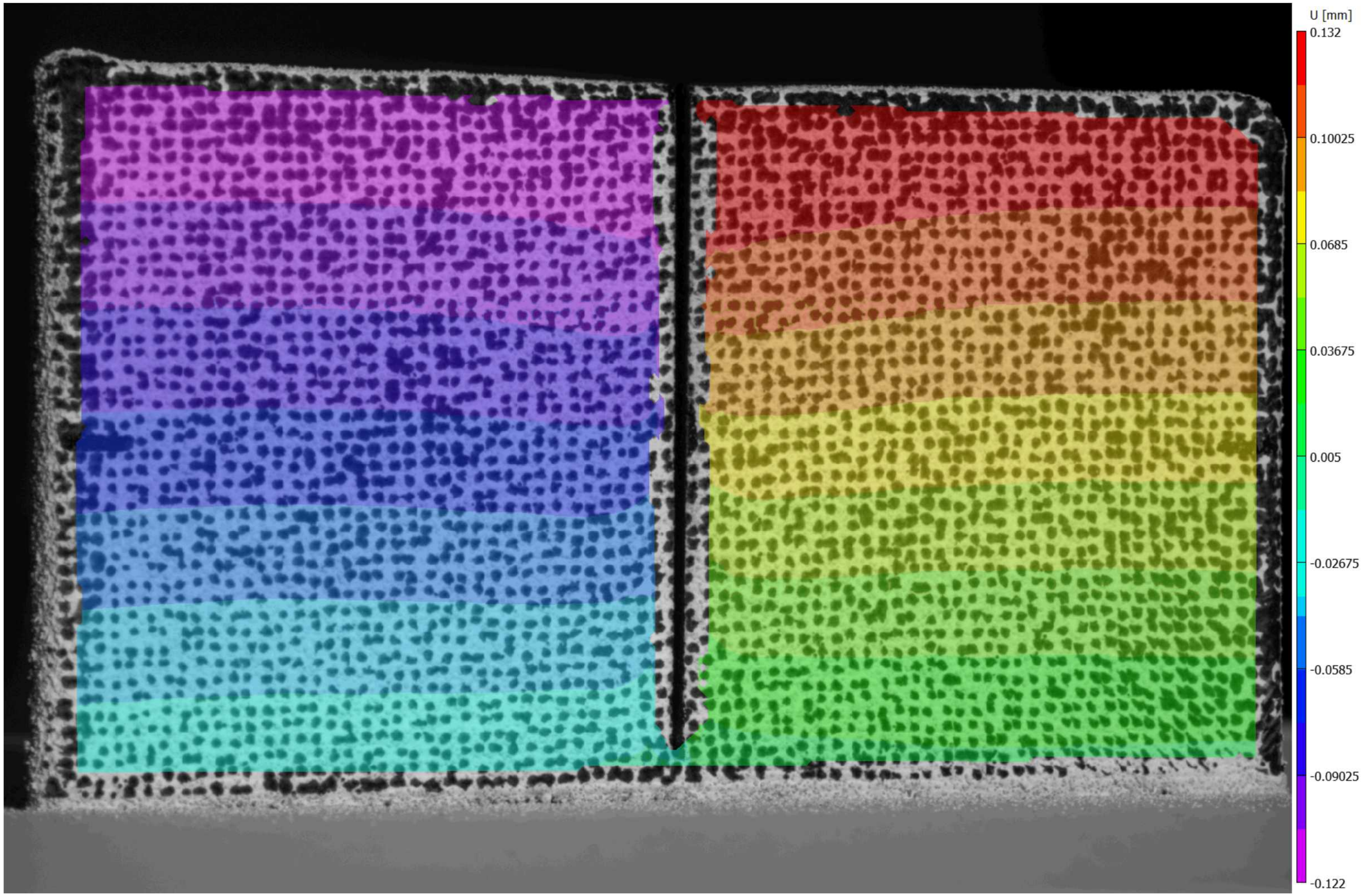
Process Parameters

Laser Power	400[W]
Powder Feedrate	6.5 [g/min]
Layer Thickness	0.25 [mm]
Hatch Spacing	N/A
Parameter Deposition Speed	400 [mm/min]
Infill Deposition Speed	N/A

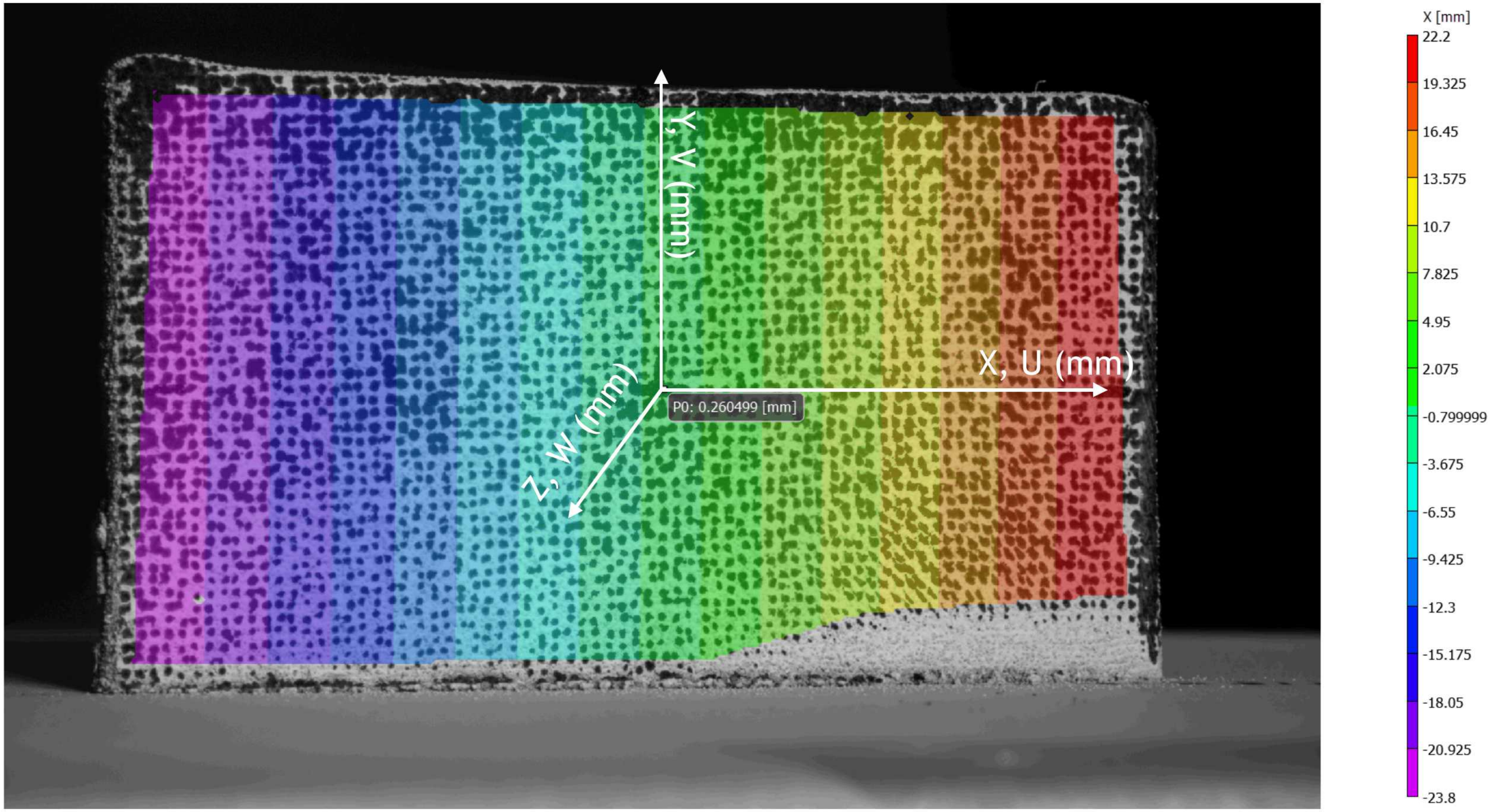
DIC Map Before Cut



Wall Shows Visible Displacement After Cut



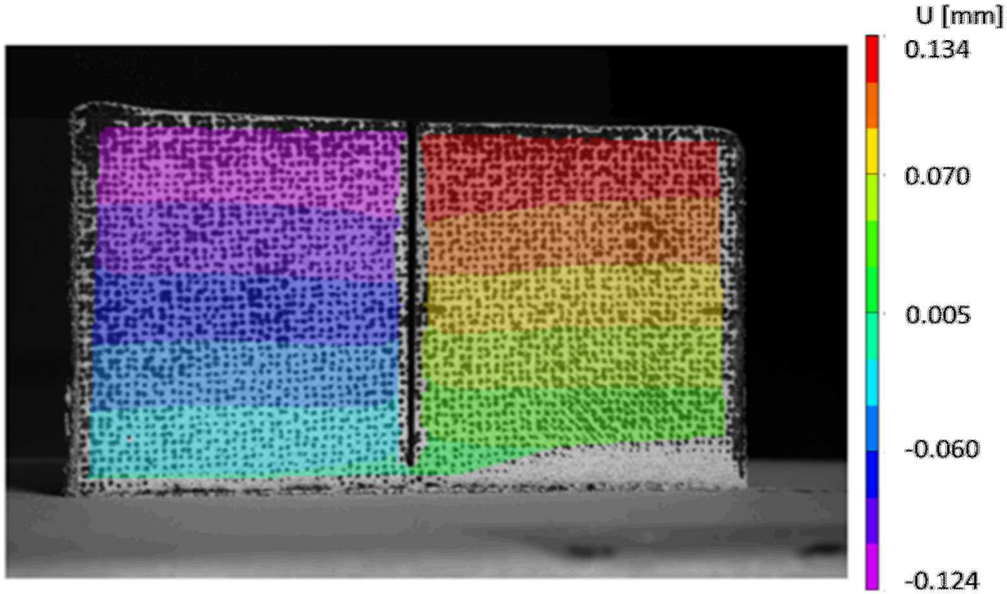
Coordinate System

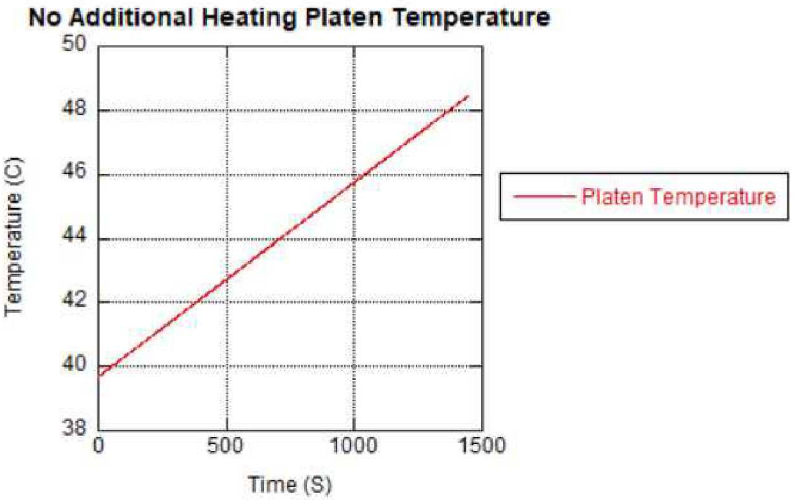


- Data that will be shown is in longitudinal (U) direction
- Slitting method is used to find stress perpendicular to slit

DIC 50℃ results

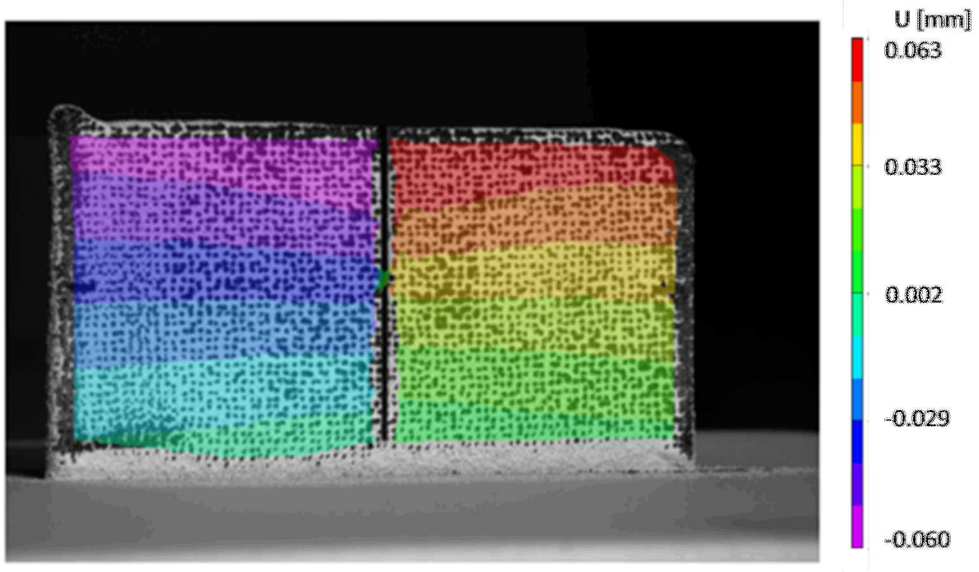
- Platen temperature of >50℃
- Maximum deformation of 0.134 mm
- Deformation is in expected direction
- Increasing substrate temperature due to laser source

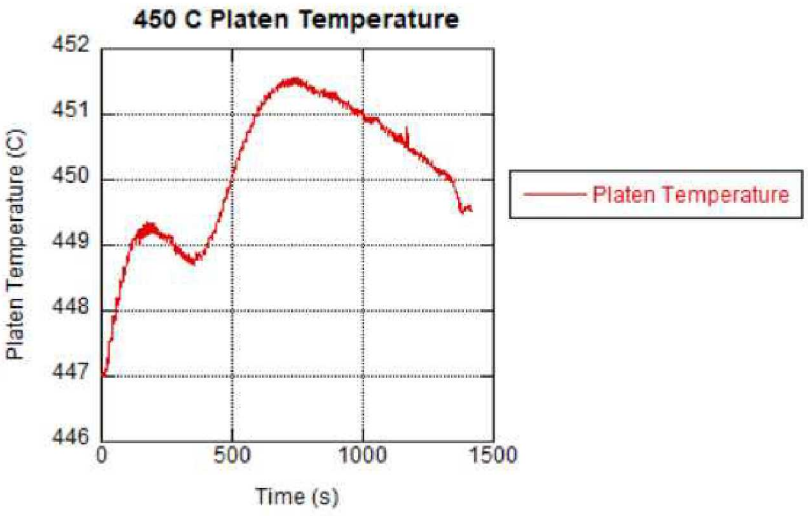




DIC 450°C results

- Platen temperature of 450°C
- Maximum deformation of 0.063 mm (Less than half of no heat added sample
- Deformation is in expected direction
- 0.063 mm < 0.134 mm which suggests significant stress reduction





Room Temperature and 450C Builds Produce Different Thermal Histories

Room Temperature Baseplate

450C Baseplate

First the thermal history of the part is modeled using element birth on the meshed part

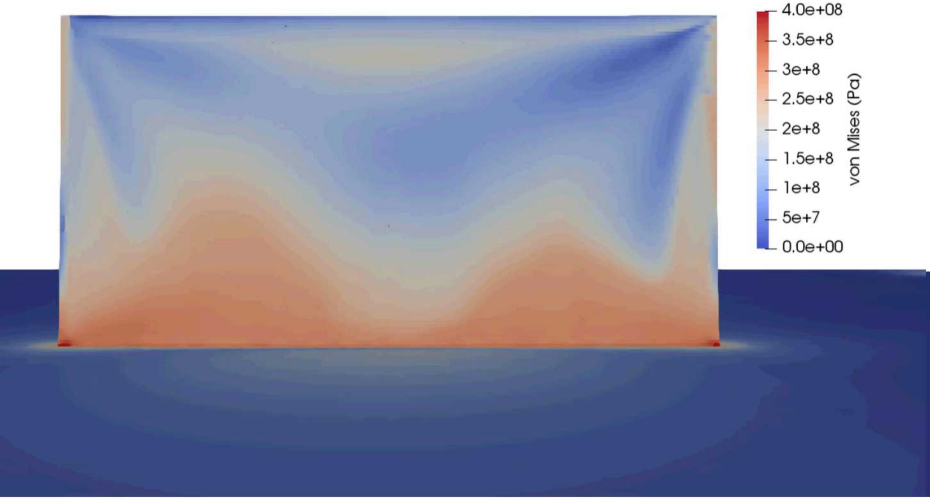
Different Thermal Histories Produce Different Stress States

Room Temperature Baseplate

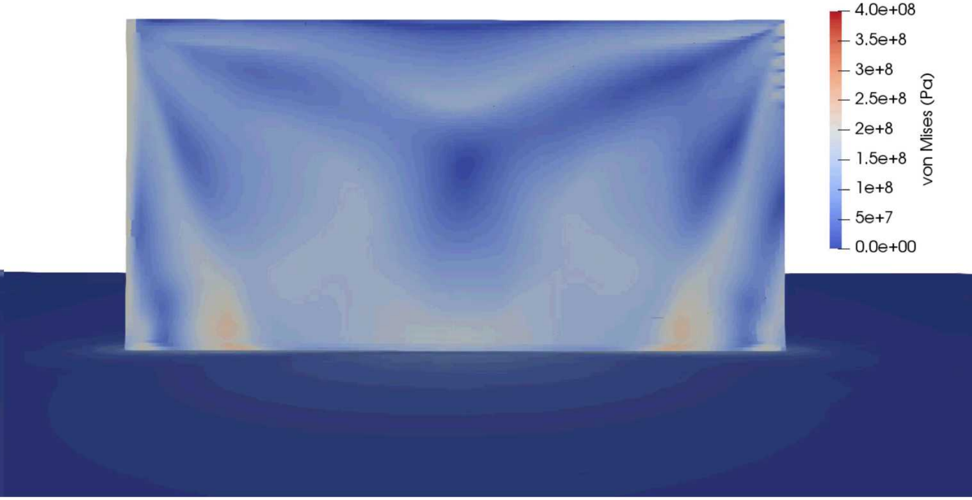
450C Baseplate

Thermal history is used as an input to the solid mechanics model that solves for Von Mises stress throughout the part

EDM Relieves Stress and Causes Distortion



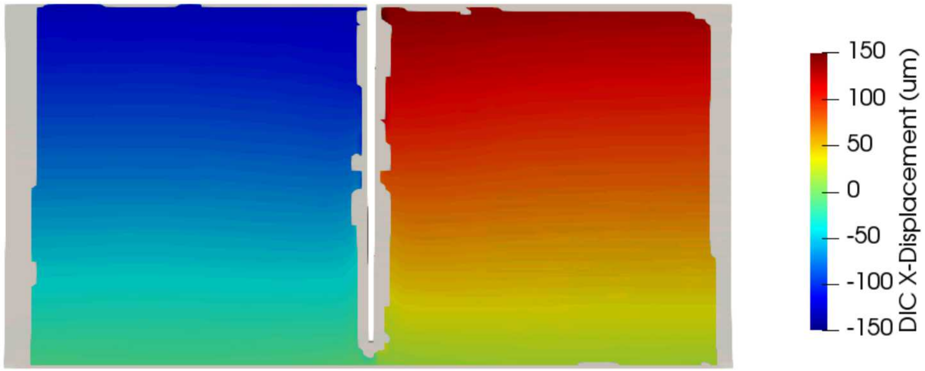
Room Temperature Baseplate



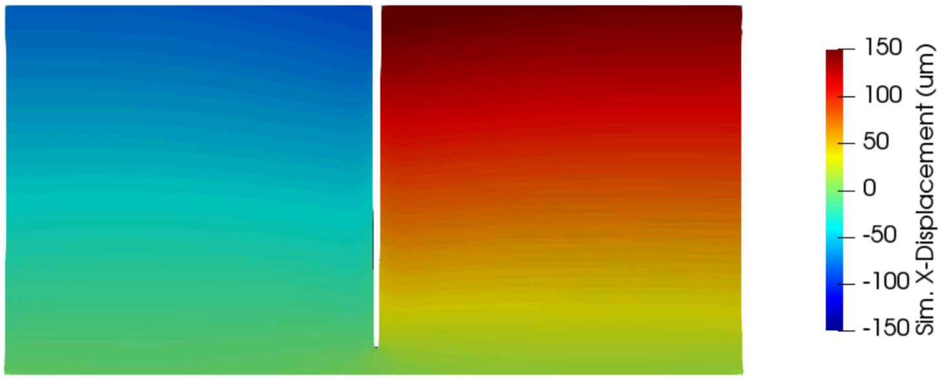
450C Baseplate

Effect of wire EDM on stress state of the part is modeled by element death

Room Temperature Build DIC Data Compares Well With Simulation Results



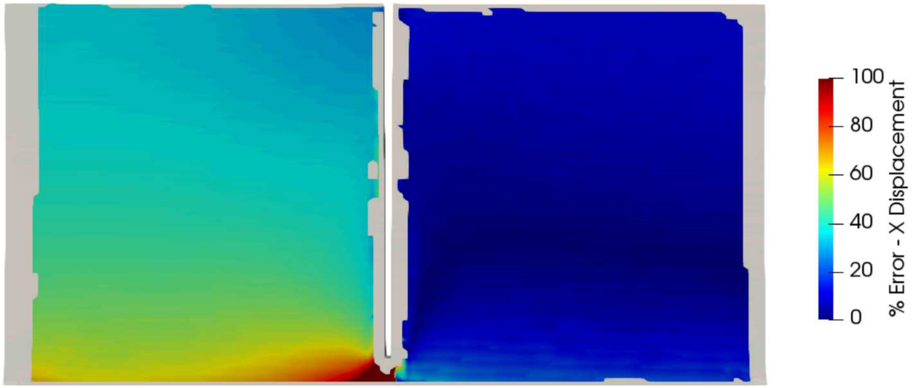
X-Displacement DIC Results Overlaid on Model



X-Displacement Simulation Results

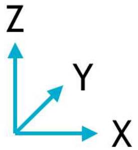
<u>Possible sources of error</u>

- Split the error between two sides
- Spatial Resolution
- Twist (Movement in Y and Z)

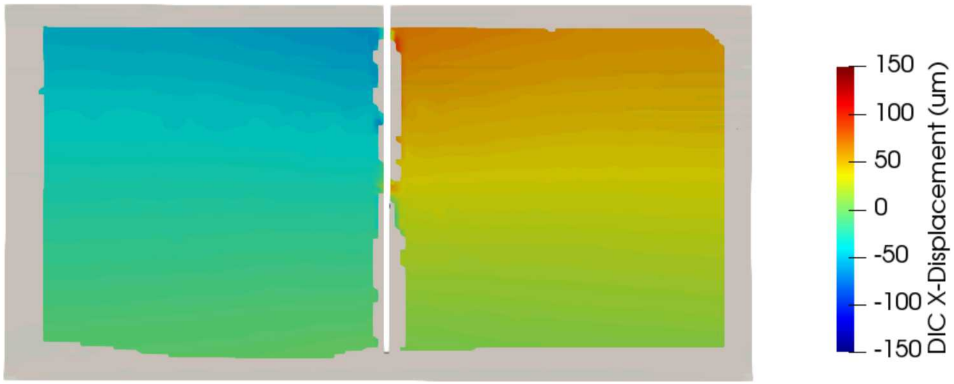


Percent Error

$$\% \, Error = \frac{|\Delta x_{sim} - \Delta x_{exp}|}{\Delta x_{exp}}$$



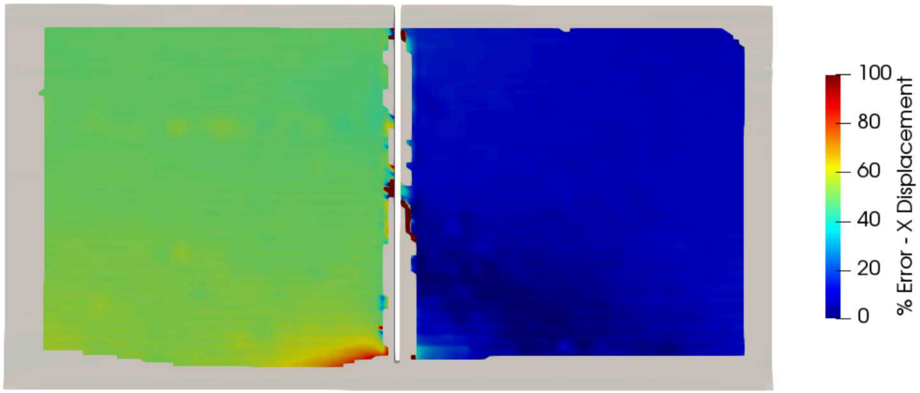
450C Build Shows Reduced Distortion Compared to Room Temperature Baseplate



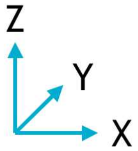
X-Displacement DIC Results Overlaid on Model

X-Displacement Simulation Results

$$\%\ Error = \frac{|\Delta x_{sim} - \Delta x_{exp}|}{\Delta x_{exp}}$$



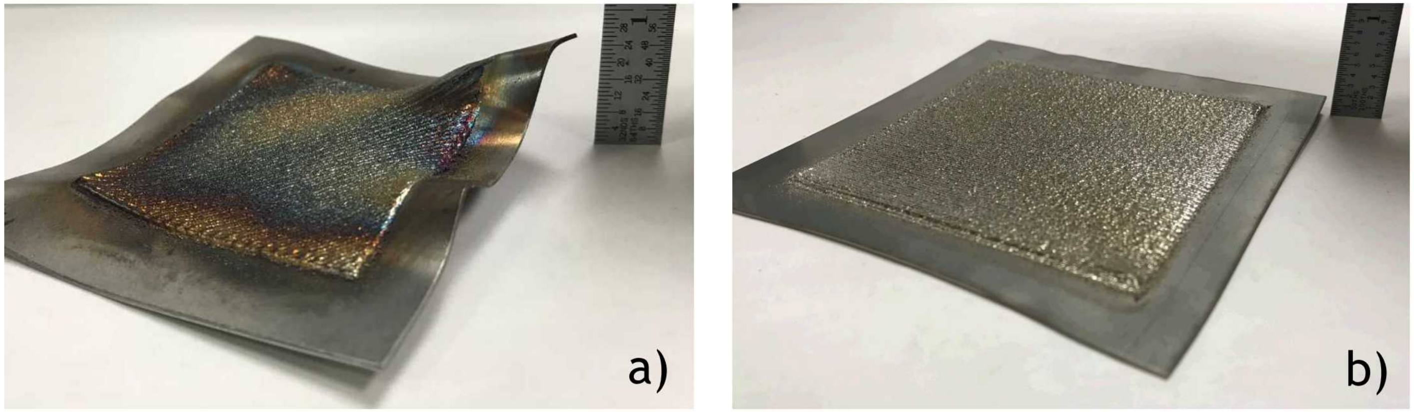
Percent Error



Conclusions

Both experimental data and solid mechanics model show that additional heat during build reduces residual stress

Heating the platen reduces stress by minimizing thermal gradient and reducing cooling rate of melt pool



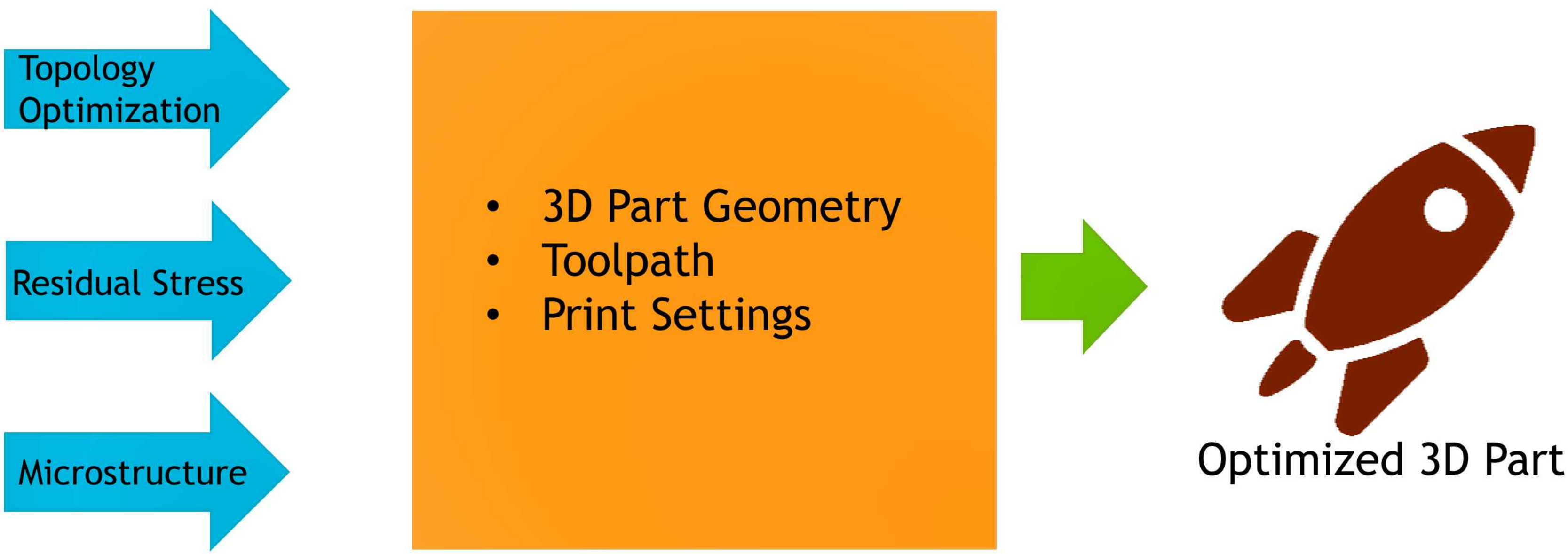
Printing of 3 layer pad on 0.030" shim stock A)No added platen heat. B) Platen temperature of 450°C.

Future Work

- Generalized Relaxation 3D stress field maps
- Explore how part orientation changes stress
- Study the effect of heating on final microstructure of the part
- Expand to other materials
- Combine modeling predictive modeling efforts with toolpath generation to create automated ways of controlling residual stress.
- Transform understanding into a design guide

Impact

- Less warping in parts
- Improved ability to repair parts
- Minimizes need for post print heat treatments
- Greater material selection
- Higher quality parts for aerospace and defense industries



Questions?

Contact Information

Shaun Whetten
srwhett@sandia.gov
505-362-2011

Questions to explore

Heat into substrate

How does warping affect heat transfer into a substrate?

How does clamping affect warping and the heat transfer?

Is there a lag in substrate heating compared to the platen temperature?

Thermal gradient through height of 3D part

What substrate temperature is need to minimize stress in 3D printed parts?

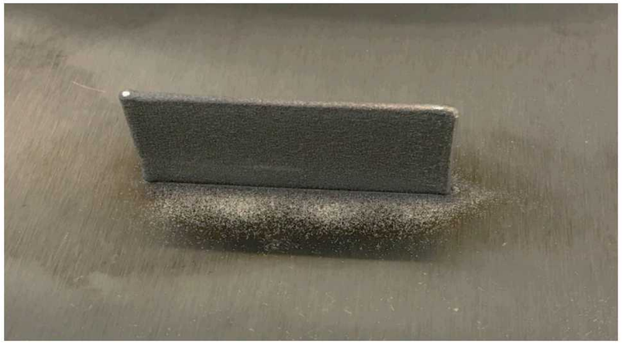
How does part geometry affect the temperature history of a printed part?

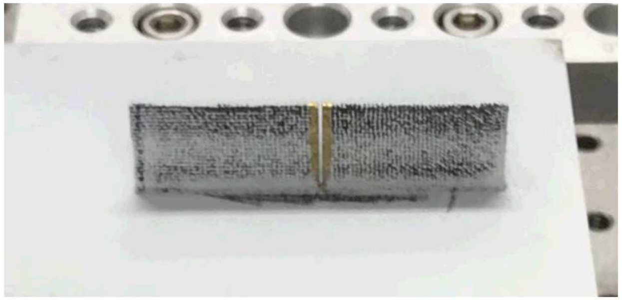
How do substrate heating (bottom) and laser heating (top) affect thermal gradient in printed parts? Are sections of the part at a lower temperature than the temperature of the substrate?

Slitting Method

Destructive/ Relaxation method

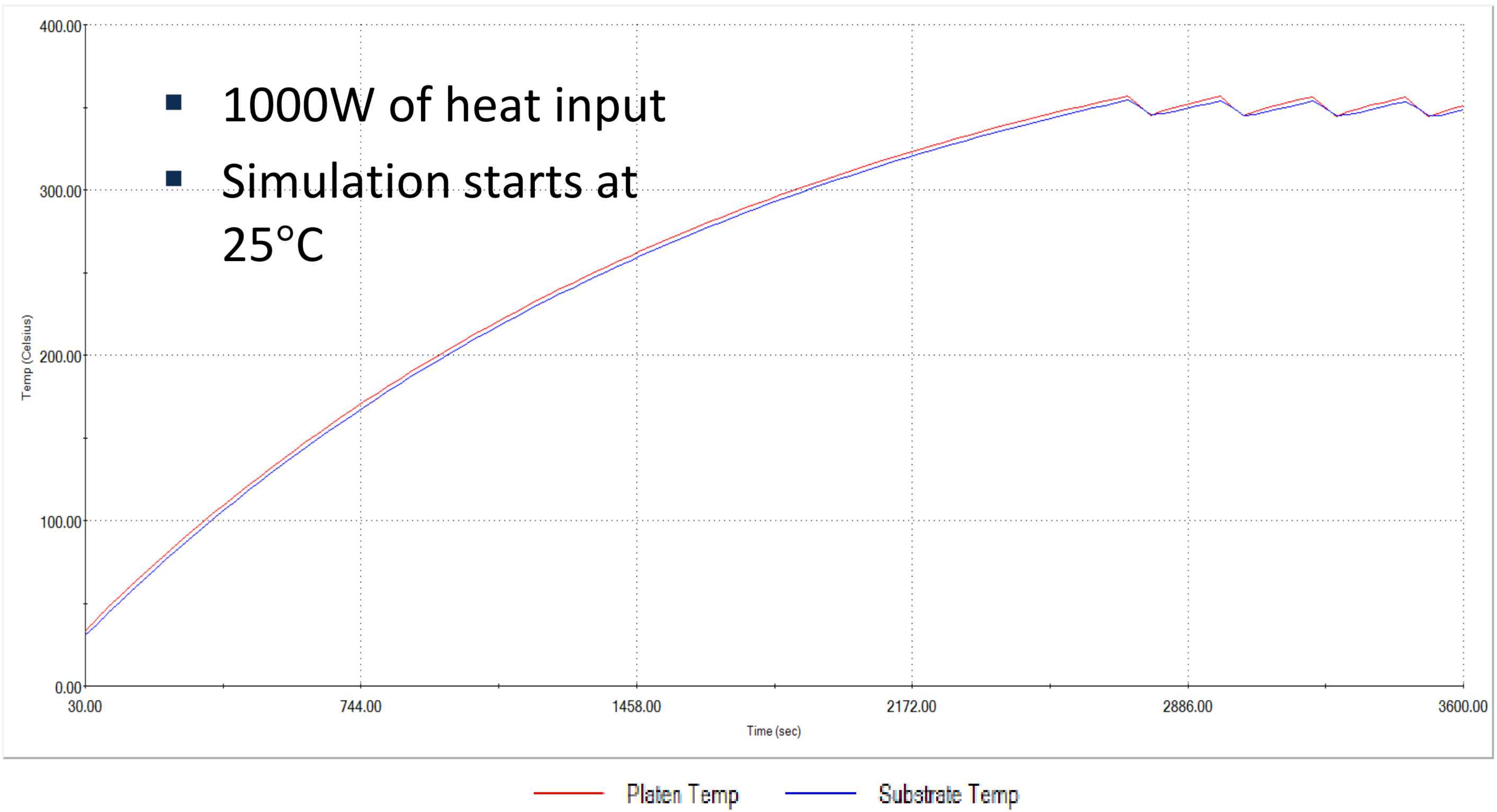
Possible to solve for stress profile over through height of part





Platen temperature vs. Substrate temperature

- 1000W of heat input
- Simulation starts at 25°C



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

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

- 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)