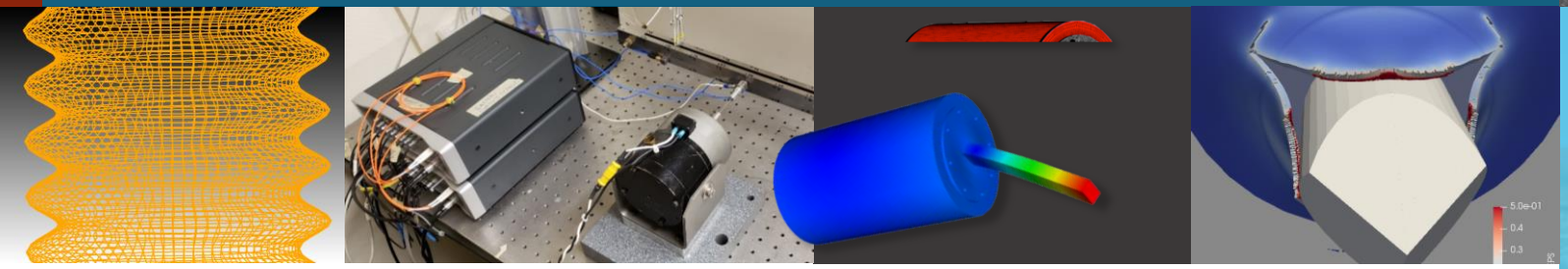
A Distortion Compensation Workflow Accounting for the Effects of Post-Processing in Metal Additive Manufacturing



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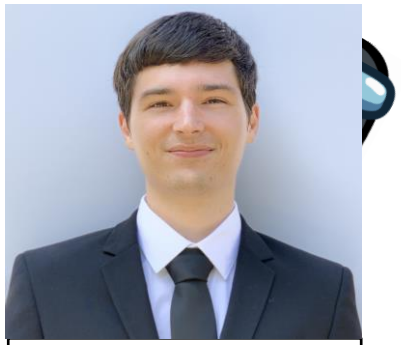

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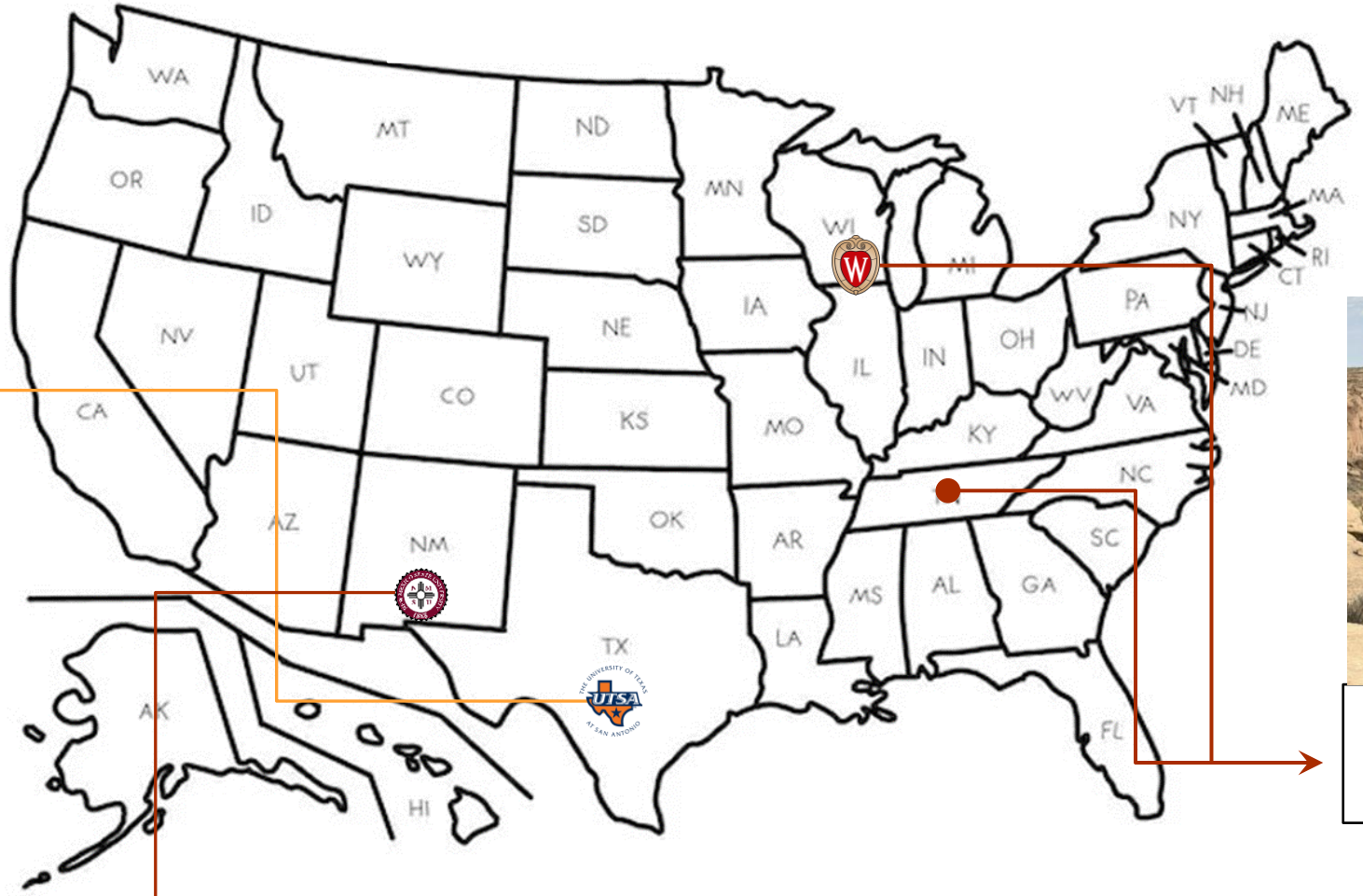


Varun Gudibanda

Contents

- Background information: Distortion in metal additive manufacturing
- Post-processing effects
  - Heat treatment
  - Baseplate removal
- Distortion compensation optimization algorithm
- Numerical results

BACKGROUND & MOTIVATION

Metal Additive Manufacturing: Selective Laser Melting (SLM)

- Thin layer of metal powder is melted
- Part is built layer-by-layer
- Various materials can be utilized

https://youtu.be/qzhLijYn4Ng?t=38

Post-Processing for Metal AM- Heat Treatment

- Thermal process to reduce internal stress in AM components.
- Heat treatment process:
  - Annealing
    - Heating phase
    - Holding phase
  - Quenching
    - Cooling phase
- Relieves residual stress
- Deformation occurs
  - Thermal expansion
  - Residual stress relief

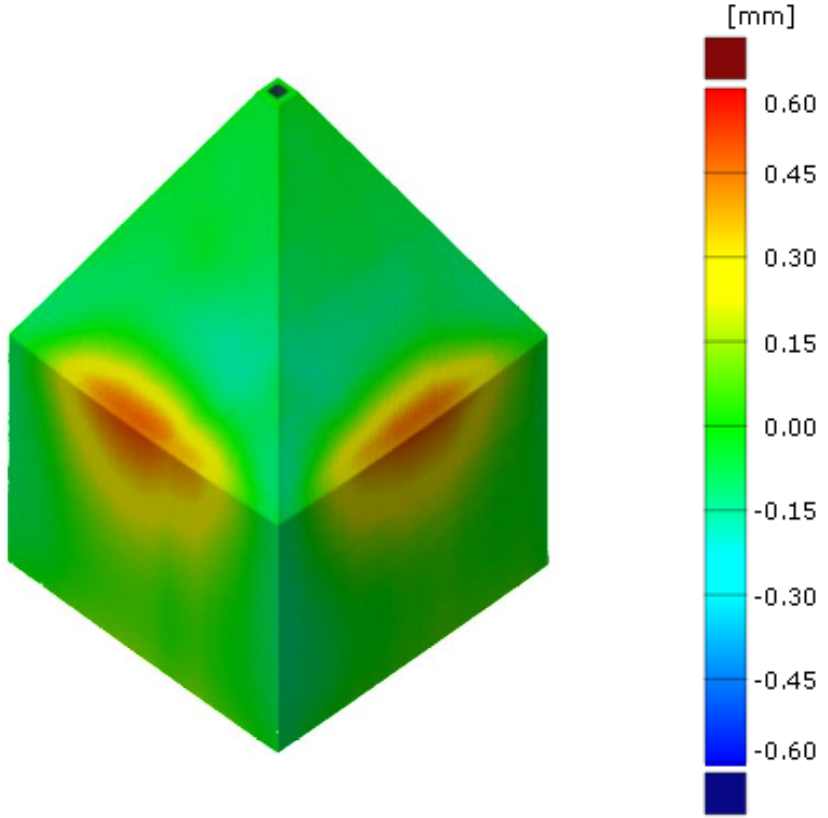
Post-Processing for Metal AM- Baseplate Removal

- A part needs to be removed from the baseplate after it is built
- Electrical Discharge Machining (EDM) wire removes the part from the base plate
- Deformation occurs from stress relief when baseplate is detached

Problem: Distortion Occurs During AM Process

- High temperature gradients are created during SLM process
- Temperature gradients generate residual stress within the component
- Stresses cause the part to distort away from the as-designed geometry

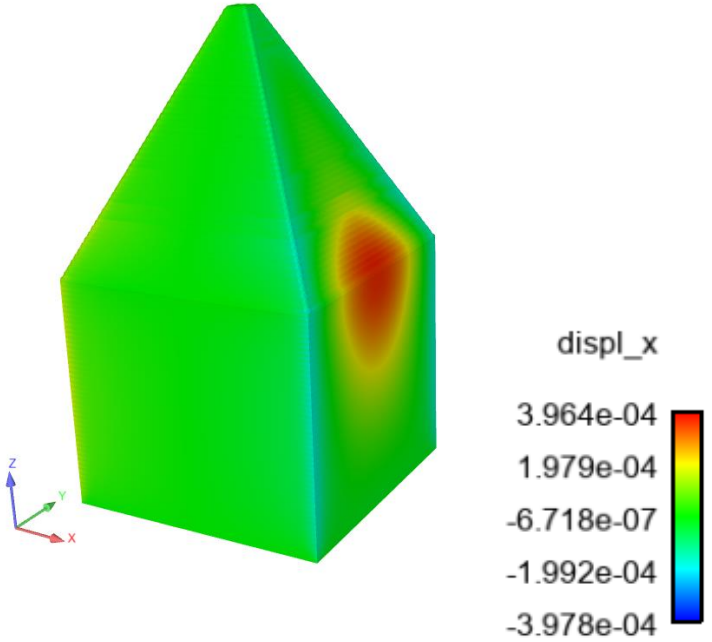
Distortion of uncompensated printed part relative to CAD geometry



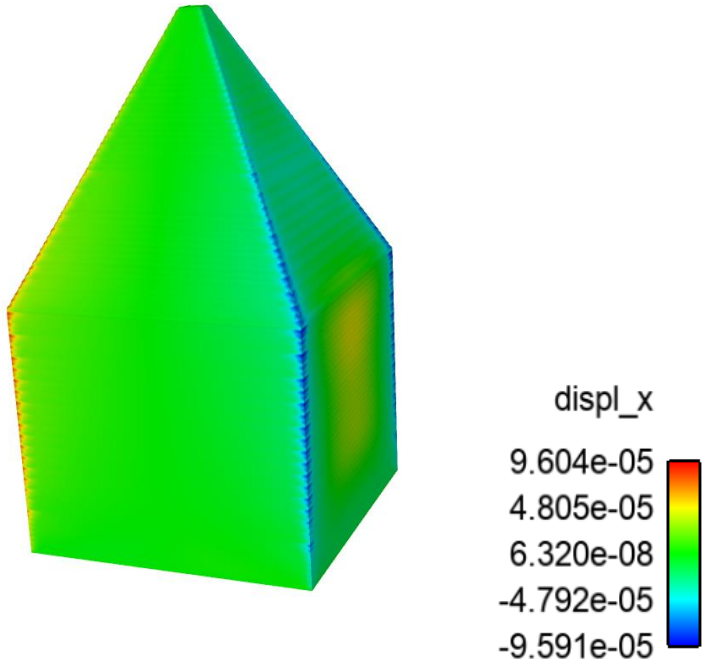
Proposed Solution: Distortion Compensation

- Model AM process in Finite Element Analysis (FEA)
- Iteratively scale nodal coordinates to obtain the as-designed-part within a specified tolerance

Original Distortion

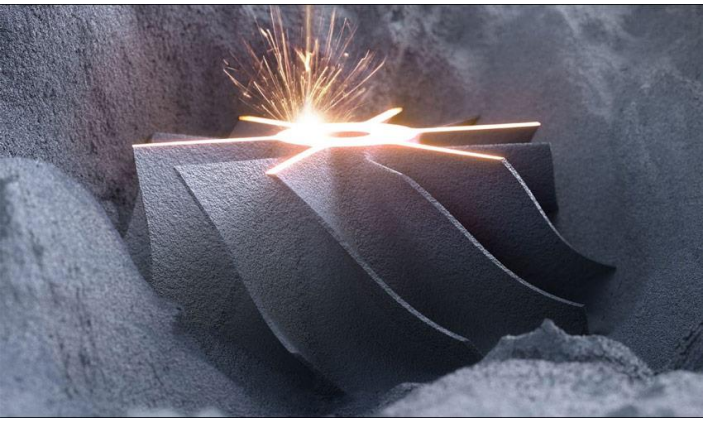


Final Distortion

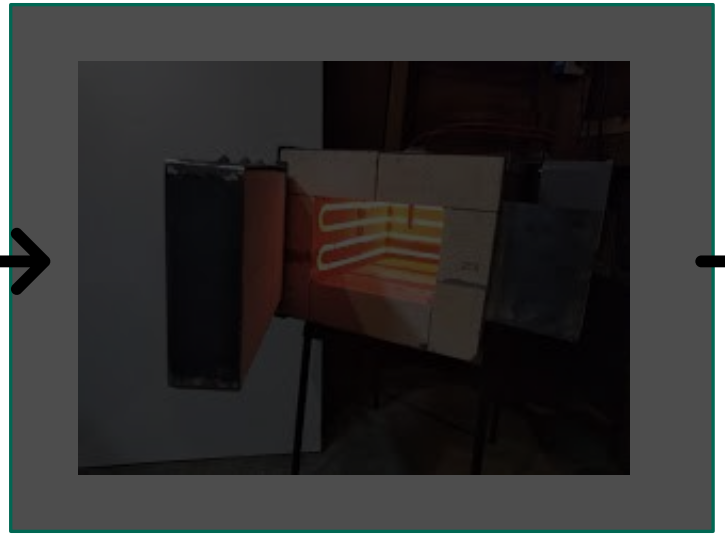


PROJECT WORKFLOW

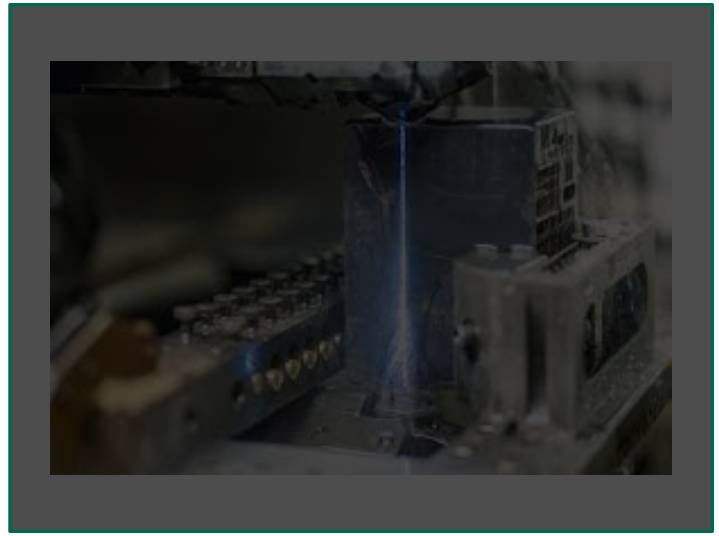
AM Process



Printing Process

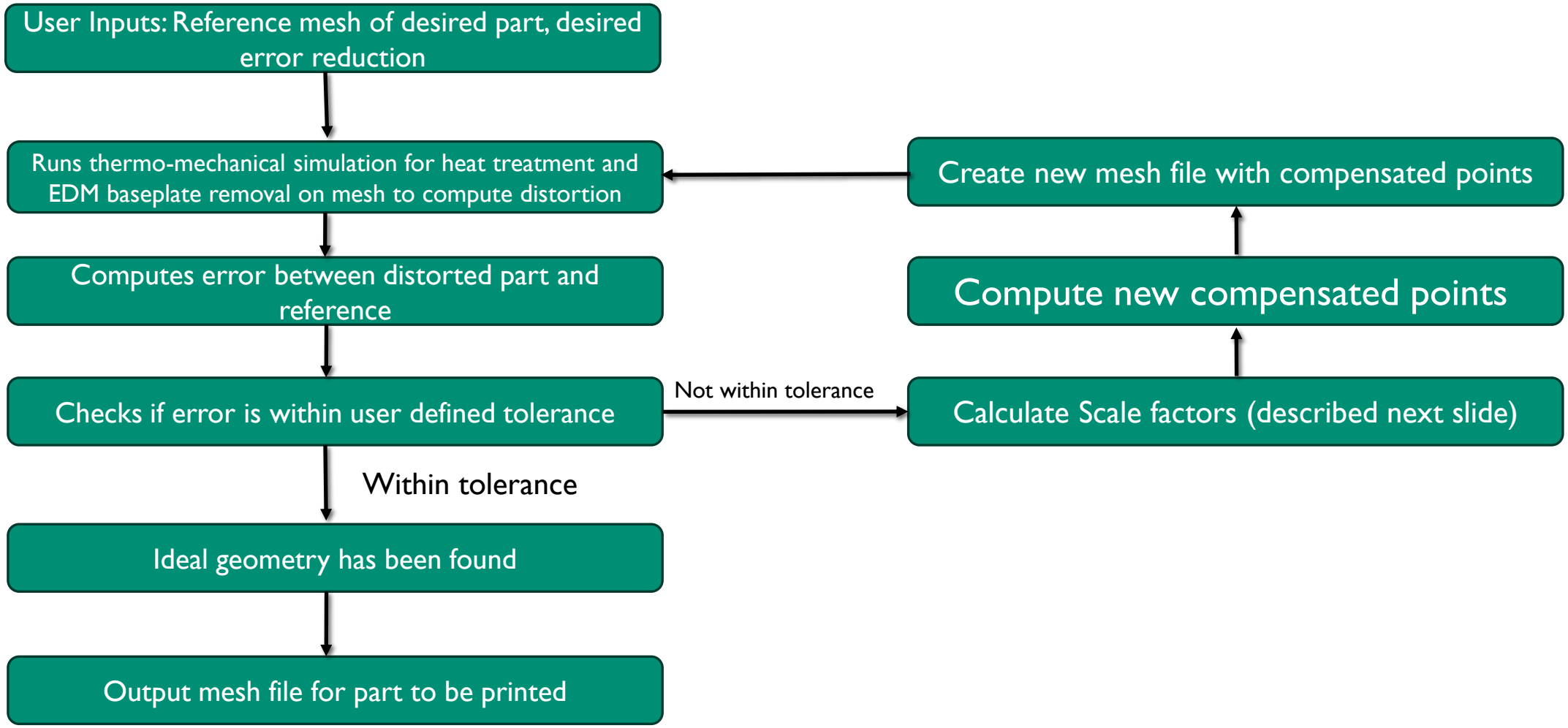


Heat Treatment

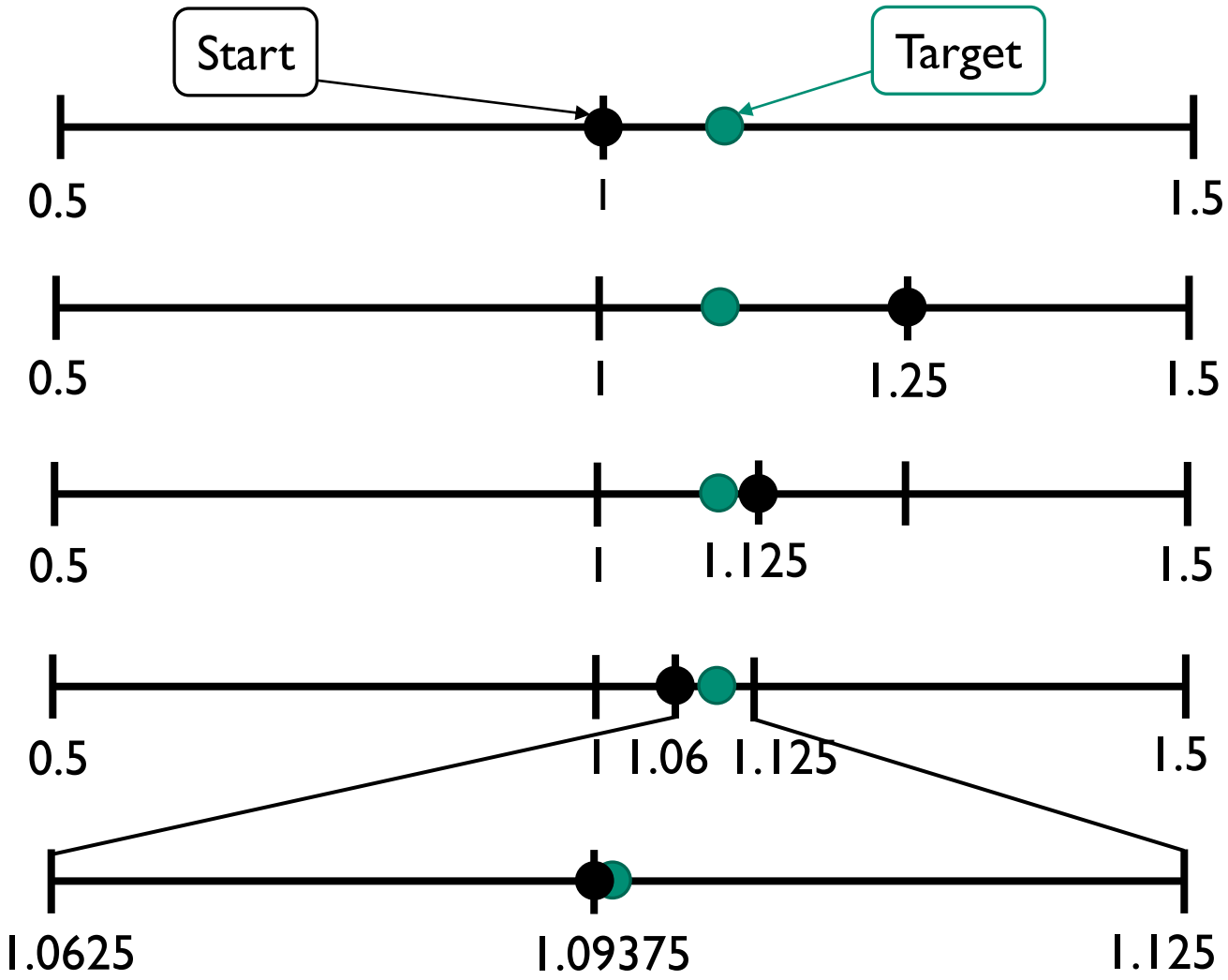


Baseplate Removal

Compensation Algorithm



Distortion Compensation Algorithm Example



Apply initial distortion compensation (100%)

Distortion too high; same sign as initial distortion → increase scale to 125% for second iteration

Distortion changed sign → overcompensated! Invert previous operation: reduce scale to 112.5%

Distortion has same sign, decreased in magnitude → repeat previous operation: reduce scale to 106.25%

Distortion changed sign → overcompensated! Invert previous operation: increase scale to 109.375%

Distortion within tolerance after final iteration, print corresponding geometry.

PROJECT RESULTS

Deformation Prediction

Challenges in finite element modeling stem from the wide range of spatial and temporal resolution required for additive manufacturing modeling

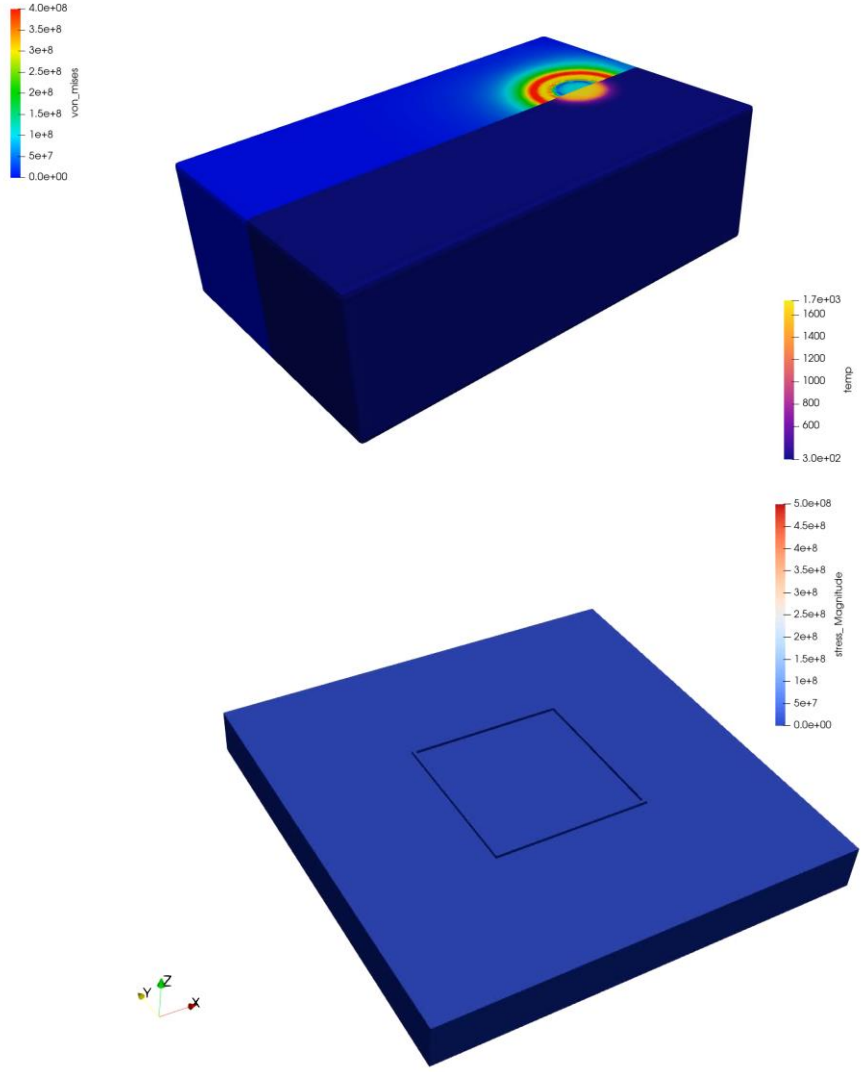
Thermal/Fluid/Solid coupling

- High fidelity models with lots of relevant physics
- Very high computational cost

Modeling Approaches

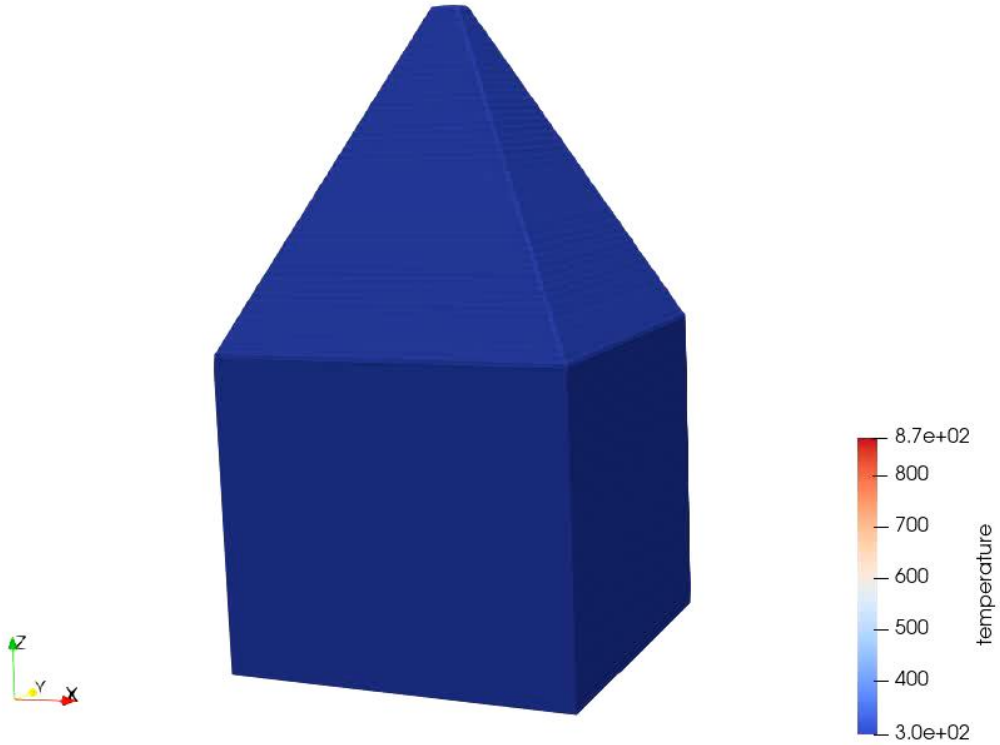
- Inherent strain method: mechanical simulations
- Apply uniform strain to elements

- Only approach efficient enough for inverse analysis
- Inherent strain parameters are calibrated from experiments



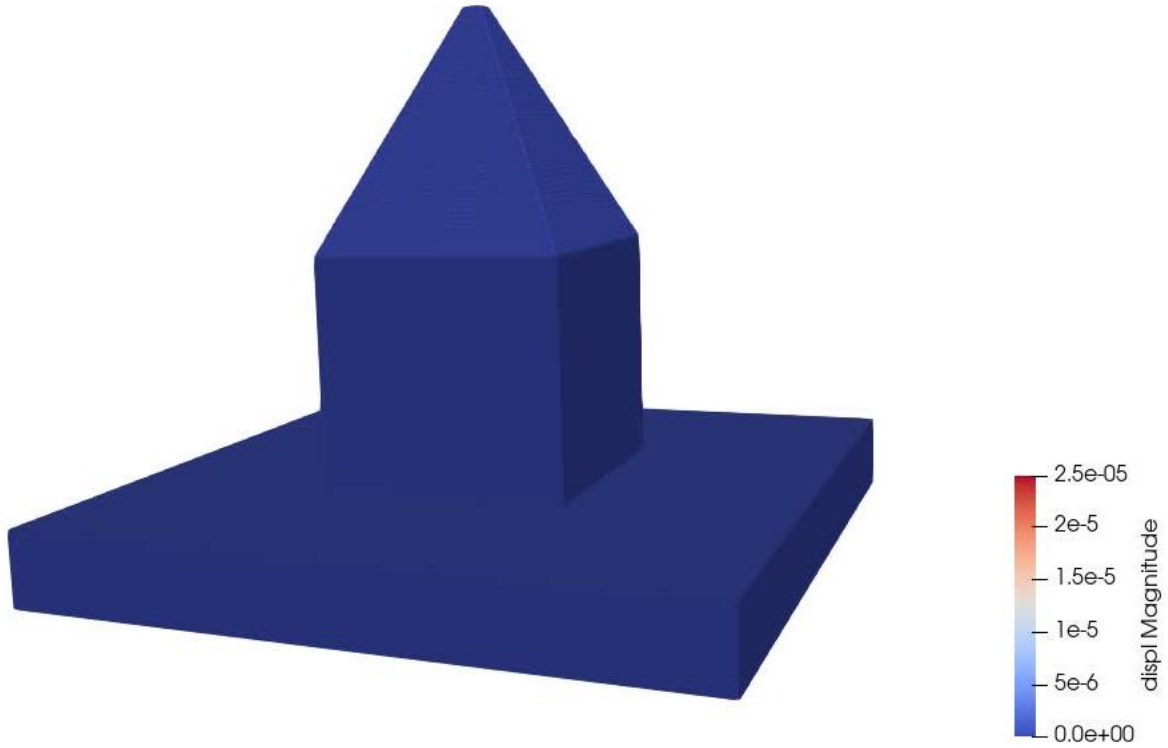
Heat Treatment Simulation

- Principal annealing temperature is specified before simulation runs
- Heating phase (oven heated) increases temperature at 1°C/minute from room temperature
- Holding phase (in oven) lasts for one hour
- Quench phase (air cooled) decreases temperature at 0.67°C/minute
- Arpeggio (coupled Sierra Adagio and Aria) used to integrate part build and heat treatment

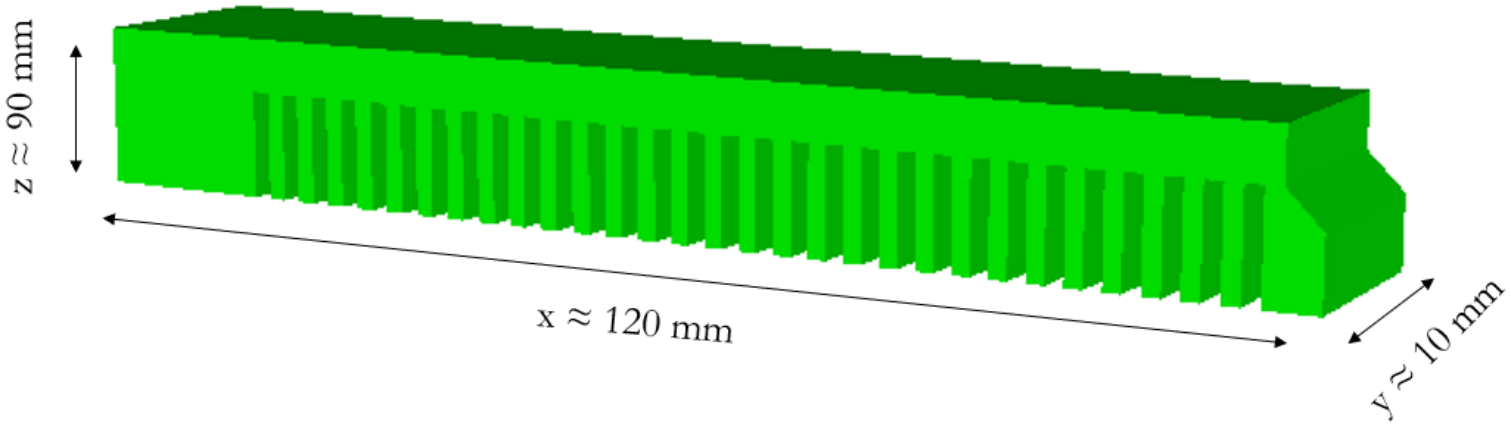


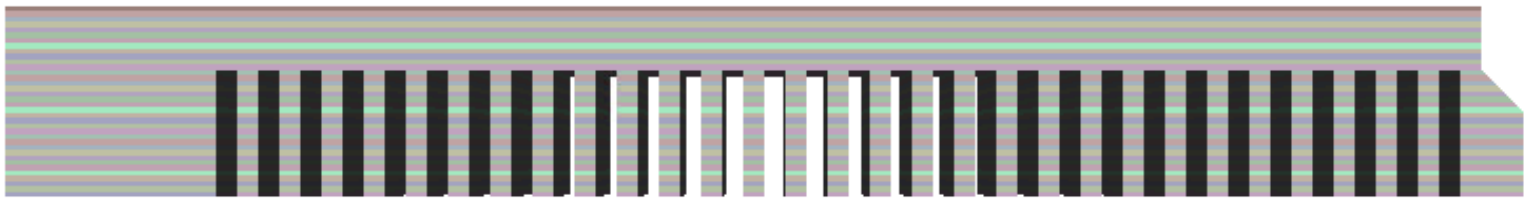
Baseplate Removal

- Cylindrical EDM wire cut is performed
- Tool pathing begins at the edge of the baseplate
- Can be enabled before or after heat treatment step in simulation
- Element death used to kill elements using a cylindrical spatial criteria
- Wire diameter can be changed as needed



Model & Mesh Overview



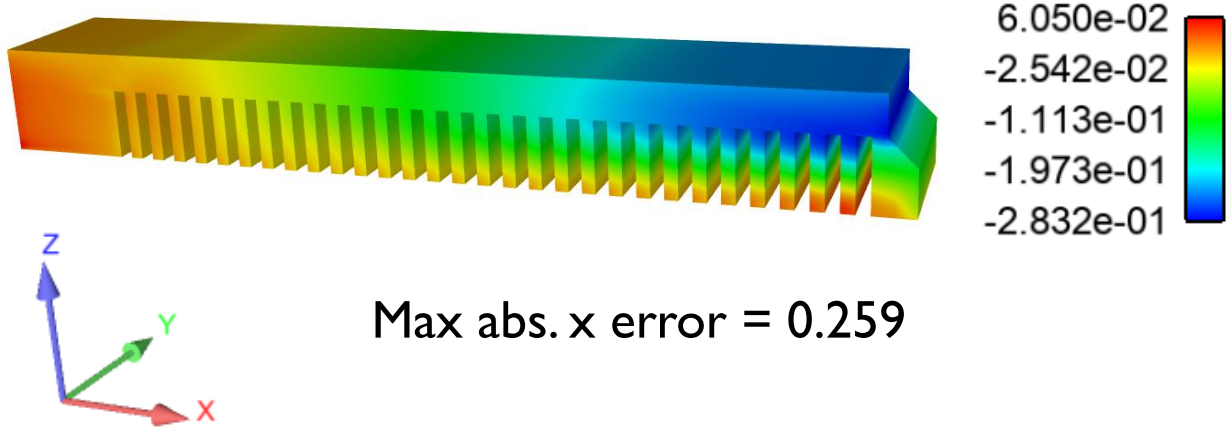


'Harmonica' Geometry

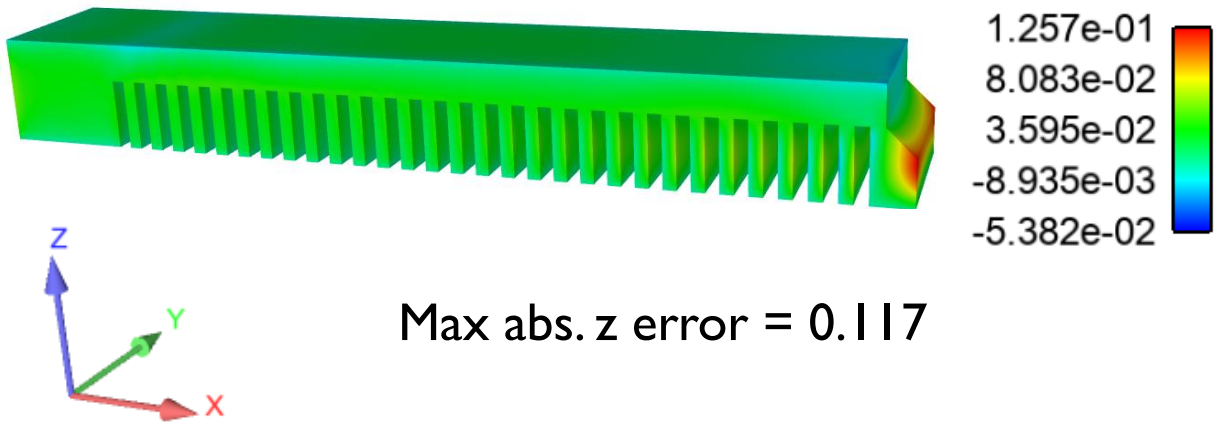
- Number of Layers: 36
- Element Type: HEX8
- Number of Elements: 22132
- One row of elements per layer

Harmonica Results: Heat Treatment then EDM

Original Distortion

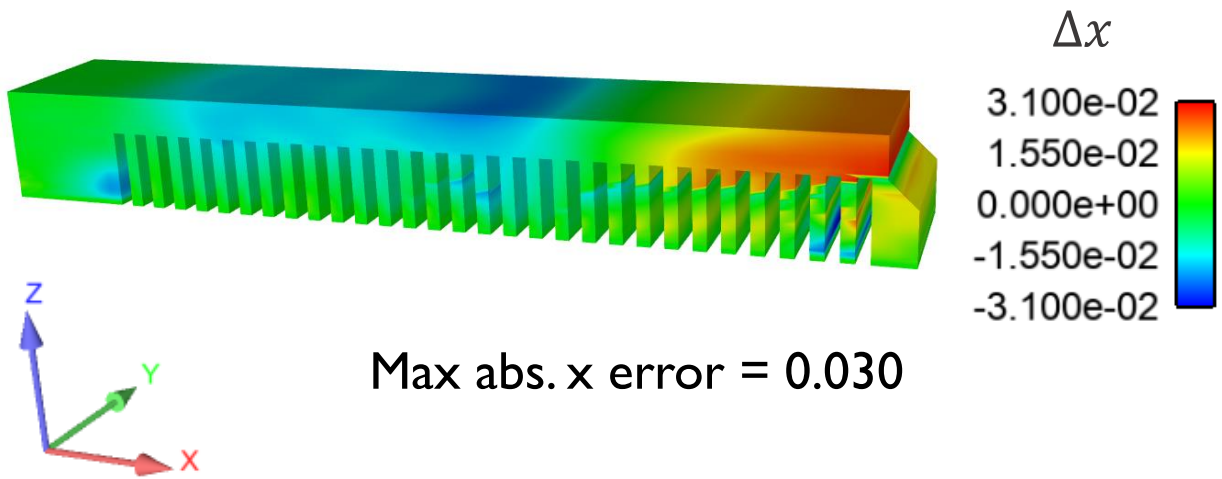


Max abs. x error = 0.259

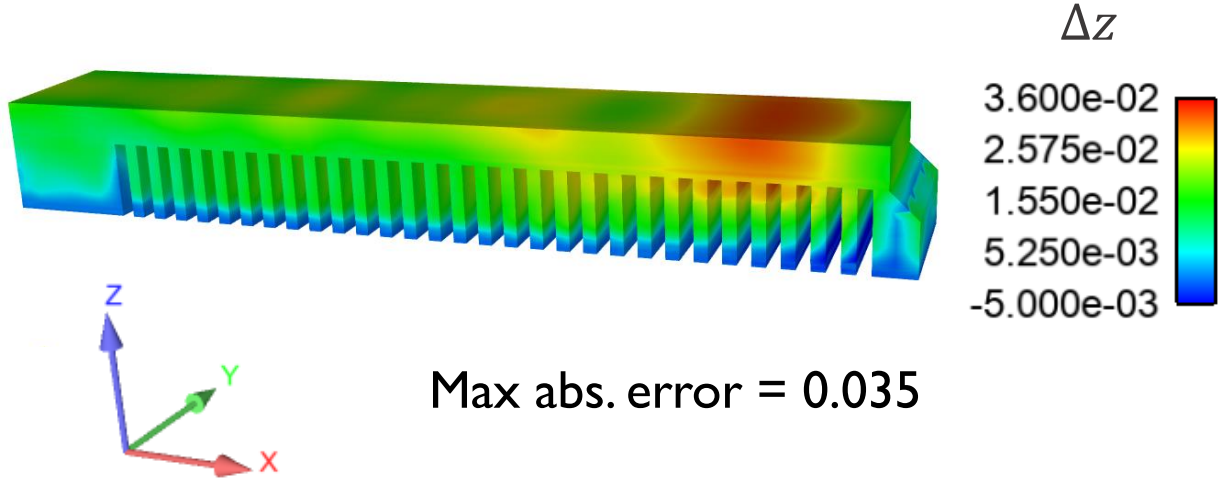


Max abs. z error = 0.117

Final Distortion from as-designed-geometry of final iteration (2 iterations)



Max abs. x error = 0.030

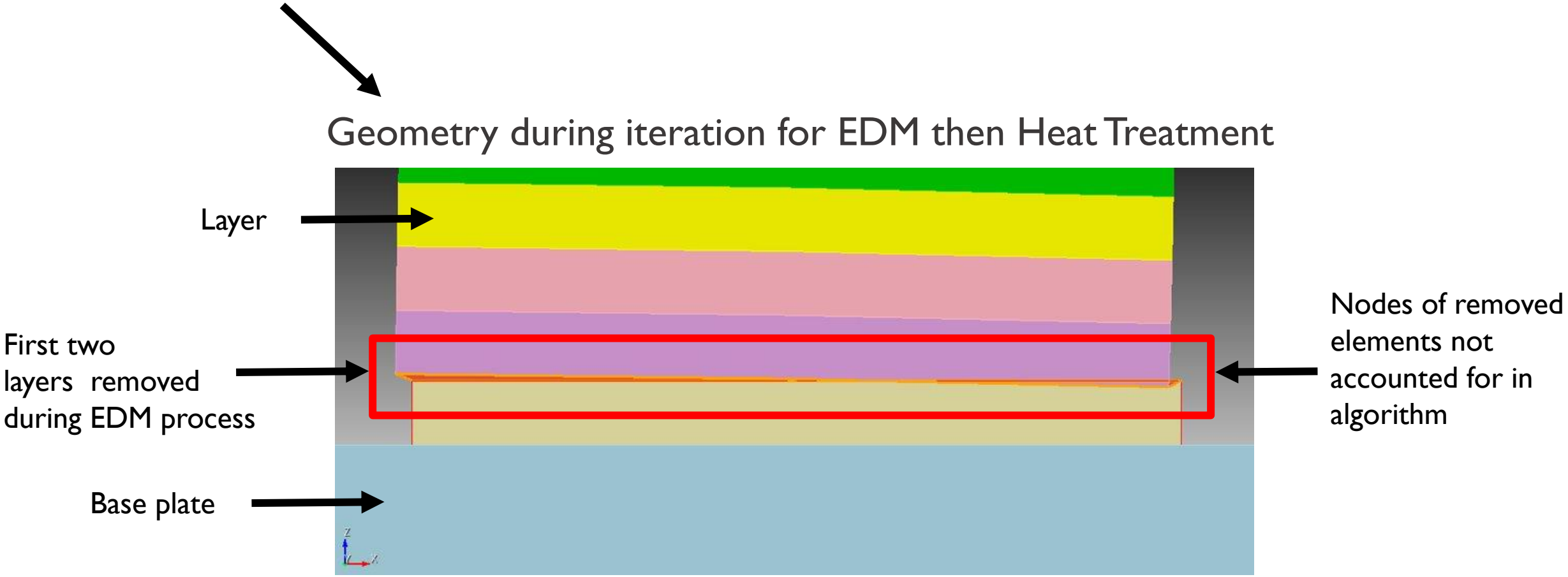


Max abs. error = 0.035

Current Developments

- Convergence issues based on maximum nodal displacement
- Geometry quality during iterations

Geometry during iteration for EDM then Heat Treatment



Conclusions

- Implemented thermo-mechanical simulations to simulate heat treatment and EDM wire baseplate removal
- Implemented post-processing effects into the distortion compensation workflow
- Tested this workflow on the harmonica geometry and identified potential issues

Future Work

- Experimentally validate the algorithm with a printed proof-of-concept
- Experimentally validate distortion from heat treatment and EDM baseplate removal
- Investigate optimization methods to improve computational efficiency and robustness of convergence
- Implement remeshing methods to avoid negative element volume

Acknowledgements

- The authors would like to acknowledge the support of our mentors, Kyle Johnson, Michael Stender, Carl Herriott, Ellen Wagman, and Sannmit Shinde.
- The authors would also like to acknowledge the previous interns who worked on this project: Collette Gillaspie, Mehmet Sirtalan, and Theresa Honein.
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- Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & 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.

THANK YOU!

We will take your questions at this time.

BACKUP SLIDES

Introducing Ourselves

Varun Gudibanda

- Has played the hit game Among Us (available on iOS and Android for free)

Ezekiel Granillo

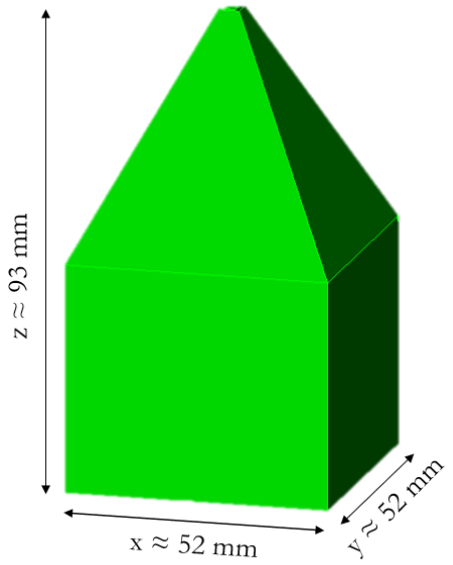
-Can solve a Rubik's Cube as of less than a month ago

Matthew Balcer

-Afraid of things that move

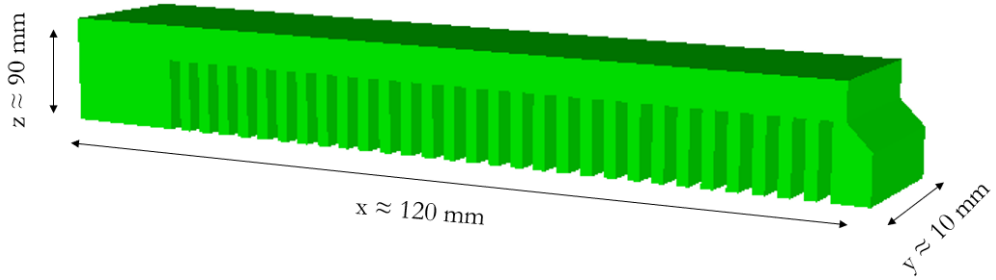
-LANL

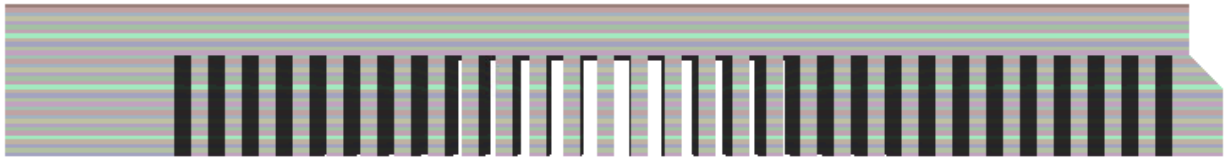
Model & Mesh Overview



'Short House' Geometry

- Number of Layers: 93
- Element Type: HEX8
- Number of Elements: 257108
- Two layers of elements per row





'Harmonica' Geometry

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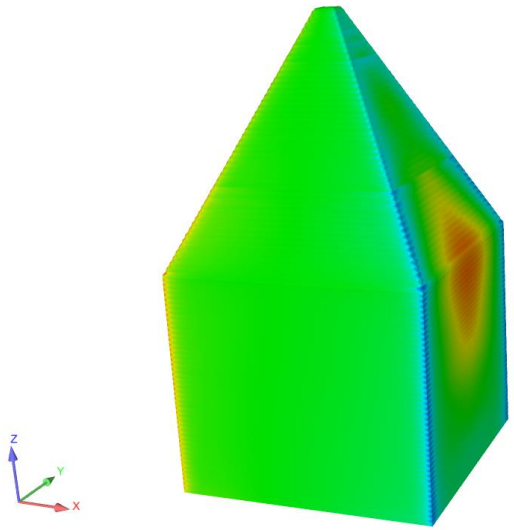
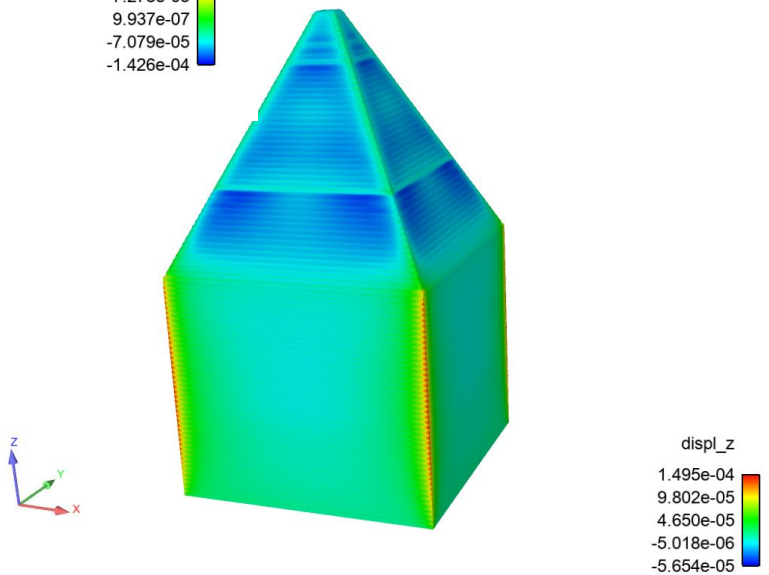
Shorthouse Results: Heat Treatment then EDM

Distortion of original part

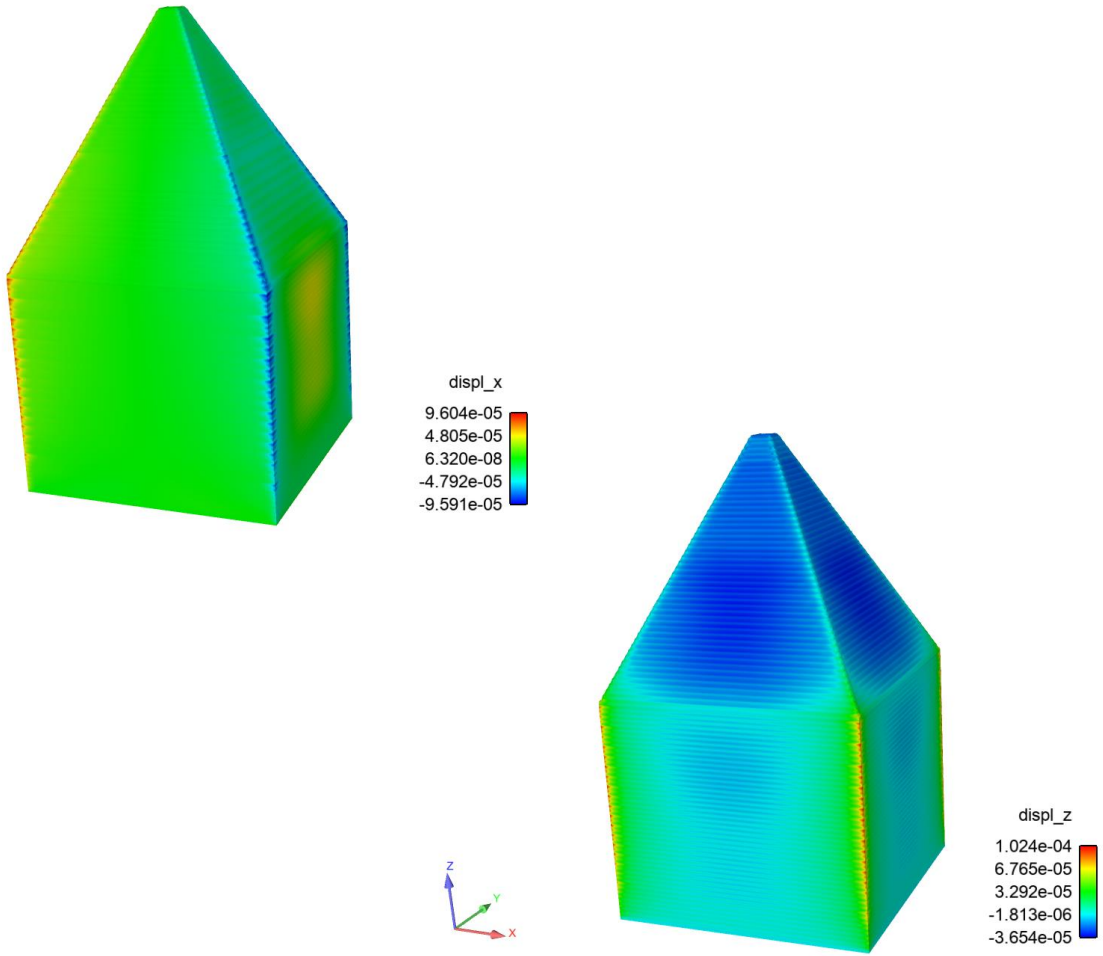


Distortion from as-designed-geometry of final iteration (2 iterations)



Shorthouse Results: EDM then Heat Treatment

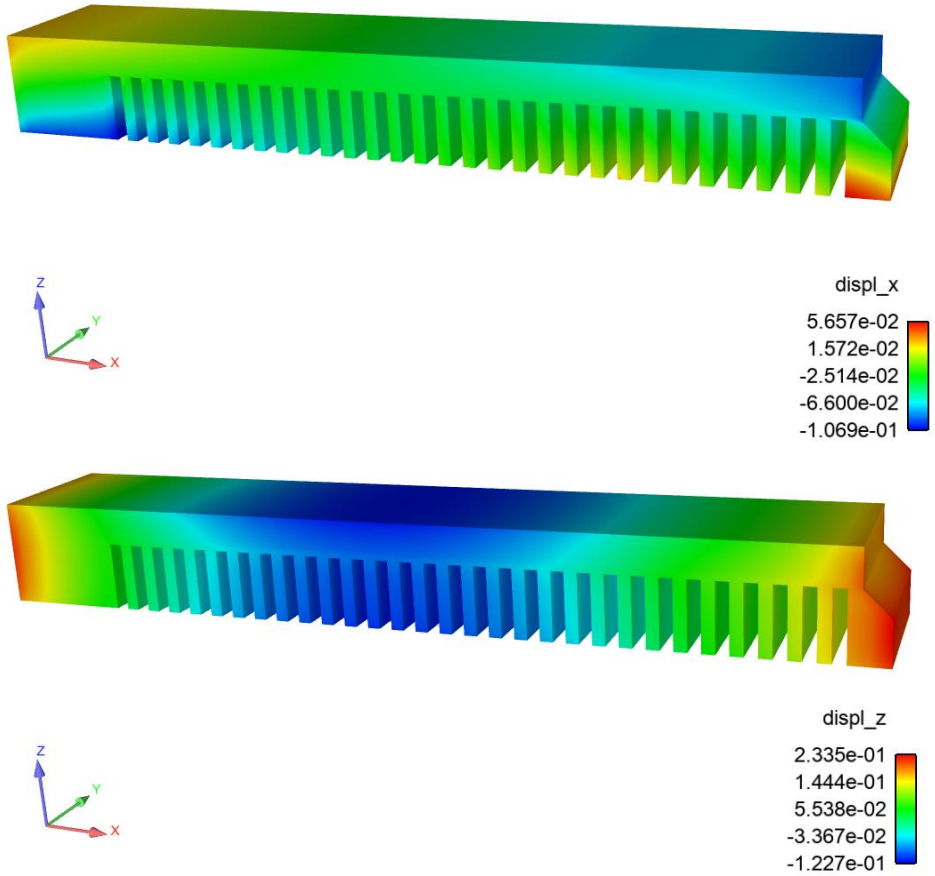
Distortion of original part



Distortion from as-designed-geometry of final iteration (3 iterations)

Harmonica Results: EDM then Heat Treat

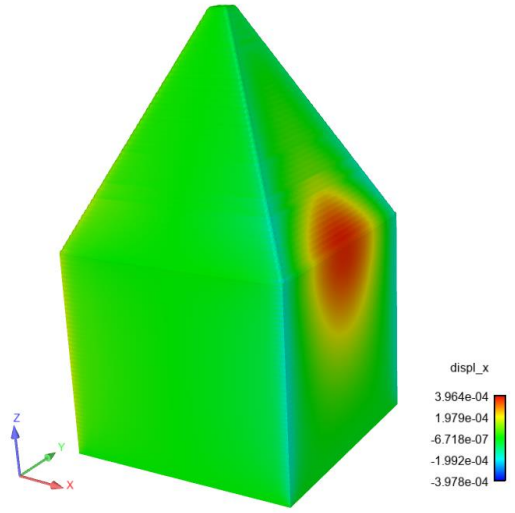
Distortion of original part

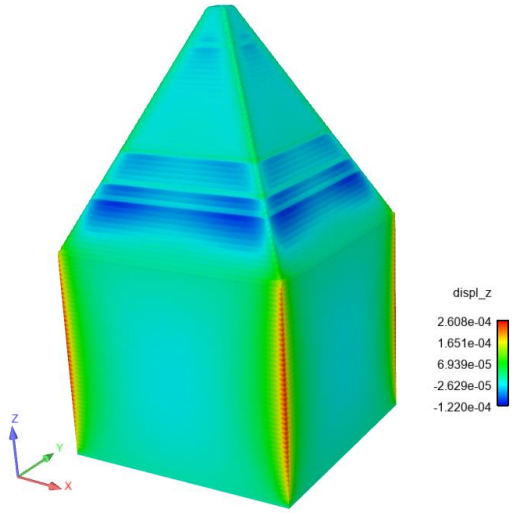


Distortion from as-designed-geometry of final iteration (failed)

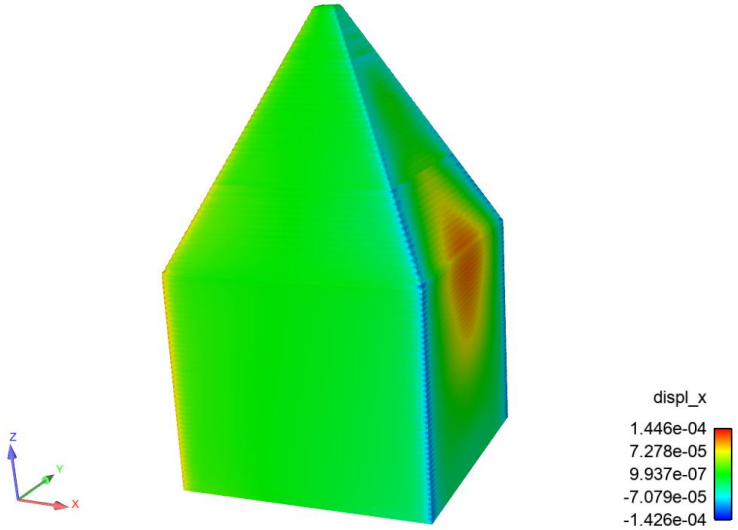
Comparison of distortion with and without heat treatment

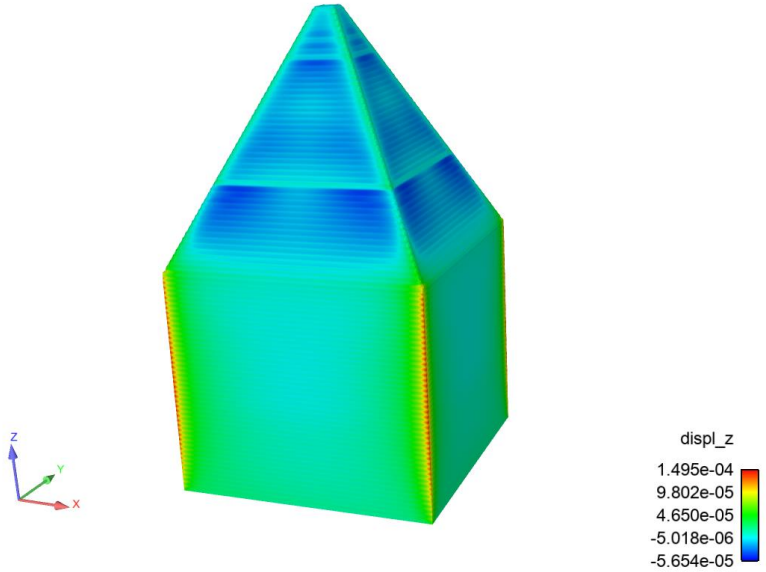
Build only





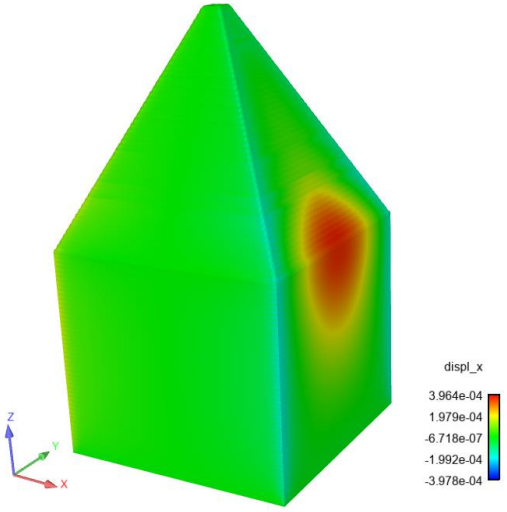
With EDM then heat treatment

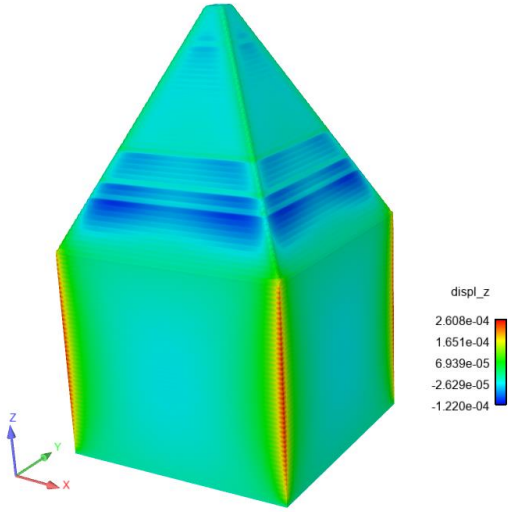




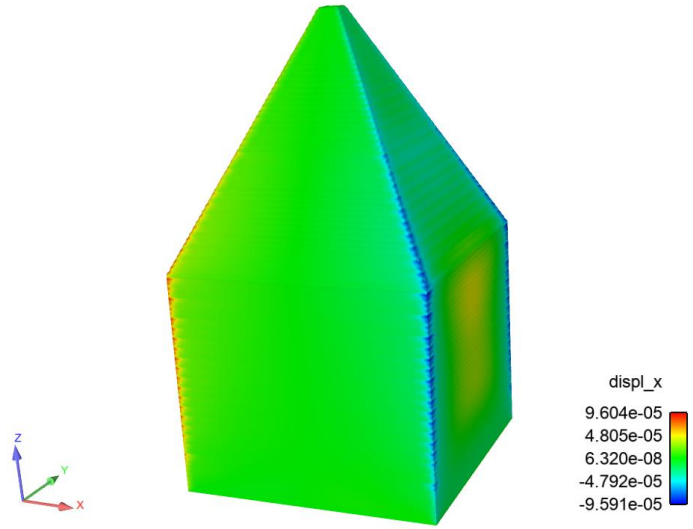
Comparison of distortion with and without heat treatment

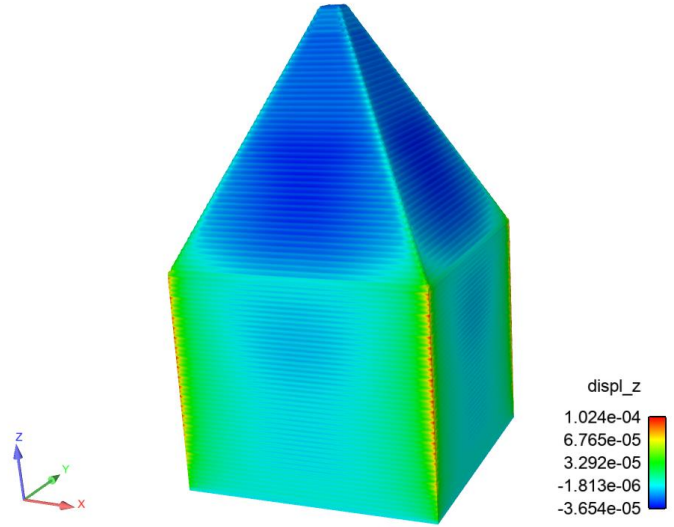
Build only





With heat treatment then EDM



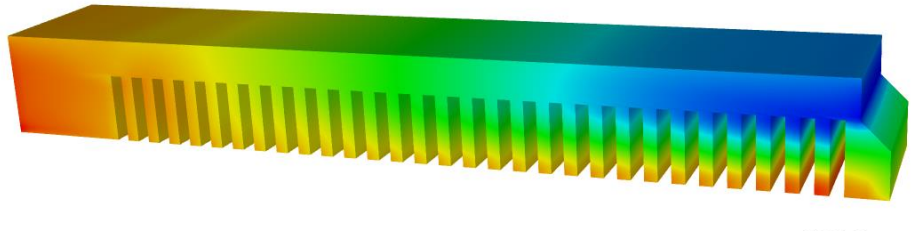


Harmonica Results: Heat Treatment then EDM

Distortion of original part

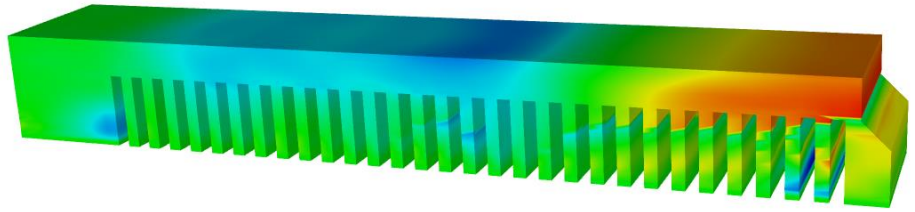
Distortion from as-designed-geometry of final iteration (2 iterations)

x-axis (horizontal)



Δx
6.050e-02
-2.542e-02
-1.113e-01
-1.973e-01
-2.832e-01

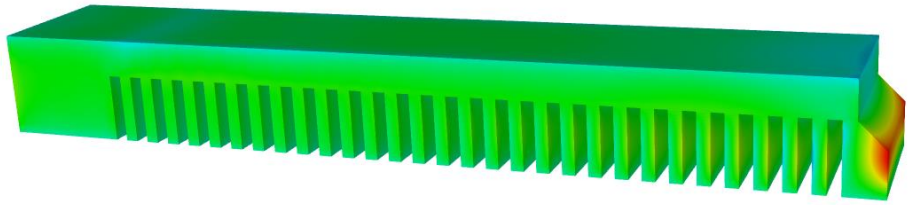
Max abs. x error = 0.259



Δx
3.100e-02
1.550e-02
0.000e+00
-1.550e-02
-3.100e-02

Max abs. x error = 0.030

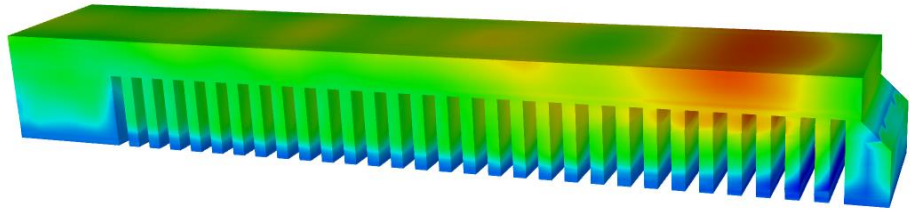
z-axis (height)



Δz
1.257e-01
8.083e-02
3.595e-02
-8.935e-03
-5.382e-02

Z
Y
X

Max abs. z error = 0.117



Δz
3.600e-02
2.575e-02
1.550e-02
5.250e-03
-5.000e-03

Max abs. error = 0.035