Distortion Compensation for Metal Additive Manufacturing

Collette Gillaspie (TAMU)
Mehmet Sirtalan (UW-Madison)
Theresa Honein (UC-Berkeley)

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Mentors
Kyle Johnson
Carl Herriott
Michael Stender
Ellen Wagman
Richard Deering (KCNSC)

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Contents

• Background information: Distortion in metal additive manufacturing
  ◦ Why distortion happens?
  ◦ How do we quantify it?

• Distortion compensation optimization algorithm

• Results validation: It works!
BACKGROUND & MOTIVATION
Metal Additive Manufacturing: Selective Laser Sintering (SLS)

Fig. 1 Video on metal additive manufacturing. [https://www.youtube.com/watch?v=yiUUZxp7bLQ](https://www.youtube.com/watch?v=yiUUZxp7bLQ)
Metal Additive Manufacturing: Selective Laser Sintering (SLS)

Fig. 2 Images of metal additive manufacturing.

Metal Additive Manufacturing
Problem Formulation
Deformation Prediction
Problem: Distortion

High temperature gradients → Residual stress → Stress causes distortion

Fig. 3 Distortion of uncompensated printed part relative to CAD geometry.
**Problem: Distortion**

High temperature gradients → Residual stress → Stress causes distortion

**Solution: Distortion Compensation**

Get deformations → Back apply them to initial geometry → Print modified geometry

**Goal: Printed Geometry Distorts Into Desired Geometry**
Deformation Prediction

- Modeling Approaches
  - Thermomechanical simulations
  - Inherent strain method: mechanical simulations
  - Modified inherent strain methods

Fig. 4 Element birth simulation using Abaqus.
https://www.youtube.com/watch?v=FqE3kp9ESVc

- Optical approaches

Fig. 5 ATOS Compact Scan: Blue Light 3D Scanner.
https://www.youtube.com/watch?v=T-RkQioXHYg
Deformation Prediction

- Modeling Approaches
  - Thermomechanical simulations
  - Inherent strain method: mechanical simulations
  - Modified inherent strain methods

- Optical approaches

Fig. 6 Element birth simulation using Abaqus. [Video](https://www.youtube.com/watch?v=FqE3kj9ESVc)

Fig. 7 ATOS Compact Scan – Blue Light 3D Scanner. [Video](https://www.youtube.com/watch?v=T-RkQioXHYg)
PROJECT WORKFLOW
Distortion Compensation Optimization Workflow

1. Desired geometry
2. Mesh geometry
3. Run FE simulation
4. Calculate error metric
5. Error < tol
   - yes: Print geometry
   - no: Distortion compensation algorithm (next slide)
Distortion Compensation Algorithm Workflow

Calculate node displacement from optimal location

- \( \text{disp}[t] \approx 0 \)
  - yes: Final scale factor
  - no: sign\( (\text{disp}[t]) = \text{sign}(\text{disp}[t-1]) \)
    - yes: Search upper half for new scale factor
    - no, yes: Scale\([t-1]\) < Scale\([t-2]\)
      - yes: Search opposite half of previous iteration for new scale factor
      - no: Search lower half for new scale factor

- Move nodes by a scale factor of the nodal displacement

Optimization Workflow
Algorithm Workflow
Algorithm Example
Distortion Compensation Algorithm Example

1. Apply initial distortion compensation (100%)
2. Distortion too high; same sign as initial distortion → increase scale to 125% for second iteration
3. Distortion changed sign → overcompensated! Invert previous operation: reduce scale to 112.5%
4. Distortion has same sign, decreased in magnitude → repeat previous operation: reduce scale to 106.25%
5. Distortion changed sign → overcompensated! Invert previous operation: increase scale to 109.375%

Distortion within tolerance after final iteration, print corresponding geometry.
PROJECT RESULTS
Model & Mesh Overview

- Number of Layers: 93
- Element Type: HEX8
- Element Size: 0.50 mm
- Number of Elements: 257108

- Number of Layers: 185
- Element Type: HEX8
- Element Size: 0.25 mm
- Number of Elements: 1531176
Material Models

- 300 series austenitic stainless steel (304L and 316L)
- Elastic model fit to widely established 304L data
  - Young’s modulus: 200e9 Pa
  - Poisson’s ratio: 0.25
- Elastic-Plastic model fit to 316L tensile data
  - Young’s modulus: 200e9 Pa
  - Poisson’s ratio: 0.3
  - Yield stress: 500e6 Pa
  - Hardening modulus: 500e6 Pa
  - Hardening exponent: 0.55

![Stress-strain curve for 316L stainless steel.](image)

**Fig. 8** Stress-strain curve for 316L stainless steel.
Element Birth Scheme

- Layer-by-layer element birth
- Inactive elements accumulate no thermal strains
Distortion Results: Elastic-Plastic Model

- Number of Processors: 128
- Inherent Strain Values:
  - Strain in x ≈ -2%
  - Strain in y ≈ -2%
  - Strain in z ≈ 2%
Distortion Results: As-Built Distortion Significantly Reduced

**Fig. 9** Simulated deformation of elastic-plastic model without distortion compensation.

**Fig. 10** Simulation deformation of elastic-plastic model with optimized distortion compensation.
Distortion Results: Elastic Model

- Number of Processors: 128
- Inherent Strain Values:
  - Strain in $x = -0.2\%$
  - Strain in $y = -0.2\%$
  - Strain in $z = 0.2\%$
Fig. 11 Simulated deformation of elastic model without distortion compensation.

Fig. 12 Simulation deformation of elastic model with optimized distortion compensation.

Distortion Results: As-Built Distortion Significantly Reduced
## Algorithm Statistics: Errors

<table>
<thead>
<tr>
<th>Model</th>
<th>Iteration</th>
<th>Iteration Avg 2-Norm Error</th>
<th>Minimized Avg 2-Norm Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic-Plastic</td>
<td>1</td>
<td>2.45E-7</td>
<td>2.45E-7</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>4.30E-8</td>
<td>4.17E-8</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3.32E-8</td>
<td>2.58E-8</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2.45E-8</td>
<td>2.58E-8</td>
</tr>
<tr>
<td>Elastic</td>
<td>1</td>
<td>1.70E-7</td>
<td>1.70E-7</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>3.49E-8</td>
<td>3.39E-8</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2.46E-8</td>
<td>2.06E-8</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1.96E-8</td>
<td>1.65E-8</td>
</tr>
</tbody>
</table>

**Fig. 13** Elastic-plastic model error per iteration.

**Fig. 14** Elastic model error per iteration.
## Algorithm Statistics: Runtimes

<table>
<thead>
<tr>
<th>Model</th>
<th>Average SIERRA Time per Iteration</th>
<th>Average EPU Time per Iteration</th>
<th>Average Algorithm Time per Iteration</th>
<th>Average Total Time per Iteration</th>
<th>Number of Iterations</th>
<th>Total Time for all Iterations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic-Plastic</td>
<td>21.5 min</td>
<td>4.3 min</td>
<td>7.1 sec</td>
<td>25.9 min</td>
<td>4</td>
<td>1.73 hrs</td>
</tr>
<tr>
<td>Elastic</td>
<td>20.4 min</td>
<td>5.8 min</td>
<td>9.8 sec</td>
<td>26.9 min</td>
<td>4</td>
<td>1.76 hrs</td>
</tr>
</tbody>
</table>

**Fig. 15** Elastic-plastic model runtime per iteration.

**Fig. 16** Elastic model runtime per iteration.
Conclusions & Future Work

• Conclusions:
  • The distortion of metal builds with SLS is an impediment to the reliability and widespread adoption of additive manufacturing.
  • We developed an efficient numerical distortion compensation optimization workflow which outputs a CAD file that will distort into the desired geometry when printed.
  • We developed a comprehensive tool to obtain a geometrically compensated stereolithography file from a mesh input.
  • We tested this algorithm on a thin house geometry, and it works!

• Future work:
  • Integrate coupled thermomechanical modeling techniques into the workflow.
  • Validate the algorithm with a printed proof-of-concept.
Acknowledgements

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THANK YOU!

We will take your questions at this time.
BACKUP SLIDES
IS vs MIS methods

\[ \epsilon_{to} = \epsilon_e + \epsilon_p + \epsilon_{th} + \epsilon_{pt} + \epsilon_{cr} \]
\[ \epsilon^* = \epsilon_{to} - \epsilon_e = \epsilon_p + \epsilon_{th} + \epsilon_{pt} + \epsilon_{cr} \]

Original inherent strain method
\[ \epsilon^* = \epsilon_p \]

Contribution of the plastic deformation to the IS of the AM process
\[ \epsilon^*_p = \epsilon_p \]

Contribution to the IS in the AM process
\[ \epsilon_{th} = \epsilon_e - \epsilon_e^S \]

Modified inherent strain model
\[ \epsilon^* = \epsilon_p^* + \epsilon_{th}^* \]

\( \epsilon_{to} \) total strain
\( \epsilon_e \) elastic strain
\( \epsilon_p \) plastic strain
\( \epsilon_{th} \) thermal strain
\( \epsilon_{pt} \) phase transformation
\( \epsilon_{cr} \) creep strain
\( \epsilon^* \) inherent strain
\( \epsilon_p^l \) largest compressive plastic strain at intermediate state
\( \epsilon_e^l \) elastic strain at the intermediate state
\( \epsilon_e^S \) elastic strain at the steady state
Compensated Geometry: Elastic-Plastic Model

**Fig. 17** Simulated deformation without distortion compensation.

**Fig. 18** Distortion compensated file (final geometry to be printed).
Compensated Geometry: Elastic Model

Fig. 19 Simulated deformation without distortion compensation.

Fig. 20 Distortion compensated file (final geometry to be printed).
Comparing Experimental Data vs Simulated Data for Uncompensated Build

Fig. 21 Elastic-plastic model.

Fig. 22 Elastic model.